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Comparison of soil improvement techniques on the development of efficient consolidation response

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Abstract

A comprehensive experimental program including two distinct series of consolidation tests was performed on clay specimens prepared at different dry weight proportions including 0%, 1%, 2.5%, 5%, 7.5%, 10% polypropylene fiber or lime by weight mixed with clayey soil. Fiber inclusion into clay resulted in enhancement of compressive strength characteristics, improvement of hydraulic properties that is an advantage for modification of stability and durability properties of clayey soil under loads. Similarly, the higher hydraulic conductivity of clay resulted that will shorten duration of consolidation settlement, hence, eventually influence completion of plastic consolidation deformation favorably for soft clays. Lime-treatment on clay specimens showed that the compressibility properties are improved such that the strength of clay against loading enhances, exhibits less consolidation deformation under load owing to increase in lime content. On the other hand, clay becomes highly impermeable, displays substantially larger water-resistant properties because of increased lime mass proportion (i.e. time-extension) in clayey soil that results in prolongation of expulsion of excess porewater pressure from clay due to load application, relevant induced stresses. Fiber-inclusion resulted in exhibiting logarithmic decrement with a mild rate of decline while lime-treatment led to exponential reduction with a sharp rate of drop for compression index (C_c), compressibility coefficient (α_v), volume compressibility coefficient (m_v). Further, fiber-inclusion stimulated exponential and quadratical increment whereas lime-treatment induced exponential decrement for coefficient of consolidation (c_v), hydraulic conductivity (k), respectively. As a result, the C_c, α_v, m_v enhanced on the order of within 10 at average of 80% to 90% with a minimum of 70% by value for both fiber-reinforcement and lime-stabilization soil-stabilization techniques. The c_v, k improved on the order of within 10 at average of 75% to 85% by value for fiber-reinforcement whereas dis-improved on the order of within 10 at average of 70% to 80% by value for lime-stabilization.

1. Introduction

The solution of geotechnical and geoenvironmental problems that arise in construction projects involves in application of various methods to strengthen soils, and thus, increase load bearing capacity and improve deformation and compressibility characteristics as well as enhance hydraulic properties. Within this context, the effectiveness of soil improvement techniques on the efficient consolidation response of clayey soils in landfill barriers is significant as the strength and deformation properties, and thus, the settlement characteristics of barriers ultimately affect the performance of barrier systems. Over the decades, a number of experimental studies have been carried out on this perspective by adding different additives (e.g. cement, lime, fly ash and fibers) to the soil in order to improve soil index and strength properties, and the results have been reported in the literature on a purpose to alleviate the geotechnical problems in engineering projects, and thereby, to find a solution to those problems. Furthermore, fiber reinforcement and lime stabilization are two widespread soil stabilization techniques extensively applied for design and implementation of infrastructural facilities. Fiber reinforcement is under a subcategory of soil reinforcement using randomly-distributed fiber-reinforced soils in the form of discrete filexible fibers (i.e. natural, synthetic or waste product fibers). The improvement of engineering properties of soft fine grained soils (i.e. clays) in terms of consolidation behavior and settlement response under loading can be facilitated by inclusion of polymeric fibers characterized by filexibity, modified stiffness so as that the firmness and steadiness of clayey soils will be enabled. On the other hand, lime soil treatment is a chemical process in which lime (quicklime, hydrated lime or lime slurry) is mixed with the in-place subgrade soil and a chemical reaction takes place. The lime reacts with the clay particles in the soil to create a relatively sturdy/intense cementitious matrix as compared to pure clays. To this end, in order to extend understanding for the effectiveness of fiber and lime soil improvement techniques on the development of efficient consolidation response, a comprehensive experimental program was carried out in the laboratory, the results and scientific findings of which will provide substantial technical benefit and profound knowledge on the proficient performance of fiber reinforcement and lime stabilization soil improvement methodologies applied in the field for the proper construction of infrastructural facilities. Further comprative analysis have been carried out to quantitatively present experimental investigation on the effectiveness and efficiency of soil stabilization techniques in consideration based on the detected values of engineering parameters and their variation with a change in fiber or lime contents for the improvement of clayey soil properties and enhancement of consolidation characteristics. The research work presented herein in the paper is unique in terms of clayey soil properties examined and the resulting engineering behavior detected as most of the previous studies dealt with unconfined compressive strength behavior, direct shear response, or triaxial behavior of fiber-reinforced and/or lime-stabilized clayey soils.

2. Soil stabilization

Under the application of loads and external forces, all soils will settle that will result in settlement of structures and infrastructures founded on or within them, respectively. If the settlement is not kept to a tolerable limit, the desired use of the structure/infrastructure may be impaired, and hence, the design life may be reduced. Structures in general may settle uniformly or nonuniformly. The latter condition is called differential settlement and is often the crucial design consideration. To this end, several soil stabilization techniques including physical stabilization, chemical stabilization and mechanical stabilization have been applied by the engineers in order to reinforce soil by modifying mechanical strength characteristics, by improving consolidation settlement behavior of clayey soils as well as by enhancing hydraulic properties (i.e. hydraulic conductivity or imperviousness characteristics) [1]. Among the most commonly employed stabilization methodologies for design and construction of infrastructural applications, the fiber reinforcement and the lime stabilization are the two primary techniques for which the scientific background will be discussed comprehensively and comparatively throughout this section.

2.1. Fiber reinforcement

Fibers as a densified reinforced polymeric composite material have attracted the attention of many researchers in the past. To explore the characteristics of fiber-reinforced soils, an enormous number of relevant experiments including unconfined compression tests, triaxial tests, CBR tests, direct shear tests, and permeability tests have been carried out within experimental programs run by the researchers. The most important ones of those studies can be listed as follows: Maher and Ho, [2]; Santoni and Webster, [3]; Cai et al. [4]; Tang et al. [5]; Tang et al. [6]. All these previous research findings have shown that the addition of fibers effectively and efficiently improves and increases the strength, ductility, and permeability of the soil. However, a comprehensive study on how and in what way the fiber additive affects the consolidation characteristics of the soil, based on detailed measurements, has not yet been presented in detail.

Fiber reinforcement based on the mixing of soil with randomly oriented fibers in the structure provides randomly distributed/dispersed discrete and flexible fibers (for example; natural, synthetic or waste product fibers) within the soil. On the other hand, the improvement of engineering properties of soft and fine-grained soils (e.g., clays), to what degree, in terms of consolidation behavior and settlement reaction under load can be achieved in what extent (i.e., in what optimum ratio) by the inclusion of the polymeric fibers characterized by flexibility and modified strength properties needs to be examined in detail. The primary advantage of randomly oriented and distributed fibers in the soil is the absence of potential planes of weakness which can develop parallel to the reinforcement in systematically reinforced soils that contain geosynthetic reinforcement inclusions, oriented in a certain direction and orientation, such as geogrids and geotextiles [7]. Furthermore, many researchers have performed triaxial, unconfined compression, CBR, direct shear, tensile and flexural strength tests on soil specimens reinforced with paper, metal, nylon, and polyester fibers that one of the primary ones of those studies was conducted by Kumar et al. [8]. As such, the incorporation of polyester fibers into a highly compressible clay resulted in a significant increase in unconfined compressive strength of clayey soil was observed. They revealed that an increase in strength of about 50% to 68% when added to clayey soils at 0.5% to 2% dry weight ratios from 3 mm sized fibers. They also reported a 70% increase in strength when 6 mm straight and crimped fibers were used, while a 115% increase in strength was observed when 12 mm fibers were used. Those experimental findings showed that the strength could be increased by increasing the fiber percentage. Those results were similar and comparable with that obtained by Tang et al. [9] who reinforced kaolin clayey soil with polypropylene fibers and as a result of which they observed a significant increase in unconfined compressive strength. Similarly, steel fibers can increase the strength of soil, but this strengthening method cannot be compared to the increase in strength obtained using other fiber types [10, 11]. Furthermore, as a distinct approach in the assessment of different soil improvement methods, the strength and stiffness optimization of fly-ash admixed deep cement mixing (DCM) columns constructed in clayey silty sand was extensively studied by Ekmen et al. [12] and revealed how the targeted strength and stiffness values defined in the guidelines can be achieved considering the water content and the incorporated cementitious materials. Similarly, an optimization of fiber-reinforced deep cement-fly-ash mixing column materials was studied by Ekmen and Algin [13]. The effects of mixture quality responses on the performance of DCM columns per strength considerations were investigated. They revealed that the incorporation of carbon fiber significantly improves the mixture quality characteristics of segregation and swelling as well as the parameters of flexural strength and unconfined compressive strength.

2.2. Lime stabilization

Lime stabilization is based on a chemical process established through physical mixing with the in-place soil along with addition of limited amount of water to facilitate (i.e. catalyze) and accelerate the chemical reaction for the formation of clay-lime cementitious matrix. In this regard, lime is preferred to be utilized as a modifier as well as a binder for cohesive high or low plasticity soils such as clays. The benefits/outcomes of lime treatment of clayey soils involves in; (i) the treatment of clays with high plasticity results in a decrease of the plasticity index, and thus, the clay becomes possessing less affinity with water to exhibit substantial volume changes (dilation and/or expansion), (ii) the pozzolanic action in fine grained cohesive soils accompanies strength increment in soil, (iii) lime can also provide binding action even for admixture soils including course grained (i.e.granular) soils in addition to fine grained (i.e. cohesive) soils. The lime-treatment process principally being a chemical stabilization method comprised mainly of chemical reactions in between lime and soil particles such that an improvement for the performance of soil layer is achieved by controlling volume change, and also, by increasing strength. The mineralogical properties of the soils, as per stabilization, determines their degree of reactivity with lime, and hence, the ultimate strength that the stabilized layers will develop. Owing to pozzolanic action in fine grained soils such as clays, the strength increment (i.e. gaining resistance against loads) is particularly expected in clayey soils so as that the stabilization of the soil layer is accomplished [1, 14].

In the lime-treatment process, there are two stages of soil-lime chemical reaction. The initial stage – categorized as immediate or short-term treatment – develops within a few hours or days after the lime admixed with soil in which three primary chemical reactions, namely as; cation exchange, flocculation-agglomeration and carbonation are observed. The latter stage – categorized as long-term treatment – requires several months or years for completion in which a principal chemical reaction, namely as pozzolanic reaction is detected [14, 15]. During the course of lime-treatment process, the increase in soil workability as a result of drying of wet soil is attributed to immediate treatment and the increase in soil strength and durability is associated with long-term treatment [16]. As such, the calcium ions (Ca^{+2}) and the hydroxide anions (OH^{-}) are produced as a result of the addition of lime into soil multiphase system including water in pore space. Then, during the process of cation exchange in soil, bivalent calcium ions (Ca^{+2}) are replaced by monovalent cations. The Ca^{+2} ions link to the soil minerals possessing negative charges in the encapsulation of diffused double layer, and thus, resulting in reduction of the repulsion forces leading to the shrinkage of thickness of the diffused double layer (i.e. water layer) around clay particles so as that the bonds between the soil particles are strengthened. The reduction in the thickness of diffused double layer results in the proximity (i.e. closeness) of clay particles, thereby the soil texture changes and the multiphase soil matrix becomes densified causing a strength increment in the soil. The remaining hydroxide anions (OH^{-}) in the solution existing in the voids (i.e. pore spaces) of soil media catalyze and induce an increment in alkalinity. This physiochemical process is called as flocculation and agglomeration which is the main factor of the increase in the strength of soil or the enhancement of the bearing capacity to exhibit better performance and greater resistance against loadings [17].

3. Experimental methodology

A comprehensive experimental program was conducted to comparatively examine effectiveness of soil stabilization methods including fiber-reinforcement and lime-stabilization for development of efficient consolidation response, thereby, to investigate effect of stabilization, improvement of clay properties. In this way, the influence of fiber and lime soil improvement techniques on the development of relatively more effective consolidation responsive behavior was investigated. Within the scope of the study, the results and the scientific findings will provide substantial technical benefit and profound knowledge on the proficient performance of fiber reinforcement and lime stabilization soil improvement methodologies applied in the field for the proper construction of infrastructural facilities. Since the research work presented herein in the paper is unique in terms of clayey soil properties examined and the resulting engineering behavior detected as most of the previous studies dealt with unconfined compressive strength behavior, direct shear response, or triaxial behavior of fiber-reinforced and/or lime-stabilized clayey soils while this study in particular is interested in efficient consolidation behavior of clayey soils for which the engineering strength and durability properties are enhanced and improved by means of two widespread soil improvement methodologies including fiber-reinforcement and lime-stabilization. Within this scope, the experimental methodology conducted in the laboratory for performing the comprehensive testing program will be explained along with the knowledge provided on the engineering properties of the testing materials as well as the description given regarding to the testing device and the experimental procedures carried out for the preparation of test specimens, installation of the equipments and the placement of the specimen in the experimental set-up.

3.1. Materials

A fine grained cohesive soil selected to be used in the testing program was Bentonite (Figure 1a) that is an industrial clay for which the physical, chemical and index properties are suitable for the engineering standards. The lime (Figure 1b) admixed into the clayey soil as a stabilizing agent was slaked lime of which the chemical composition is comprised mainly of Calcium (CaO) that transforms to a white powder and constitutes $Ca(OH)_2$ by reacting with water vapor in the air, thereby leading to obtain white amorphous material. The fiber (Figure 1c) added and mixed with the clayey soil is produced from a base polymer of polypropylene (PP) which inherently posesses enhanced material characteristics including relatively high tensile strength, durability, and toughness properties.

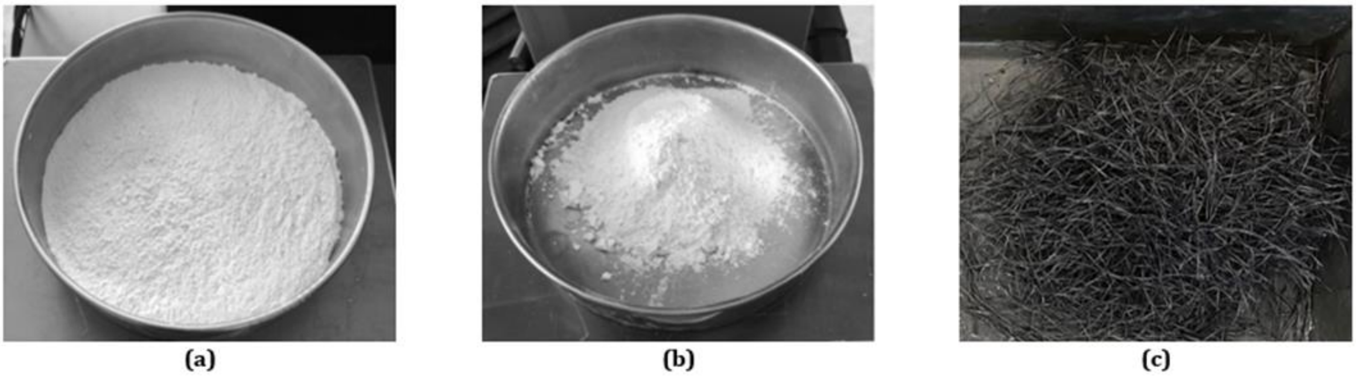

(a) (b) (c)

Figure 1. Materials tested: **(a)** Bentonite Clay; **(b)** Lime; **(c)** PP Fiber.

The powdered form sodium bentonite clay used in the testing program is comprised of the montmorillonite group of minerals. As such, the bentonite clay used in the experimental program is an absorbent swelling clay consisting mostly of montmorillonite and is classified as high plasticity clay (CH) based on USCS that was determied by following an ASTM standard on standard practice for classification of soils for engineering purposes [18]. Accordingly, the mean grain size (D_{50}) and the effective particle size (D_{10}) for the tested bentonite clay are 79 μm and 46 μm, respectively. Moreover, the physical (specific gravity: G_s [19] and the index properties [20] (liquid limit: LL; plastic limit: PL; plasticity index: PI)) of the bentonite clay, determined by following an ASTM standard on standard test methods for specific gravity of soil solids by water pycnometer [19] and an ASTM standard on standard test methods for liquid limit, plastic limit, and plasticity index of soils [20], respectively, is presented in Table 1. Prior to use in the testing program, the slaked lime composed of 82% calcium has been sieved to 2 mm. Accordingly, the residue weight after the screening of 2 mm was 5% by content. The moisture content (w) of the lime used in the experimental program was 2%. Further, the CO_2 content in the lime was 6%. Those properties of lime comply with the relevant Turkish standard – TS EN 459-1 [21] which determines and reports the criteria for conformity and specifications of construction lime.

The polypropylene (PP) fiber used in the testing program is one of the most common synthetic materials employed in the infrastrcutural applications to reinforce soil owing to its adventageous inherent properties including nontoxicity, corrosion resistance and high tensile strength. The physical and mechanical properties of PP fiber used is presented in Table 2 below.

Table 1. Physical and index properties of bentonite clay.

Material	G_s	LL	PL	PI
Bentonite	2.74	298%	59%	239%

Table 2. Physical and mechanical properties of PP fiber.

Property	PP Fiber
Average Diameter, D (mm)	0.02 – 0.05
Density, ρ (g/cm³)	0.9
Tensile Strength, τ_{max} (MPa)	360
Maximum Elongation, ε_{max} (%)	15

3.2. Testing device

Consolidation is the time-dependent elasto-pastic settlement of soils resulting from the expulsion of water from the soil pores. This important plastic deformation response (i.e. settlement behavior) of particularly fine grained soils including clays can be measured as well as the resulting detected behavior can be evaluated by means of a very useful device called oedometer (i.e. 1D consolidation device). As such a floating ring cell consolidometer in which the ring containing the soil sample is unrestrained in the container was utilized in the laboratory to perform consolidation tests on clayey soil –fiber or lime admixture specimens in order to evaluate as well as comparatively examine the effectiveness and the efficiency of soil stabilization techniques including fiber reinforcement or lime stabilization, respectively (Figure 2).

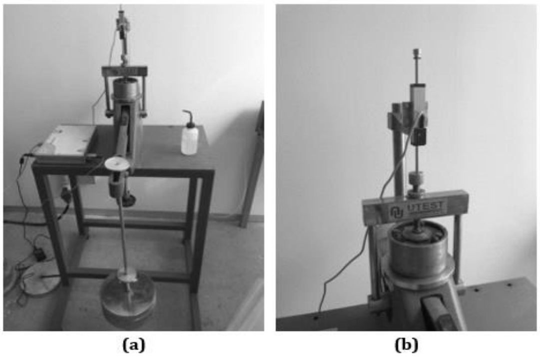

(a) (b)

Figure 2. Testing device: **(a)** Consolidation device; **(b)** Floating ring cell consolidometer (Close up view).

A linear variable differential transformer (LVDT) was employed in the system to measure vertical displacement in evaluating consolidation deformations developing in the soil specimen under the application of load during the tests. The LVDT sensors employed in the automated testing system were calibrated prior to the experimental program. As a result of precise calibration procedure comprised of accurate proper technical measurements, the regression trend lines with a perfect values (i.e. > 99%) of coefficient of determination (R^2) have been obtained which shows that the data readings from the LVDT are perfectly consistent and identical with the real displacement measurements. The displacement readings are logged into a computer through a multi-channel data logger such that the communication with the computer is enabled using RS-232 ports for which the frequency is arranged as 2400 Hz with a bid period of 1/2400 facilitating data streaming in $4.17x10^{-4}$ seconds. Consequently, the on-time readings of the sensors can be detected and monitored on the user interface of the testing controller program on the computer screen effectively with a relatively very good data transfer intervals. Accordingly, the noise correction process was handled and performed automatically by the controller program. As such, the processing/operating steps of the program is in such a way that the controller software gathers current in-time data readings from the sensors and the instrumentation available on the consolidation device, and thereafter, converts those data readings to engineering units (quantities) for measuring and identifying the current engineering behavior.

3.3. Experimental procedures and testing program

A consistent, proper and repeatable experimental procedure based on test standards was conducted in the laboratory for the fiber-reinforcement as well as the lime-stabilization processes. As such, for fiber-reinforcement work in the laboratory, a predetermined amount of fibers was added to the pulverized soil, and subsequently mixed and moisture conditioned. Subsequently, the mixtures were placed into the mould and appropriately mixed with the stirring rod so that the even and homogeneous distribution of fibers in the soil was accomplished. Later, test sample was compacted in three layers by static pressuring method to obtain an optimum moisture content, w_{opt} (%) = 20% reached in a consistent manner [22]. The formation of weak surfaces between each sequential neighbor layers was prevented in such a way that the surface of the initial layer soil is deeply scraped by rhombus with a cutter, then the second layer soil is placed into the mould and compacted for ten minutes. Thereafter, the sample was extracted from the mould, and then, trimmed and shaped into stiff consolidometer metal ring. On the other hand, for lime-stabilization work in the laboratory, the pulverized soil is mixed with lime, and then, moisture conditioned. The curing room has relative humidity of 95% and ambient temperature of 20 °C. Further, the curing age was maintained 28 days after which the test specimens were compacted to the required compaction level with an optimum moisture content, w_{opt} (%) = 20% attained consistently. Afterwards, the specimens were trimmed, moulded and placed in the stiff consolidometer metal ring.

One-dimensional consolidation test, based on Terzaghi's one-dimensional consolidation theory; aims to investigate consolidation parameters by providing drainage in the vertical direction under a controlledly increased vertical stress in the sample where horizontal deformation is prevented. For the assessment of fiber reinforcement on the develeopment of efficient consolidation behavior, the homogeneous admixtures were prepared by adding polypropylene (PP) fiber into bentonite clay at predetermined dry weight ratios as listed in Table 3. Subsequent to this, those prepared sample mixtures were made ready for consolidation test by adding water, and thereafter, kneading them. Afterwards, the one series of one-dimensional (1D) consolidation tests was carried out on those clay specimens prepared at different dry weight proportions including 0%, 1%, 2.5%, 5%, 7.5%, and 10% polypropylene (PP) fiber by weight mixed with clay soil using the oedometer (Figure 2) to determine the compressibility properties and consolidation parameters as well as hydraulic characteristics (C_c, α_v, m_v, c_v, k) of fiber – bentonite admixtures by following an ASTM standard on the test method for one-dimensional consolidation properties of soils [23].

Table 3. Dry weight proportions of PP fiber added or lime mixed with bentonite clay.

Weight Proportions	**1**	**2**	**3**	**4**	**5**	**6**
Fiber Content in Clay	0%	1%	2.5%	5%	7.5%	10%
Lime Content in Clay	0%	1%	2.5%	5%	7.5%	10%

For the assessment of lime stabilization on the development of efficient consolidation behavior, the other series of consolidation tests [23] were performed in the laboratory at different lime contents (lime:lime-clay-mixture proportions by dry weight: 0%, 1%, 2.5%, 5%, 7.5%, and 10%) on the test specimens prepared in the laboratory to investigate the effect of lime-stabilization, and thereby, the improvement of clay properties (Table 3). Turkish Lime Stabilization Specification [24] was followed for proper determination of appropriate index and physical properties. The results of consolidation tests conducted were used to determine consolidation engineering parameters including; compression index (C_c), compressibility coefficient (α_v), coefficient of volume compressibility (m_v), coefficient of consolidation (c_v) for evaluating load versus consolidation deformation behavior as well as to identify an important hydraulic property such as coefficient of permeability (k) for assessing hydraulic characteristics.

A predetermined amount of fibers was added to the soil and mixed by hand. Then, the mixtures were put into the mold and mixed with the stirring rod so that the fiber evenly distributed. Sample was compacted in three layers by static pressuring method [22]. In order to avoid the formation of weak surface between each two layers, the surface of the first layer soil is deeply scraped by rhombus with a cutter, thereafter the second layer soil is put into the mold and compacted, and finally, the sample was taken out from the mold. The fiber-clay as well as the lime-clay samples were formed, moulded, and shaped as a disk of soil test specimens (i.e. diameter: 6.0 cm and height: 2.5 cm), enclosed in a stiff metal ring, 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. As such, both the metal platen and the upper porous stone can move vertically inside the ring as the soil settles under the applied vertical stress. In this way, the soil specimen inside the ring was loaded and the resulted vertical displacement (i.e. elasto-plastic one-dimensional consolidation deformation) was measured and recorded in the computer by means of the testing controller program to obtain consolidation behavior, and thus, settlement response of the admixture soil specimens.

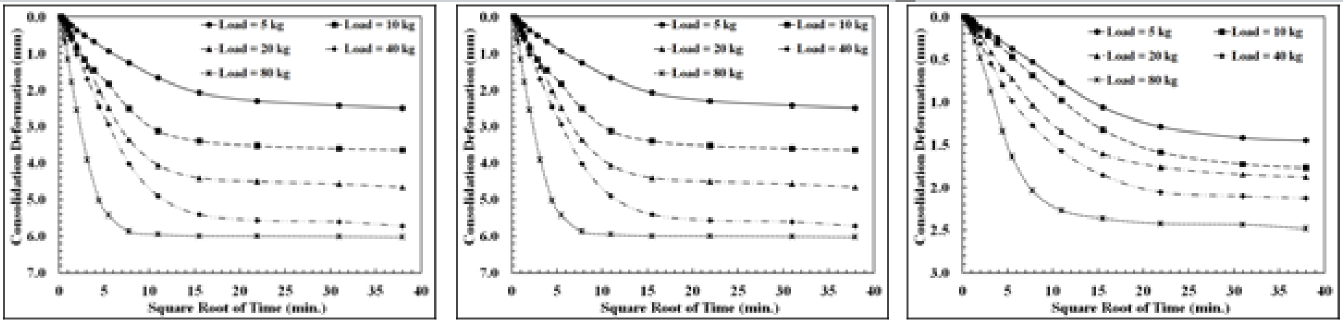
During the test progress of consolidation process, incremental loads were applied to the platen, and the settlement of the soil specimen at distinct fixed times under each load increment was measured by the transducer (LVDT). Each test continued five days with sequential incremental loads of 5, 10, 20, 40, and 80 kg, successively. As such, each load increment was doubled and allowed to remain on the soil until the change in settlement is negligible and the excess porewater pressure developed under the current load increment has dissipated. For many soils, this usually occurs within 24 hours. Therefore, the vertical displacements (i.e. consolidation deformations) occurred in the specimen at every load increment were measured and recorded automatically in the computer over 24 hours (i.e. 1 day) at time intervals of logged data as follows: 0.05, 0.1, 0.2, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, 960, 1440 minutes, successively. Further, it should be emphasized that the ratio of the load increment to the previous load called as the load increment ratio (LIR) was selected as two conventionally and intentionally to see the proper consolidation behavior. Similarly, the measurement time interval for reading the deformations develeoped in the specimen under loading were also selected with the increment ratio of two purposefully and intentionally to examine consolidation behavior in a comprehensive manner by following an ASTM standard on the test method for one-dimensional consolidation properties of soils [23].

4. Fiber reinforced cohesive soils

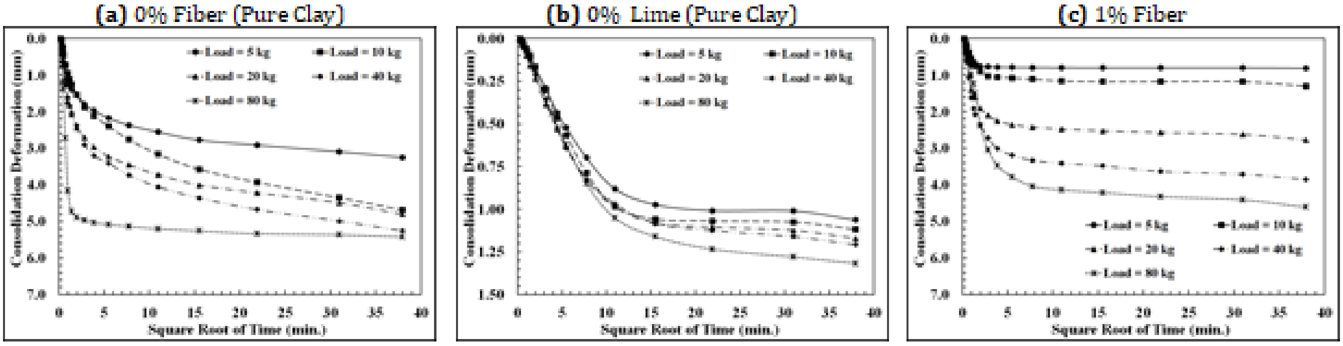
Test results and experimental findings obtained as a result of a series of consolidation tests applied to a variety of admixture clay specimens prepared at different dry weight proportions ranging from 0% up to 10% polypropylene (PP) fiber by weight within the scope of laboratory test program carried out to examine the improvement of engineering properties in terms of consolidation behavior and settlement reaction under load application for fiber-reinforced fine grained soils constituted by the random distribution of discrete and flexible fibers in the soil will be presented in detail throughout this section.

4.1. Development of consolidation deformation with time

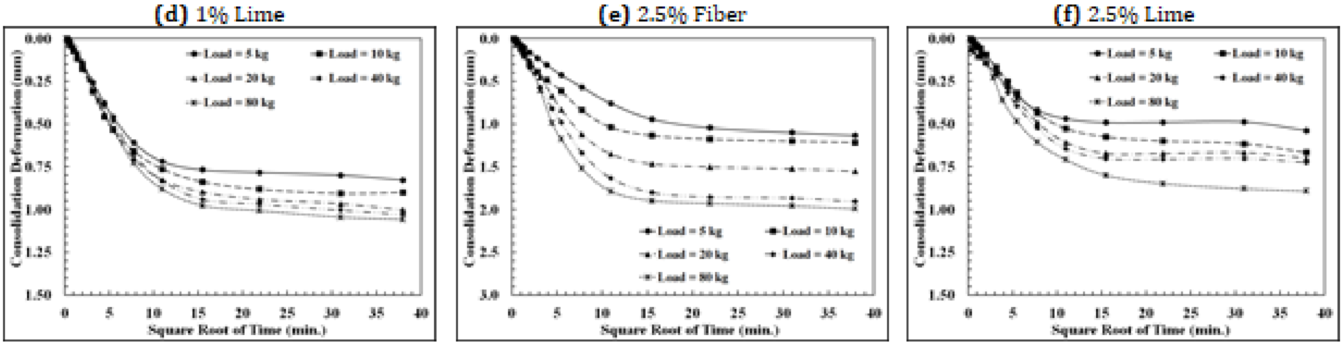
The development and progression of consolidation deformation with time is presented by means of the generated deformation curves obtained as a result of one-dimensional (1D) consolidation tests applied on clayey admixture soil specimens prepared by mixing polypropylene (PP) fiber at different dry weight ratios ranging from 0% up to 10% by dry weight with clayey soil are shown in Figure 3. The consolidation deformation responses of the clayey specimens containing different fiber contents as presented from Figures 3a, 3c, 3e, 3g, 3i, and 3k for; (i) 100% Bentonite – 0% Fiber, (ii) 99% Bentonite – 1% Fiber, (iii) 97.5% Bentonite – 2.5% Fiber, (iv) 95% Bentonite – 5% Fiber, (v) 92.5% Bentonite – 7.5% Fiber, (vi) 90% Bentonite – 10% Fiber admixtures, respectively, under different and successively increased loading conditions ranging from 5 kg up to 80 kg with a load increment ratio of two between two consecutive loads are unique. As such, the curves obtained generally demonstrates settlement deformations with a decreasing rate at the beginning, and thereafter, reaches to a saturation value, and thus, maintains more or less constant along with marginal and trivial varitions and deviations from constant saturation value, respectively. Regardless of the mixing ratios (i.e. the amount PP fiber in the admixture), the one-dimensional (1D) deformation/displacement increased with an increase in the magnitude of load for each soil specimen tested. In other words, the larger 1D displacements were detected at greater loads in all clayey soil admixture specimens. In addition, as the fiber content in the soil increased, the magnitude of the 1D deformations observed under different loading conditions decreased. That is to say, as the fiber mass proportion in the soil content increased, the soil samples containing a higher amount of fiber became more resistant against the load as well as against the external forces, and thereby, showed larger strength as well as they were subjected to much less 1D deformation, and hence, the amount of displacement occurred decreased when one-to-one comparing each applied load among themselves in the testing program (Figures 3a, 3c, 3e, 3g, 3i, and 3k).



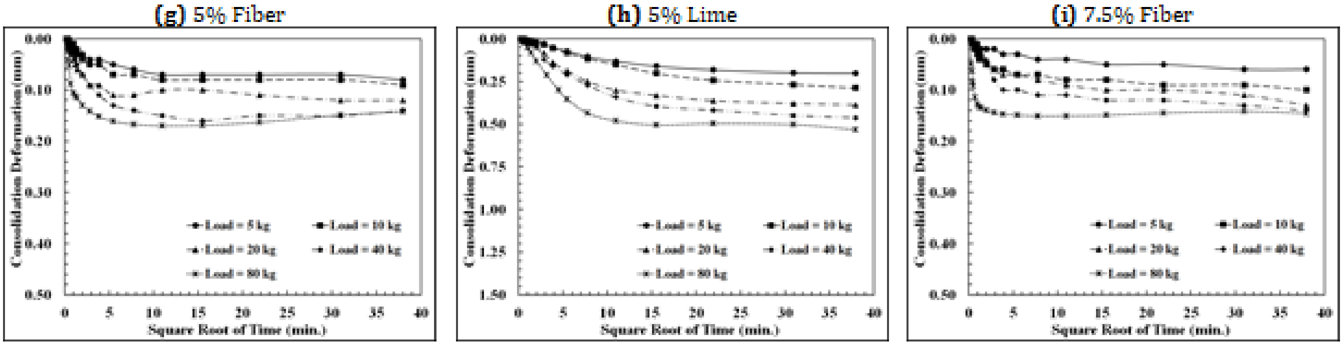
(a) 0% Fiber (Pure Clay) **(b)** 0% Lime (Pure Clay) **(c)** 1% Fiber



(d) 1% Lime **(e)** 2.5% Fiber **(f)** 2.5% Lime



(g) 5% Fiber **(h)** 5% Lime **(i)** 7.5% Fiber



(j) 7.5% Lime **(k)** 10% Fiber **(l)** 10% Lime

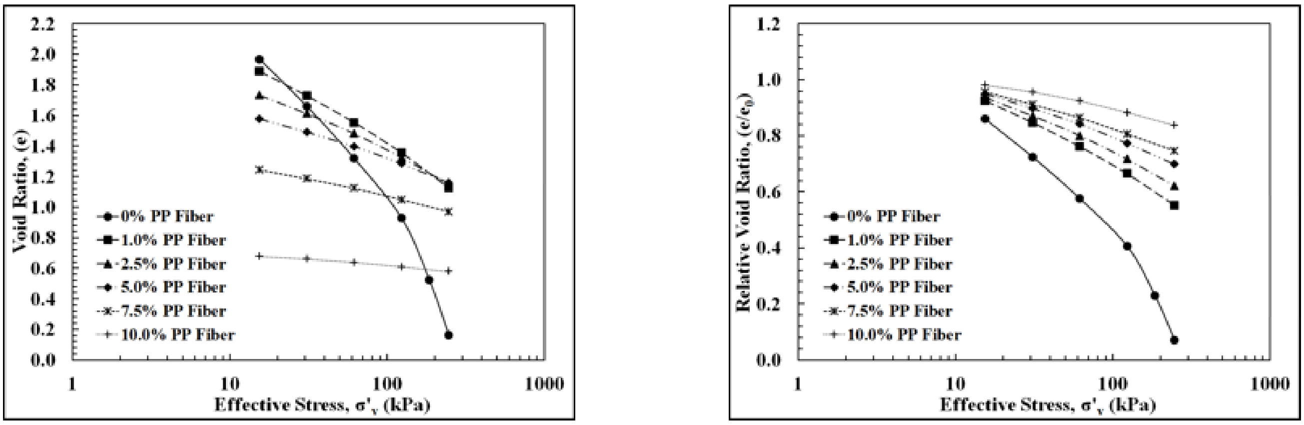
Figure 3. Development and progression of consolidation deformation with time at different **fiber (a, c, e, g, i, k)** or **lime (b, d, f, h, j, l)** contents (Scales of y axis in plots are different to show/highlight development of diverse behaviors).

4.2. Volumetric compression under increasing loading

As explicitly known, for one-dimensional consolidation, the volumetric strain (ε_{3D}) is analogous and equivalent to the vertical strain (ε_{1D}). In this regard, in order to examine the development of the settlement response in clayey soil under gradually increasing load, the void ratio (e) versus effective stress (σ'_v) curves were developed by using 1D deformation data obtained as a result of the consolidation test, and in this way, the consolidation behavior of the clayey soil has been investigated and revealed. Those developed curves provide explicit information about how severe the clayey soil will settle under loading in the field, that is, its consolidation response under increasing load and the settlement reaction the soil will mobilize to compensate the applied loads and external forces. Within this context, the void ratio (e) – effective stress (σ'_v) as well as the relative void ratio (e/e_0) – effective stress (σ'_v) curves of clayey soils containing PP fiber at different dry weight proportions are presented in Figure 4a and Figure 4b, respectively. As such, the mobilized volumetric compression (Figure 4a) as well as the observed relative volumetric compression (Figure 4b) behaviors of fiber-reinforced cohesive soils as a function of varied fiber contents under increasing loading conditions were investigated accordingly. In this way, an innovative engineering evaluation parameter being the relative void ratio (e/e_0) was developed and proposed in the study in order to identify and realize the reduction in void ratio, and hence, the change in volumetric contraction (compression) with respect to the increased load relatively in comparison to the magnitude of initial void ratio of the soil specimen tested.

The maximum decrease in void ratio with increasing load was exhibited in pure bentonite (100% Bentonite – 0% Fiber). On the other hand, the least change (decrease) in the void ratio was displayed in 90% Bentonite – 10% Fiber specimen containing the largest amount of fiber among different admixture soil samples. In other words, as the fiber content in the cohesive soil increases, the reduction in the void ratio under increasing load gradually reduces. The decrease in the void ratio in cohesive soil indicates/remarks consolidation settlements that occur as a result of water escaping from the soil due to loading; that is, subsequent to the outflow of water, the deformations that follow up in the clayey soil are reduced by the fiber additive and inclusion which results in soil ground showing greater strength, and thereby, becoming more resistant and robust against external forces and loads. While the void ratio (e) – effective stress (σ'_v) curve in pure bentonite is more vertical and inclined; with the increase in fiber additive and content added/mixed into the cohesive soil, this slope decreases and the curve becomes more horizontal and displays relatively lateral fashion response (Figure 4a).

The curve of relative void ratio (e/e_0) belongs to pure clay (100% Bentonite – 0% Fiber) exhibits a distinct and exceptional behavior as compared to all other admixture soils such that a substantial decrease in the value of the e/e_0 was displayed along with a relatively large slope of this sharp reduction occurred with an increase in load. This dissimilar response observed in the pure clay is attributed to the absence of reinforcing PP fibers in cohesive soil that resulted in the mobilization of larger consolidation deformations generated under induced external loads. Additionally, the relative void ratio (e/e_0) curve of the pure clay is located at lower place of the void ratio versus effective stress space as compared to the locations of curves belongs to the fiber mixed specimens. Further, as the fiber content in the cohesive soil increases, the curve is located at higher locations on the graph space owing to the benefit of fiber addition/inclusion into the soil that leads to smaller reductions displayed in the detected value of void ratio, and thus, relatively lower magnitude of volumetric contractions developed resulting in smaller amount of consolidation deformations mobilized in clay under load application. Moreover, the slope of the curves became smaller with increasing fiber content that the inclusion of the PP fiber into clay improves load resistance, and hence, bearing capacity of the cohesive soil. As such, while the relative void ratio (e/e_0) – effective stress (σ'_v) curve for pure bentonite was displayed more vertical and inclined, this slope decreased and the curve became more horizontal and exhibited relatively lateral fashion response with an increase in fiber additive/content added/mixed into the cohesive clayey soil. Consequently, the enhancement of mechanical properties and consolidation characteristics in terms of the improvement of consolidation deformation/settlement features by showing greater resistance against applied loads have been achieved because of the contribution of PP reinforcing fibers into the clay (Figure 4b).



(a) **(b)**

Figure 4. Volumetric compression **(a)** and Relative volumetric compression **(b)** versus Incremental loading for **fiber** reinforced cohesive soil.

4.3. Consolidation engineering design parameters

Using the consolidation curves (void ratio (e) – effective stress (σ'_v)) and the displacement curves (consolidation deformation – root time) developed based on experimental data/findings obtained from the test measurements, the compression index (C_c) and the consolidation coefficient (c_v), respectively, were determined. In this way, the most crucial engineering design parameters required to evaluate the consolidation deformation behavior and settlement response properties under different load conditions in the field are; the compression index (C_c) (Figure 5a) for the further evaluation of the load-deformation characteristics (mechanical properties); and besides, the coefficient of consolidation (c_v) (Figure 5b) were attained for the assessment of the rate/speed of consolidation settlement as well as hydraulic properties and its variation with fiber addition/inclusion was investigated.

The following theoretical methods were carried out to determine the engineering design parameters including consolidation strength-deformation-time properties:

- The compression index (C_c) (Equation 1) – that is the average slope of compression stage in the e versus log(σ') plots (i.e. the mean value of the C_c values obtained from different portions of very slightly non-linear plots) – was determined using the void ratio (e) and effective stress (σ'_v) curves as presented in Figure 4a for different fiber – clay admixtures.

$$C_c = \frac{\Delta e}{(log(\sigma'_2/\sigma'_1))} \quad (1)$$

- The coefficient of consolidation (c_v) was determined by applying "Root time method" (Taylor's method) on displacement versus square root of time curves as presented in Figure 3a, 3c, 3e, 3g, 3i, and 3k at various loads for different fiber – clay admixtures. According to Taylor's method, the c_v can be calculated as follows:

$$c_v = \frac{T_v.\left(H/_2\right)^2}{t_{90}} \quad (2)$$

Where:
T_v: Time factor
H: The specimen height at the beginning of the test (i.e. 2.5 cm)
t_{90}: Time required for 90% of consolidation has occurred

As evidently seen from the comparison of Figure 5a with Figure 5b, the experimental findings revealed that the C_c decreased, whereas the c_v increased with increasing PP fiber content in the clay. This indicates and signifies that the incorporation/inclusion of the fiber into the fine-grained soil results in the mobilization of relatively enhanced mechanical properties (Figure 5a) as well as the favorably improvement of consolidation characteristics (Figure 5b) per the rate/speed of consolidation deformation. With the addition of fiber into the fine grained soil, the greater compressive strength of soft clay soil against loading, as well as the less developed/measured compressibility properties are achieved that is an advantage for modifying the stability, resistance and toughness of clay soil under load and external forces (Figure 5a). The void ratio (e) – effective stress (σ'_v) curves earlier presented in Figure 4, where the value of C_c decreases as the fiber ratio increases; that is, becomes relatively more horizontal as the fiber dry weight percentage increases whereas it was observed that the curve became more vertical as the fiber proportion decreased. In other words, while a smaller amount of decrease in void ratio (deformation) occurs in clay soils with higher fiber content at a similar load increase, it was investigated on the other hand that a greater decrease in void ratio (settlement) developed in clay soils with lower fiber content. Additionally, the higher the coefficient of consolidation of the clay will result in a shortening/acceleration of the consolidation settlement time (i.e. speed up of consolidation displacement), and eventually favorably affect the completion of the plastic consolidation deformation as desired (Figure 5b).

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. This coefficient can be obtained from the plot of vertical strain versus stress curves or can be computed using Equation 3:

$$m_v = \frac{\alpha_v}{1+e_0}(m^2/kN) \quad (3)$$

Where:
α_v: the compressibility coefficient,
e_0: the initial void ratio of soil specimen tested.

Accordingly, the compressibility coefficient (α_v) can be calculated and determined from the plot of void ratio versus stress curves as the ratio of the reduction in the volume of void space (Δe) to the change in vertical stress (i.e. load per unit area) as shown in Equation 4:

$$\alpha_v = -\frac{\Delta e}{\Delta \sigma'}(m^2/kN) \quad (4)$$

Where:
Δe: the change in void ratio
$\Delta\sigma'$: the change in vertical pressure (i.e. stress)

Moreover, although the m_v as well as the α_v vary with respect to the stress levels, in order to reduce the effect of non-linearity in the detected values of both m_v and α_v and in the resultant developed behavior of those parameters with increasing stresses, the values of m_v and α_v were computed and determined at various intervals of the induced stress levels during the progress of the testing process with a restriction that the vertical effective stress difference in the calculations should not exceed 100 kPa, and thereafter, the computed values were averaged to obtain the mean representative characteristic values of m_v and α_v for the tested admixture specimen.

The change in the compressibility coefficient (α_v) as a function of fiber weight proportion in the admixture, quantifying the relativeness and the relation 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, is given in Figure 5c. The test results on the experimental findings have shown that a decrease in the attained values of α_v as a result of an increase in PP fiber content in the cohesive soil exhibited. Further, 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. This coefficient that can be obtained from the plot of vertical strain versus stress curves is of importance to comprehend the compressibility and strength characteristics of the clays during consolidation settlements under different loading conditions. The variation in m_v with respect to the amount of PP fiber available in the admixture is shown in Figure 5d such that a reduction in the detected values of m_v was observed while the fiber weight proportion in the mixture increases.

A similar resulting behaviors observed for those two important characteristics (α_v, m_v) of consolidation compressibility properties point out and signify that the consolidation deformational settlement exhibited in fiber-reinforced clayey soils can be reduced by the addition of fiber into the admixture cohesive soil prior to weight proportions of 1%. However, it is noted that the rate of drop in the resultant obtained values of C_c, α_v and m_v gets smaller for the fiber contents particularly above/beyond 1% by weight in the clay admixture. To sum up, the drop in the resultant values of C_c is not comparable to the decrease displayed in the measured values of α_v, m_v such that the magnitude of reduction observed in the α_v and m_v are much more significant than that of C_c. Furthermore, as similar to the C_c, the larger drops in the values of α_v and m_v were displayed for the fiber contents prior to 1% beyond which the magnitude of reductions in the resultant attained values of α_v and m_v were comparable smaller.

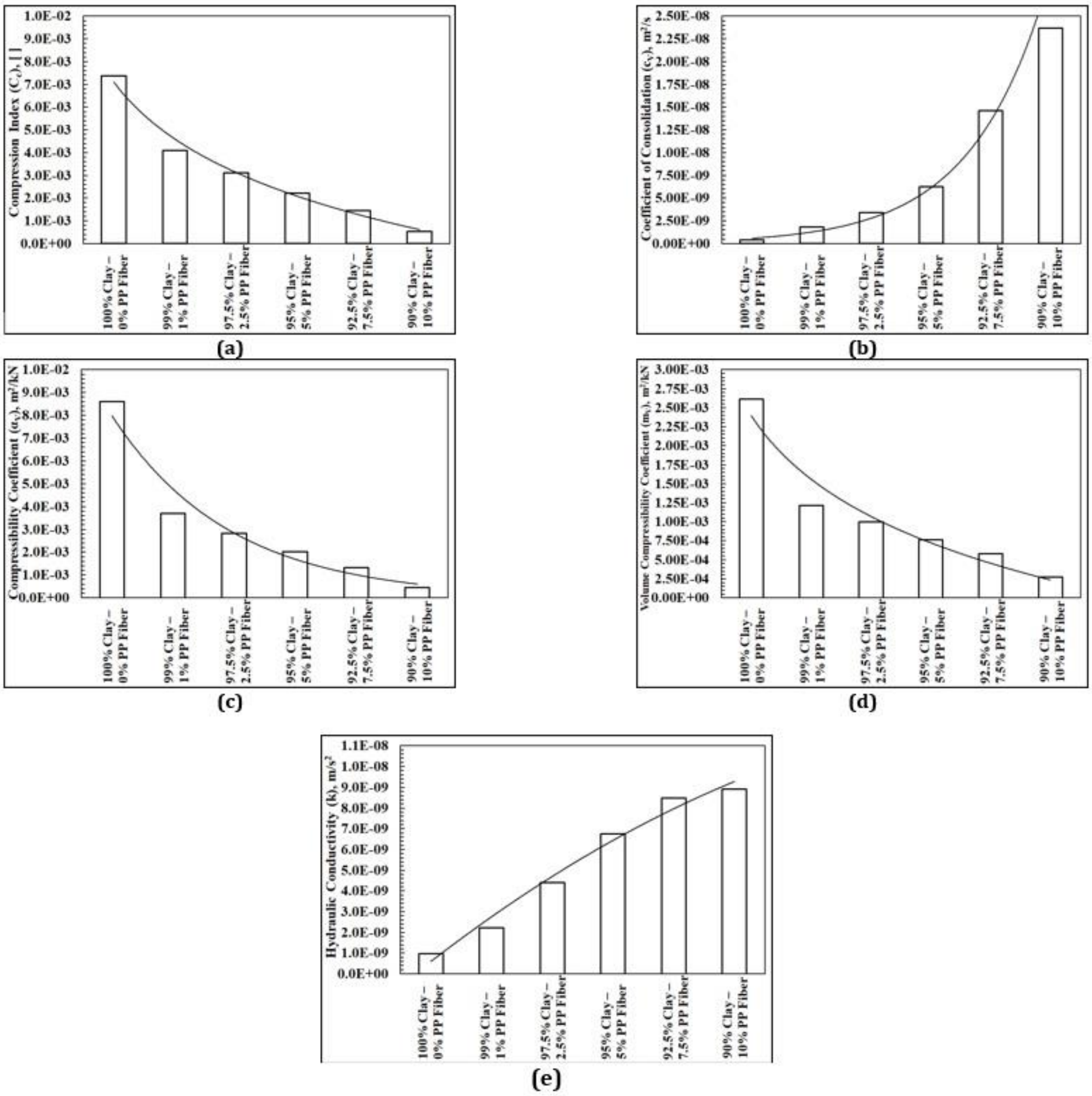


Figure 5. Consolidation engineering design parameters: **(a)** Compression index (C_c); **(b)** Coefficient of consolidation (c_v); **(c)** Compressibility coefficient (α_v); **(d)** Volume compressibility coefficient (m_v); **(e)** Hydraulic Conductivity (k).

4.4. Hydraulic properties

The hydraulic conductivity characteristics (i.e. coefficient of permeability, k) of clayey soils are associated with the time rate of consolidation properties (i.e. coefficient of consolidation, c_v) through Terzaghi's one dimensional consolidation theory such that there is a direct relationship between the permeability of a soil and the coefficient of consolidation. This relationship is based on Terzaghi's one-dimensional consolidation theory such that the permeability coefficient can be calculated and determined as given in Equation 5 based on the one-dimensional consolidation theory.

$$\boldsymbol{k = c_v . m_v . \rho_w} \quad (5)$$

Where:
k: the coefficient of permeability,
c_v: the coefficient of consolidation,
m_v: the coefficient of volume compressibility,
ρ_w: the density of water.

Based on the variation of the coefficient of consolidation (c_v) (i.e. characterizing the rate and duration of consolidation settlement and deformation, respectively) as presented in Figure 5b as well as utilizing Equation 5, the coefficient of permeability [hydraulic conductivity] (i.e. employed to assess and identify hydraulic properties) depending on the fiber content was determined and the change in the resultant values of k with increasing fiber content in the clayey soil is presented in Figure 5e.

Since consolidation settlement of a 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 a cohesive soil 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 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 fiber-reinforced clayey soil in the geotechnical infrastructural applications. To this end, the variation of c_v and k with respect to an increase in PP fiber content of the admixture soil as presented in Figures 5b and 5e, respectively, for the comparison of the developed behaviors are of importance. In this regard, it is seen that both the coefficient of consolidation (c_v) (Figure 5b) and the hydraulic conductivity (k) (Figure 5e) increased with increasing fiber content. This reveals that the rate of consolidation increases when the amount of PP fiber increases in the clayey soils. Consequently, this extends the understanding for the increment in the rate of consolidation deformation with an increase in fiber mass proportion in the fine-grained clayey soils such that the consolidation settlement will ease, speed up and accelerate owing to greater fiber proportion in the admixture soil designed and constructed in the field. This could be an advantageous situation for achieving settlement process faster under loading, force and stresses within relatively short time duration for fiber-reinforced clayey soil fills employed in geotechnical infrastructures so as that the soil fill will possess larger bearing capacity facilitating higher strength and resistance within a relatively shorter time durations against forces and stresses mobilizing within infrastructural fill.

Similarly, it was investigated that the coefficient of permeability (k) increased as the amount of PP fiber increased in the mixture. This is attributed to the improved hydraulic conductivity properties of the fibers when included in a clayey soil so as to facilitate the enhanced drainage of excess porewater pressure (building up due to external loads and forces could be exerted to infrastructural fiber-reinforced clayey soil fills) from clayey soil owing to inclusion of more and more fiber amount into the admixture cohesive soil. This will ease and expedite the progression of consolidation deformation, and hence, long-term settlement can be accomplished within relatively short period in fiber-reinforced fine-grained cohesive soil fills designed and constructed by utilizing fiber-stabilized clays in the infrastructural applications to reach higher bearing capacities in a short amount of time interval.

5. Lime stabilized cohesive soils

Test results and experimental findings obtained as a result of a series of consolidation tests applied to a variety of admixture clay specimens prepared at different dry weight proportions ranging from 0% up to 10% lime contents by weight within the scope of laboratory experimental program carried out to examine the improvement of engineering properties in terms of consolidation behavior and settlement response/reaction under load application for lime-stabilized fine grained soils constituted and prepared by the inclusion of lime additive into the clayey soil will be presented in detail throughout this section along with supplementary theoretical descriptions and technical explanations. One purpose for changing lime content (i.e. dry mass percentage) in clay soil was to examine and unveil the mass proportion of lime content required to change the characteristics of the clayey soils, and thus, dominating the consolidation behavior, settlement characteristics and engineering properties.

5.1. Development of consolidation deformation with time

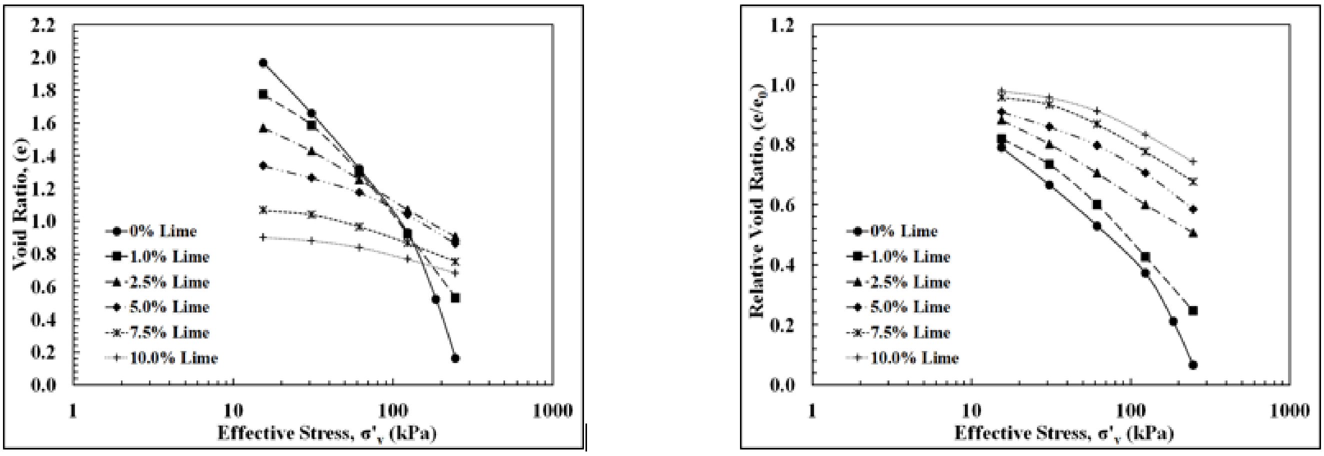
The development and progression of consolidation deformation with time is presented by means of the generated deformation curves obtained as a result of one-dimensional (1D) consolidation tests applied on the admixture specimens prepared by mixing lime at different dry mass proportions including 0%, 1%, 2.5%, 5%, 7.5%, and 10% by dry weight with clayey soil are presented in Figures 3b, 3d, 3f, 3h, 3j, and 3l for; (i) 100% Bentonite – 0% Lime, (ii) 99% Bentonite – 1% Lime, (iii) 97.5% Bentonite – 2.5% Lime, (iv) 95% Bentonite – 5% Lime, (v) 92.5% Bentonite – 7.5% Lime, and (vi) 90% Bentonite – 10% Lime admixtures, respectively, under different and successively increased loading conditions ranging from 5 kg up to 80 kg incrementally applied during the course of each consolidation test. In this way, the deformation readings with time are demonstrated, that is to say, the developed consolidation displacements measured in the tests as a function of time for different clay – lime admixtures are shown in the order of incremental loads sequentially.

The amount of the generated consolidation deformation for the pure clay as well as for the admixture soils containing different lime contents ranging from 1% up to 10% increased with an increase in vertical load from 5 kg up to 80 kg. As anticipated, the greater the magnitude of load and/or external forces, the larger amount of consolidation settlement will mobilize and generate within the soil. Furthermore, the resultant amount of the generated consolidation deformation reduced siginificantly with an increase in lime content in the clayey soil at every loading condition (5 kg – 80 kg) owing to the lime chemical properties such that the formation of clay-lime cementitious matrix binding modifies the inherent strength characteristics cohesive high or low plasticity soils such as clays. The benefits of lime treatment of clayey soils as a result of the pozzolanic action developed in fine grained cohesive soil accompanies with strength increment in the clay. Consequently, the clayey soil becomes strengthful by possesing larger resistance against loads and external forces as well as stresses. This results in exhibiting relatively less amount of consolidation settlement generated in the clayey soil due to induced loads and forces. Moreover, for the specimens including lime content by dry weight proportion particularly above 5%, the displacement curves at different loading conditions (low, medium, or high) displayed in a fashion by becoming closer to each other on the graph space, whereas for the specimens containing lime content having dry mass proportion especially below 5%, the displacement curves exhibited distant and far away from each other on the graph space at different loading conditions (low, medium, or high) with an increase in the magnitude of the applied load from 5 kg to 80 kg (Figures 3b, 3d, 3f, 3h, 3j, and 3l).

5.2. Volumetric compression under increasing loading

Soil is a multiphase material that consists of solid soil particles and void space filled by fluid and/or occupied by air exhangeably. As explicitly known, the relative proportion of the volume of void space with respect to the volume of the solid soil particles is called void ratio (e). This engineering parameter is used very commonly to examine the change in volume of soil (i.e. volumetric compression) as a result of loading. Since, for one-dimensional consolidation, the volumetric strain (ε_{3D}) is analogous and equivalent to the vertical strain (ε_{1D}). To this end, the change in void ratio of the clay–lime admixtures (at different dry weight proportions) measured in the consolidation tests due to load increment (an increase in the effective stress (applied load/specimen area)) are presented in Figure 6a. The compression stage is evident in the curves such that the soil specimens exhibited elastoplastic behavior. That is, some part of the volumetric compression under the load (i.e. settlement under loading) is recoverable, while the other part is permanent quantized through an engineering design parameter and a consolidation property called compression index (C_c). The consolidation engineering parameter (C_c) (obtained from Figure 6a) helps us extend the understanding on the estimation of the soil compressibility characteristics as well as the amount of consolidatiton settlement the soil will undergo due to application of overburden in the field, and thus, the displacement response of the soil under loading and/or external forces induced. As such, the load-deformation behavior of the clayey soil is assessed through the detected behavior and based on the resultant attained value of the important engineering parameter; C_c. Further, the coefficient of consolidation (c_v) (obtained from Figures 3b, 3d, 3f, 3h, 3j, and 3l) aids in the evaluation of the rate of the consolidation settlement, and thus, time characteristics of the soil subjected to loading in the field as leading to comprehend strength performance of the clayey soil under loading.

As evidently seen in Figure 6a, the larger the lime content in clayey soil, the more horizontal volumetric compression (i.e. Δe) – effective stress (σ'_v) curve was displayed. Besides, the slope of the curves became smaller as the lime weight proportion in clay increased. The curve that belongs to the pure clay (100% Clay – 0% Lime) exhibited a distinctly different behavior such that the greatest reduction in the detected value of void ratio (e) with an increse in effective stress (σ'_v) was observed. Therefore, the pure clay is more compressible in comparison to the lime admixture soils. As the lime content increases in the clay, the lime – clay admixture soil resulted in more strengtful, less compressible under loading. Addtionally, a relatively steep slope curve for the pure clay was displayed as compared to those of the other curves that belong to the lime admixture soils. The decline in the resultant detected value of the slope indicates that the admxiture soil became more resistant against loading owing to the contribution of lime in the clay in terms of the improvement of the compressibility characteristics.



(a) (b)

Figure 6. Volumetric compression **(a)** and Relative volumetric compression **(b)** versus Incremental loading for **lime** stabilized cohesive soil.

The relative void ratio (e/e0) versus effective stress (σ'v) curves are shown in Figure 6b. The curves for the higher lime content specimens were located at upper locations of the graph space, while the curves for the lower lime content specimens were placed at lower part of the graph space. As such, increasing the lime content in the clay resulted in the shifting up/moving up of the curves that the curve for the pure clay located at the very bottom, whereas the curve for the admixture soil including the largest lime content of 10% (i.e. 90% Clay – 10% Lime) among the other specimens located on the very top in the graph space along with a smallest drop in the detected value of e/e0 as a function of increasing effective stress (σ'v). This shows that the inclusion of lime into the clayey soil enhances the strength, and thereby, improves compressibility characteristics.

Consequently, it is noted that a relatively much smaller reduction in the current void ratio (e) of the soil developed with respect to the initial void ratio (e0) with increasing loading and/or exerted external forces/stresses that the lime addition benefits the inherent soil properties of clay – lime admixtures by showing greater resistance against loads with a relatively lower marginal amount of consolidation deformation response mobilized as a result of induced stresses.

5.3. Consolidation engineering design parameters

The most crucial consolidation engineering design parameters were determined based on further analysis of experimental findings as well as test results and presented in Figure 7. The change in compression index (C_c) that measures and evaluates the amount of volumetric compression generated, and therefore, the magnitude (i.e. severity) of consolidation deformation (i.e. settlement) mobilized in the soil as a result of loading in the field with an increase in lime content in lime stabilized clayey soil is shown in Figure 7a. It was observed a very sharp reduction in the value of C_c with further inclusion of lime into the clay. Consequently, the compressibility properties of the clayey soil was improved owing to the addition of lime leading to formation of relatively strong and robust soil fabric at micro-state as a result of chemical reactions that influences attaining stronger soil structure at micro-state against loads/forces. This is attributed to the pozzolanic action of lime in fine grained cohesive soils which accompanies strength increment in soil as well as provides binding action within the soil fabric.

The variation of coefficient of consolidation (c_v) which governs and regulates the speed/rate of consolidation process in fine-grained cohesive soils with an increase in lime content in the clay is demonstrated in Figure 7b. As similar to the behavior observed in C_c, the resultant value of c_v declines sharply with incresing lime weight proportion in the clayey soil which specifies that the inclusion of lime into a cohesive soil impact negatively (i.e. impair) the speed of consolidation deformation. This causes the prolongation of consolidation process in the fine-grained soil, and hence, the extension of settlement progress generated in the clay due to induced loading and exerted external forces. This is not a desired consequence or outcome of a stabiliation technique and operation in the field. However, as aformentioned, the improvement in compressibility characteristics because of benefiting from increased strength properties of the clay owing to lime addition is generally given a priority and preferred comparatively rather than the adversely occurrance of the extension in finalization of consolidation process (i.e. deformation), and therefore, settlement progress in the field. That's why, the lime-stabilization of cohesive clayey soils is a commonly opted strategy and widespread applied stabilization methodology in the geotechnical practice. Since, the rate of consolidation could be managed/resolved and boosted with the installation and use of wick-drains to achieve higher speed consolidation process.

The change in the compressibility coefficient (α_v) and the coefficient of volume compressibility (m_v) with lime content are presented in Figure 7c and 7d, respectively. Both consolidation engineering design parameters exhibited exponential decrements/decays in the detected values with an increase in lime mass proportion in the clay. This is attributed to the positive contribution of lime inclusion into the cohesive soil accompanied by chemical binding, and hence, strength increment in fine-grained cohesive clay. In this way, the clayey soil has become relatively more resistant (i.e. strong) to loads, forces as well as stresses and exhibiting comparatively much less consolidation deformation, vertical strain and settlement under the action of increasing loads and forces. On the other hand, the drop in the resultant values of both C_c and c_v is not comparable to the decrease displayed in the measured values of α_v, m_v such that the magnitude of decline observed in both C_c and c_v is much more significant than those of the α_v and m_v. Furthermore, as similar to the C_c and the c_v, the larger drops in the values of α_v and m_v were displayed for the lime contents prior to 2.5% beyond which the magnitude of reductions in the resultant attained values of α_v and m_v were comparably smaller. To sum up, the C_c, c_v, α_v and m_v all decreased with increasing lime content in the clay. This remarks and signifies that the incorporation/inclusion of the lime into the fine-grained soil which results in the mobilization of relatively enhanced mechanical properties in terms of strength properties and compressibility responses as well as the favorably improvement of consolidation settlement characteristics. The void ratio (e) – effective stress (σ'_v) curves earlier presented in Figure 6a, where the value of C_c decreases as the lime proportion increases; that is, the curves became relatively more horizontal as the lime weight percentage increases whereas it was observed that they became more vertical as the lime proportion decreased. With the inclusion of lime into the fine grained soil, the greater compressive strength of soft clay soil against loading, as well as the less developed and measured compressibility properties were achieved that is an advantage for modifying the stability, resistance and toughness of a clay soil under load and external forces, stresses. A similar resulting behavior observed for those two important and critical characteristics of consolidation compressibility properties (α_v and m_v) point out and highlight that the consolidation deformational settlement exhibited in lime-stabilized clayey soils can be reduced substantially by an inclusion of the lime into the admixture cohesive soil prior to weight proportions of 2.5%. However, it is noted that the rate of drop in the resultant obtained values of C_c, α_v and m_v gets smaller for the lime contents particularly above 2.5% by weight in the clay admixture.

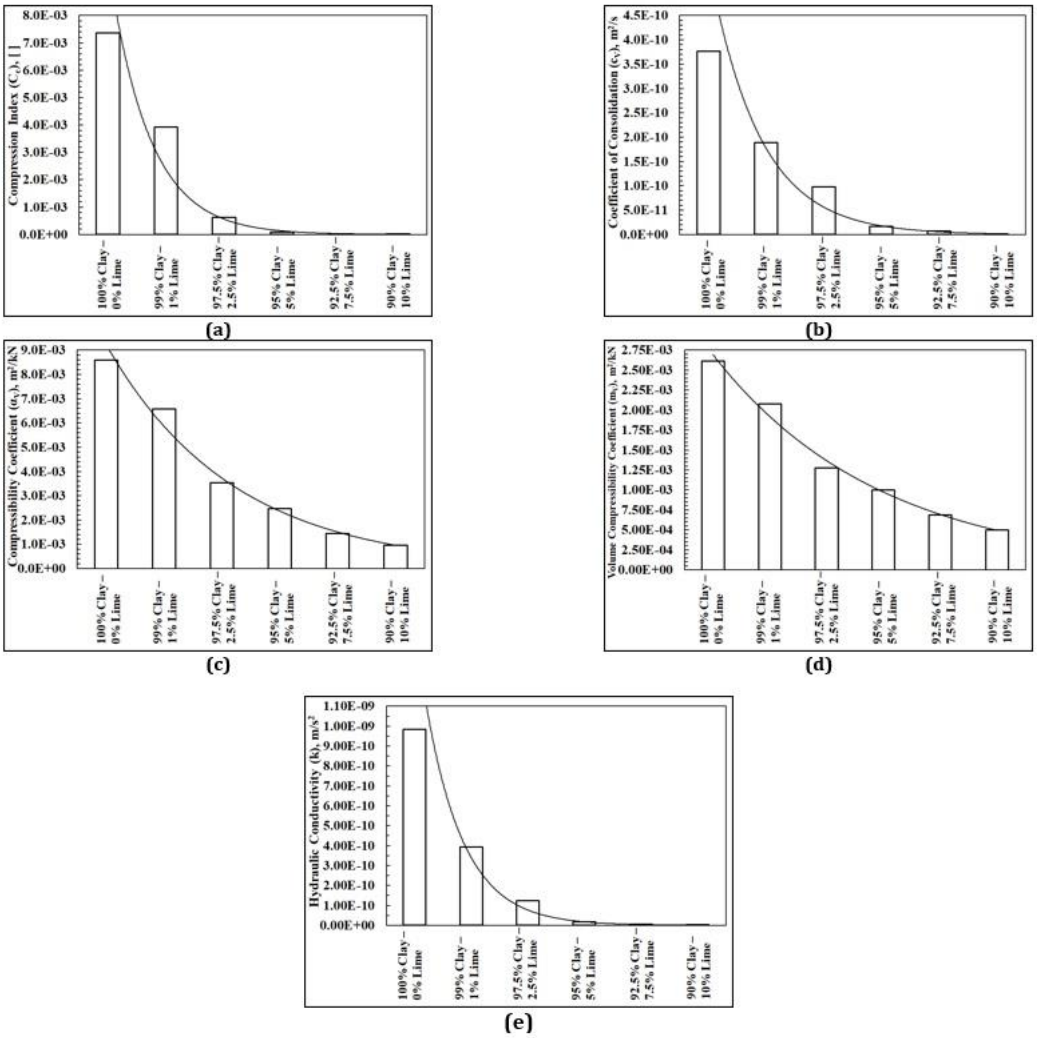


Figure 7. Consolidation engineering design parameters: **(a)** Compression index (C_c); **(b)** Coefficient of consolidation (c_v); **(c)** Compressibility coefficient (α_v); **(d)** Volume compressibility coefficient (m_v); **(e)** Hydraulic Conductivity **(k)**.

5.4. Hydraulic properties

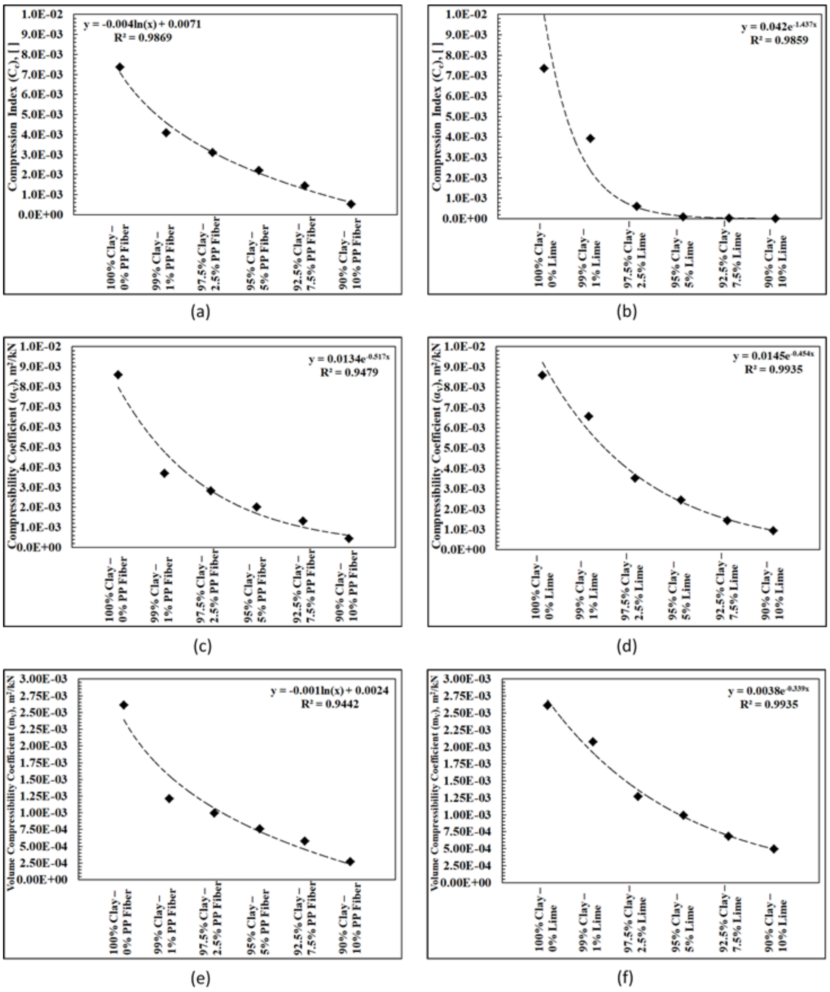
The coefficient of consolidation (c_v) controlling the rate and speed of consolidation settlement for a cohesive soil in the field as well as the coefficient of permeability (k) regulating the drainage and expulsion of excess pore-water pressure from void space resulting in the increase of vertical effective stress within 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 comprehend consolidation characteristics and hydraulic properties of lime-stabilized clayey soil in the geotechnical infrastructural applications. To this end, the variation of c_v and k with an increase in lime content of the admixture soil are presented in Figures 7b and 7e, respectively, for the comparison of the developed behaviors. It is seen that both the coefficient of consolidation (c_v) (Figure 7b) and the hydraulic conductivity (k) (Figure 7e) decreased with increasing lime content. As opposed to the test results obtained from the stabilization technique of fiber-reinforcement method, the experimental findings from the lime-stabilization methodology point out and reveal that the rate of consolidation declines when the amount of lime increases in the clay. This could be a disadvantageous situation for achieving settlement process faster/quicker under loading, force and stresses within relatively short amount of time duration for lime-stabilized clayey soil fills employed in geotechnical applications. On the other hand, the addition of lime into the cohesive fine-grained clayey soil will result in possessing larger bearing capacity that facilitates higher strength and resistance against forces and stresses mobilizing within infrastructural fill designed and constructed by following lime-stabilization technique. Therefore, the improvent in compressibility characteristics as a result of benefiting from strength properties of the clay owing to lime addition is held precedence and preferred comparatively rather than the adversely occurrance of the extension of finalization of consolidation process (i.e. deformation), and hence, settlement progress in the field. Similarly, it was investigated that the coefficient of permeability (k) dropped sharply and significantly as the amount of lime in the admixture soil is increased as evidently seen for the developed behavior in Figure 7e. This indicates the generation of deteriorated (i.e. diminished) hydraulic conductivity properties of clay-lime cementitious matrix due to chemical reactions (i.e. pozzolanic action) taking place in the soil fabric at micro-state level. As a consequence of the pozzolanic action, the formation of the resulting clay-lime micro-structure as new clayey soil fabric eventually prohibit/prevent the proper drainage of excess porewater pressure (building up due to external loads and forces could be exerted to infrastructural lime-stabilized soil fills) from clayey soil due to addition of a stabilizing agent lime into the admixture cohesive soil for the improvement of mechanical and compressibility properties. This will ultimately prolong the progression of consolidation deformation, and hence, the accomplishment of long-term settlement within acceptable period of time duration would be inhibited and restricted in lime-stabilized fine-grained cohesive soil fills. However, the application and use of consolidation accelerator methods including wick drains would ease and facilitate the progress of consolidation deformation and settlement. As evidently seen in Figure 7e, the rate of reduction in the measured and attained value of k gets smaller for the lime contents particularly above 2.5% beyond which a marginal decrement in the value of k was observed. Consequently, it is noted that the lime mass proportions, added into clay, especially smaller than 2.5% are critical and crucial in terms of the alteration of hydraulic properties, and thereby, drainage characteristics of the clayey soil. As a result, lime stabilization of clayey soils will benefit from improved compressibility properties whereas will lead to development of relatively greater imperviousness as compared to pure cohesive soils as a result of prolongation of expulsion of excess porewater pressure, thereby, time extension of escape of water from clay due to load application, relevant induced stresses.

6. Comparison of consolidation responses between fiber reinforcement and lime stabilization

The developed consolidation behaviors as well as the resultant detected magnitudes/values of consolidation compressibility characteristics and hydraulic properties will be comparatively analyzed based on positive contribution and/or negative detraction of the stabilization techniques including fiber-reinforcement as compared with lime-stabilization. The change/variation of consolidation compressibility engineering properties including compression index (C_c), compressibility coefficient (α_v), coefficient of volume compressibility (m_v) as a result of fiber inclusion and lime addition into the clayey soil are presented in Figures 8a and 8b, Figures 8c and 8d, and Figures 8e and 8f, respectively.

As a result of further statistical analysis performed on test data and experimental findings, a logarithmic decrease possessing a gradual decline with a relatively high value of coefficient of determination (R^2 = 98.69%) in the resultant magnitude of compression index (C_c) owing to fiber inclusion into fine-grained clayey soil was investigated (Figure 8a). On the other hand, the addition of lime into the clayey soil resulted in the development of exponential decrease having a sharp decline with a high value of coefficient of determination (R^2 = 98.59%) in the detected value of C_c (Figure 8b). As such, the slope, and thus, the degree of reduction in the C_c as a result of lime addition were relatively larger than that of fiber inclusion only within the range of lime additive mass proportion less than 2.5%. In particular, for the lime content of 2.5% and below, a dramatic significant drop in the detected value of C_c was displayed. On the other hand, beyond the mass proportion for 2.5% up to 10% of additive inclusion, the overall reduction in the resultant value of C_c was greater for the method of fiber-reinforcement compared to the technique of lime-stabilization. The compression index (C_c) representing the volumetric compression and demonstrating the magnitude/severity of a change in this engineering quantity with respect to an increase in vertical stress, and thereby, in loading defines the compressibility characteristics as well as the consolidation properties in terms of load-settlement resistance of a clayey soil. The greater reduction in the measured values of C_c with lime addition particularly for mass proportions of 2.5% and below was exhibited as compared to that of fiber inclusion at similar mass proportions. Conversely, for the mass proportions of additives greater than 2.5% until 10%, the larger reduction in the detected values of C_c with fiber inclusion was displayed in comparison to that of lime addition at similar weight proportions. Consequently, the method of lime-stabilization works more efficiently rather than the technique of fiber-reinforcement only within relatively very smaller additive mass proportions (i.e. within the range of 2.5%), whereas the fiber-reinforcement method shows more effective response rather than the lime-stabilization technique at greater additive mass contents especially for the weight proportions of the additive material into a fine grained soil from 2.5% up to 10% (i.e. >2.5% & <10%) in improving consolidation deformation response of the clay and compressibility characteristics as well as inherent strength. Moreover, the change in compressibility coefficient (α_v) as a function of PP fiber weight proportion in the admixture is given in Figure 8c. The statistical analysis on the investigated behavior has shown that an exponential decrease with a high coefficient of determination (R^2 = 94.79%) as a result of an increase in PP fiber content in the clay exhibited. Similarly, in light of the statistical analysis conducted, the decrease displayed in the value of α_v was exponential having a very high coefficient of determination (R^2 = 99.35%) with inceasing lime content in the clayey soil (Figure 8d). Based on the comparison of R^2 values, a relatively better agreement between distinct data points and continous regression curve was obtained for the method of lime-stabilization as compared to the fiber-reinforcement technique. However, the overall decrease (decline) in the detected value of α_v as a result of the fiber inclusion up to 10% by mass proportion was larger than that was displayed for the lime addition. This remarks that the method of fiber-reinforcement benefits more effectively for the enhancement of load bearing capacity by enabling sufficient load resistance of the clayey soil against induced external forces/stresses at a given relatively much smaller amount of settlement generated and/or volumetric compression mobilized in the field.

Furthermore, as clearly seen in Figure 8, the developed statistical model and the behavioral pattern in the coefficient of volume compressibility (m_v) that defines and represents the volumetric strain developed corresponding to the unit stress increase in the consolidating clay soil layer was examined comparatively for the methods of fiber-reinforcement and lime-stabilization and presented in Figure 8e, Figure 8f, respectively. The variation in m_v with respect to the amount of PP fiber available in the admixture is shown in Figure 8e such that a logarithmic decrement with a high R^2 value of 94.42% in the measured magnitudes of m_v was investigated while the fiber weight proportion in the admixture soil increases. On the other hand, the statistical analysis carried out for the variation of m_v with increasing lime content revealed a precise exponential decrease model that, as similar to the resulted behavior displayed in α_v, the distinct data points depicts a very good agreement along with continuous regression curve which results in obtaining very high value of R^2 = 99.35% indicating that the developed behavior is more accurate and robust than that observed for the fiber inclusion. Further, the overall reduction in m_v is greater owing to the fiber inclusion than that of the lime addition. This shows that the application of fiber-reinforcement technique could utilize comparatively a larger improvement of compressibility characteristics and a greater enhancement of load-resistance properties of the clayey soil over the entire range of mass proportion of the additive material from 0% to 10% along with a relatively lower amount of consolidation displacement, and hence, settlement developed against loading. Moreover, the resulting behaviors/trends (i.e. exponential or logaritmic declines) observed for three important characteristics of consolidation properties (C_c, α_v, m_v) point out and remark that the consolidation deformational settlement exhibited in fine-grained cohesive soils employed in infrastructural applications can be reduced by inclusion of PP fiber as well as by addition of lime into the admixture clayey soil fill in the field. As such, the compressibility properties (C_c, α_v, m_v) can change dramatically and significantly, in particular for the lime stabilization when the mass proportions of an additive being within the range of 2.5% (0% to 2.5%) whereas an overall variation in the detected value of compressibility properties (C_c, α_v, m_v) owing to the fiber-inclusion could be more serious and substantial when the mass proportion of the additive increases and up to as well as within the range of 10% (0% to 10%). For the additive weight proportions less than 2.5% added/included into a fine-grained clayey soil, it is noted that the lime-stabilization method, as a stabilization technique of a cohesive clay, would be able to work effectively and could accomplish the development of efficient consolidation response in a clay layer in the field. Consequently, it is stated that the lime-stabilization is a more efficient stabilization technique at lower additive contents (i.e. weight proportions < 2.5%) rather than the fiber-reinforcement. On the other hand, the fiber-reinforcement method demonstrates a more effective stabilization for relatively higher additive contents (i.e. 2.5% < additive weight proportions < 10%) compared to the response generated by the technique of lime-stabilization.



(a) (b) (c) (d) (e) (f)

Figure 8. Comparative statistical analysis on developed behavior for the variation in consolidation compressibility characteristics with increasing **fiber (a, c, e)** and **lime (b, d, f)** contents.

To sum up, in light of those scientific findings based on test results, the application of testing methodology was relatively replicable, and thus, the acquisition of the data was at high precision which resulted in the achievement of high accuracy in the reported values of consolidation parameters. Further, the values of coefficient of determination for all the consolidation parameters studied and presented in the paper were purposefully computed to demonstrate the closeness (i.e. the proximity) of the distinct experimental data values measured with the continuous regression lines/curves developed to predict the behavior and its progression with increasing fiber or lime contents. In this way, quantitative tools (mathematical models) have been aimed to be developed for practical purposes to be utilized in the relevant projects in the field for a quick engineering assessment in convenient evaluation for the variation of the consolidation parameters with a change in fiber or lime contents in the soil. Furthermore, it is anticipated that the use of PP fibers in soil stabilization would also contribute to the flexural strength of the admixture soil. As such, the load resistance and durability capacity of a soil fill constructed by applying fiber-reinforcement technique would be superior and enhanced against lateral loads as compared to the performance of soil fill constructed by following lime stabilizatin methodology. This phenomenon, not exactly being in the scope of this study, shall be analyzed and confirmed by a further testing program and the resulting experimental findings and verifications.

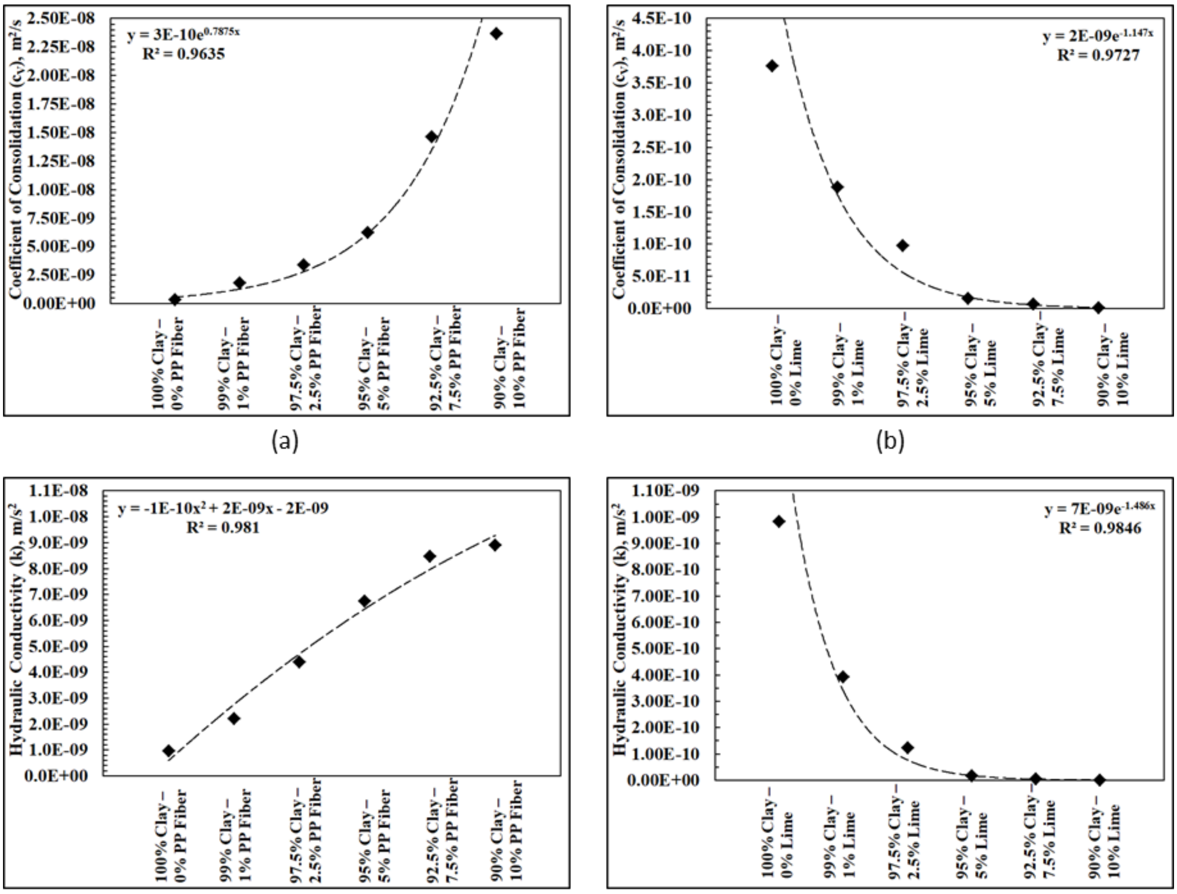
7. Further comparative analysis and discussions

The coefficient of consolidation (c_v) controlling the rate and speed of consolidation settlement for a cohesive soil in the field as well as the coefficient of permeability (k) regulating the drainage and expulsion of excess porewater pressure from void space resulting in an increase of vertical effective stress within soil body due to exerted forces and induced stresses are two critical and crucial engineering design properties to help us further comprehend the efficiency of consolidation behavior and the effectiveness of stabilization methodology in terms of proper development of consolidation deformation as well as appropriate progression of the resulting settlement in the field due to escape of excess porewater pressure leading to mobilization of suffient effective stresses within cohesive clayey soils as a result of load application in an infrastructure. An evidently opposite behaviors were observed with increasing additive content (i.e. fiber or lime) when the two stabilization techniques were compared. As such, the increase in PP fiber content resulted in an increment of coefficient of consolidation (c_v) in an exponential manner displaying a high value of coefficient of determination (R^2 = 0.9635) that represents a very good agreement between the distinct data points and the developed statistical behavior (Figure 9a). On the contrary, an inverse relationship between the c_v and the lime content was investigated such that an exponential decrement with a relatively high value of R^2 = 0.9727 as a result of incresing lime content in the clayey soil was observed (Figure 9b). The rate, and thus, the speed of consolidation deformation in cohesive soils are governed and quantified by this engineering design parameter. The inclusion of PP fiber benefits fine-grained clayey soil by enhancing the rate for the progression of consolidation process, and thus, shortening the duration of the resulting setlement in clay due to exerted external forces/loads and induced stresses. However, the addition of lime disbenefits fine-grained cohesive soil by impairing (i.e. worsening) the speed of consolidation progress, and hence, extending the time-span of the resulting settlement in clay as a result of applied loads and stresses.

The coefficient of permeability (k) defines and regulates the hydraulic conductivity characteristics of cohesive soils. The detected values of k increased quadratically (i.e. with a decreasing rate of the increment) demonstrating a perfectly large value of R^2 being 0.9810 which shows that an almost perfect agreement has been obtained between the measured data points and the attained continuous regression curve representing the overall behavioral trend for the k as a result of fiber inclusion in a clayey soil (Figure 9c). On the other hand, an exponential decrease for the detected values of k was investigated such that a very sharp reduction in the values of k was observed within the range of 2.5% lime addition into the clayey soil, while this reduction became very low for the lime contents greater than 2.5% up to 10% of lime additive being present in the clay. A perfect value of R^2 being 0.9846 was computed and obtained as a result of statistical analysis performed on the experimental data displaying an excellent proximity/closeness between distinct data points and continuous mathematical model developed as presented in Figure 9d.

To sum up, in addition to the improvement of consolidation settlement properties, when a geotechnical application requires enhanced drainage characteristics, the method of fiber-reinforcement could work more efficiently in the field during construction as well as operation stages by providing relatively more effective results of stabilization process on the clayey soil rather than the technique of lime-stabilization. Conversely, when an infrastructural application/project necessiates relatively greater water resistance and improved imperviousness characteristics, the lime-stabilization methodology would work more efficiently by showing a more desired effectiveness in stabilization of a clayey soil. Similar discussions were also stated and specified by the numerous researchers earlier in light of the evidences including test results/outputs being analogous to the exprimental findings of the laboratory testing program conducted in this research study. For instance, similar observations and arguments to the current study were also made by Mirzababaei et al. [25] for the effect of addtives in stabilization of soft soils. Moreover, it is evidently known that the construction of geo-structures including roads incorporates soil materials possesing, not only poor quality with low bearing capacity as well as having excessive settlement characteristics which are prone to the flooding, but also high moisture susceptibility into the construction.

Previous studies including Mirzababaei et al. [26], Sauceda et al. [27], Puppala [28], Kua et al. [29], Hoy et al. [30], and Yong and Ouhadi [31] reported and pointed out that the stabilization with chemical binders such as lime is a proper geoengineering solution for counter-acting the adverse effects of soft and problematic soils in construction such as pavement subgrades based on experimental measurements as similar to the results and the findings of lime-stabilization tests on clay specimens conducted in this study. Furthermore, the earlier studies including Viswanadham et al. [32], Saad et al. [33], Jamsawang et al. [34], Mirzababaei et al. [35], Soltani et al. [36], and Correia et al. [37] showed that the stabilization with fiber-reinforcement was also shown to be an appropriate geotechnological solution to deal with soft soils in a purpose of improving compressibility properties in infrastructural applications/projects such as embankments, pavement subgrades in light of experimental findings being analogous to the results of laboratory testing program within the scope of this study on the fiber-reinforced clayey soil specimens. Furthermore, the geomechanical properties of fiber-reinforced cohesive soils was studied by Ertugrul and Canogullari [38] by reviewing the test data/results of earlier studies based on mechanical experiments performed on fiber-cohesive soil mixtures in a systematical approach. It was observed as a result of comparative statistical analysis that various soil properties including soil strength improved with increasing density of the fibers. Similar results were also reported by Yilmaz and Turkoz [39] that the shear strength of high plasticity clay increased considerably with an increase in fiber presence in soil as well as an increase in compaction effort applied on to soil



(a) (b)

(c) (d)

Figure 9. Comparative statistical analysis on developed behavior for the variation in consolidation properties and hydraulic characteristics with increasing **fiber (a, c)** and **lime (b, d)** contents.

8. Conclusions

A comprehensive experimental program was conducted to comparatively examine the effectiveness of soil stabilization methods including fiber reinforcement as well as lime stabilization for the development of efficient consolidation response. The fiber inclusion into a cohesive soil resulted in enhancement of mechanical characteristics and improvement of hydraulic properties. As such, the larger compressive strength of soft clay soil against loading along with smaller amount of measured deformation established which is an advantage for modification of stability, resistance and durability of the clayey soil under loads. Samely, the higher hydraulic conductivity of clay resulted that will shorten the duration of consolidation settlement, and hence, eventually influence the completion of plastic consolidation deformation favorably for the soft clayey soils. On the other hand, lime treatment on clay specimens showed that the strength of clay against loading improves, and further, exhibits less vertical displacement (i.e. consolidation deformation) under load owing to an increase in lime content. Moreover, the clay becomes highly impermeable and displays substantially larger water-resistant properties because of increased lime mass proportion in clayey soil. In this regard, lime stabilization of the clayey soils will benefit from the improvement of bearing capacity whereas will lead to the development of relatively greater imperviousness (i.e. watertightness) as compared to pure cohesive soils that will result in the prolongation of expulsion of excess porewater presure, and thereby, time extension of escape of water from the clayey soil due to external load/force application as well as relevant induced stresses or strains.

The following important conclusions were drawn:

- In fiber-reinforcement, as similar to the C_c, the larger drops (reductions) in the values of α_v and m_v were displayed for the fiber contents prior to 1% beyond which the magnitude of reductions in the resultant attained values of α_v and m_v were comparable smaller.
- With increasing fiber content, both the coefficient of consolidation (c_v) and the hydraulic conductivity (k) increased. This reveals that the rate of consolidation increases when the amount of PP fiber increases in the fine-grained clayey soils. Consequently, this extends the understanding for the increment in the rate of consolidation deformation with an increase in fiber mass proportion in the clays such that the consolidation settlement will ease, speed up and accelerate owing to the greater fiber proportion in the admixture soil.
- In lime-stabilization, as similar to the C_c and the c_v, the larger drops (declines) in the values of α_v and m_v were displayed for the lime contents prior to 2.5% beyond which the magnitude of reductions in the resultant attained values of α_v and m_v were comparable smaller. Consequently, the C_c, α_v and m_v all decreased with increasing lime content in the clay.
- In contrast to the test results obtained from the stabilization technique of fiber-reinforcement, the experimental findings from the lime-stabilization method point out and reveal that the rate of consolidation diminishes when the amount of lime increases in the clay. As such, both the coefficient of consolidation (c_v) and the hydraulic conductivity (k) decreased with increasing lime content. This indicates the generation of deteriorated (i.e. diminished) hydraulic conductivity properties of clay-lime cementitious matrix due to chemical reactions (i.e. pozzolanic action) taking place in the soil fabric at micro-state level.
- The resulting behaviors/trends (i.e. exponential or logaritmic decreases) observed for three critical important characteristics of consolidation properties (C_c, α_v, m_v) point out and remark that the consolidation deformational settlement exhibited in fine-grained cohesive soils employed in infrastructural applications can be reduced by inclusion of PP fiber as well as by addition of lime into the admixture clayey soil fill in the field. As such, the compressibility properties (C_c, α_v, m_v) can change dramatically and significantly, in particular for the lime stabilization when the mass proportions of an additive being within the range of 2.5% whereas an overall variation in the detected value of compressibility properties (C_c, α_v, m_v) owing to the fiber-inclusion could be more serious and substantial when the mass proportion of the additive increases up to 10%. For the additive weight proportions less than 2.5% added/included into a fine-grained clayey soil, it is noted that the lime-stabilization method, as a stabilization technique of a cohesive clay, would be able to work effectively and could accomplish the development of efficient consolidation response within a clay layer in the field. Consequently, it is stated that the lime-stabilization is a more efficient stabilization technique at smaller additive contents (i.e. additive weight proportions < 2.5%) rather than the fiber-reinforcement. On the other hand, the fiber-reinforcement method demonstrates a more effective stabilization for relatively larger additive contents (i.e. 2.5% < additive weight proportions < 10%) compared to the response generated by the technique of lime-stabilization.

Consequently, to conclude, in addition to the improvement of consolidation settlement properties, when a geotechnical application requires enhanced drainage characteristics, the method of fiber-reinforcement could work more efficiently in the field during construction as well as operation stages by providing relatively more effective results of stabilization process on the clayey soil rather than the technique of lime-stabilization. Conversely, when an infrastructural application/project necessiates relatively greater water resistance and improved imperviousness characteristics, the lime-stabilization methodology would work more effieciently by showing a more desired effectiveness in stabilization of a clayey soil.

Author contributions

The manuscript is single-authored, and all contributions belong to the author.

Conflicts of interest

The author declare no conflicts of interest.

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