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Research Article

Lime stabilization of clayey landfill base liners: Consolidation behavior and hydraulic properties

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ABSTRACT

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 cementitious matrix. The design of landfill base liners including a clay layer as a fluid barrier (i.e. water-resistant impervious layer) requires a neat engineering approach considering, in particular, consolidation behavior as well as hydraulic properties of the clay contained. For sake of safe and stable design of such baseliners under the landfills, the reduction of consolidation settlement in clay when subjected to the accumulated waste load (i.e. superposed action) during operation as well as the accomplishment for ensuring the waterproof of those composite base liners (comprised of multiple different layers) not to allow the penetration of the contaminated water - produced as a result of exothermic reactions occurring in the waste body in landfills – by enabling enhanced isolation from the natural ground is of importance. In light of this, in order to address those two most important design concerns (i.e. Consolidation and Hydraulic Properties of Clay) as well as to in an attempt to develop an enhanced clay layer system for landfill baseliners that has a greater bearing capacity (i.e. load resistance), and hence, more robust against settlements, and additionally, possessing improved hydraulic properties by being relatively more water-resistant and greatly impermeable, a series of consolidation tests were performed in the laboratory at different lime contents (lime/lime-clay mixture proportions by weight: 0%, 10%, and 20%) on clay specimens to investigate the stabilization and improvement of clayey landfill baseliners. Lime treatment on clay specimens has shown as a result of the experimental program that the strength of clay against loading improves, and further, exhibits less vertical deformation (settlement) under the 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. The findings of the experimental program demonstrate that lime stabilization of the clayey soils in landfill baseliners will benefit the bearing capacity and the imperviousness (water tightness) engineering design properties as compared to standard composite multi-layered landfill baseliner systems.

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INTRODUCTION AND LITERATURE REVIEW

Lime stabilization is a chemical process established through physical mixing with the in-place soil along with the addition of a limited amount of water to facilitate (i.e. catalyze) and accelerate the chemical reaction for the formation of clay-lime cementitious matrix as well as to prevent dust emission during construction. In this perspective, over decades, lime has been used as a modifier as well as a binder for fine grained soils such as clay. Further, 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) which may cause the endangerment of the stability of the infrastructure constructed using that clay layer. Additionally, the pozzolanic action in fine grained soils accompanies strength increment in soil. Moreover, lime also provides binding action even for course grained soils.

The improvement of the engineering design properties of soil up to desired values to satisfy the project requirements is called soil stabilization for which the principal objective is to increase load carrying resistance (i.e. bearing capacity) as well as to enhance hydraulic properties of the soil layers designed in infrastructural projects in order to fulfill the constructional purpose. Landfills are one of the commonly constructed geo-environmental infrastructure applications throughout the world, particularly in the developed countries to protect the environment from the damaging impact of the contaminants that exist in the stacked and stored industrial and/or municipal waste bodies. To this end, base, side slope and cover liners of the landfill applications requires a neat engineering approach in design and development to accomplish a proper performance in terms of sufficient bearing capacity and superior hydraulic properties by enabling improved compressive strength against accumulated waste load and by providing enhanced imperviousness against infiltration of contaminated water leaking out from the waste. Within this scope, lime treatment of clay layers, essential part (component) of multi-layered composite landfill liners, leads to building and establishing a strengthened and highly water-resistant cementitious matrix in clay so as that the desired bearing capacity and hydraulic properties are achieved in the landfill liners. Furthermore, the main advantages of lime stabilization method in comparison to the other techniques including mechanical (i.e. compaction) and chemical (i.e. cement stabilization) stabilization methods are; (i) soil becomes more workable, (ii) strength is substantially improved, (iii) compressive strength is increased as high as 60 times, (iv) it is effective for most soil types. On the other hand, the disadvantages of lime stabilization could be described as follows; (i) lime is produced by burning of limestone in kilns, therefore it is harmful for the environment, (ii) the burning of limestone requires more cost, (iii) it is not effective for gravelly soils [1, 2].

Over the decades, several soil stabilization techniques including physical stabilization, chemical stabilization and mechanical stabilization have been used by the engineers in order to reinforce soil by improving mechanical strength characteristics (i.e. consolidation behavior of clayey soils) as well as by enhancing hydraulic properties (i.e. hydraulic conductivity or imperviousness characteristics) [1]. To this end, the lime-treatment process (i.e. 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 that the stabilization of the soil layer is accomplished.

In the lime-treatment process, there are two stages of the soil-lime chemical reaction. The initial stage – categorized as immediate or short-term treatment – develops within a few hours or days after the lime is admixed with soil in which three primary chemical reactions, namely; 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 a pozzolanic reaction is detected [2, 3]. During 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 [4]. As such, the calcium ions (Ca^{+2}) and the hydroxide anions (OH^{-}) are produced as a result of the addition of lime into the 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 a 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 flocculation and agglomeration which is the main

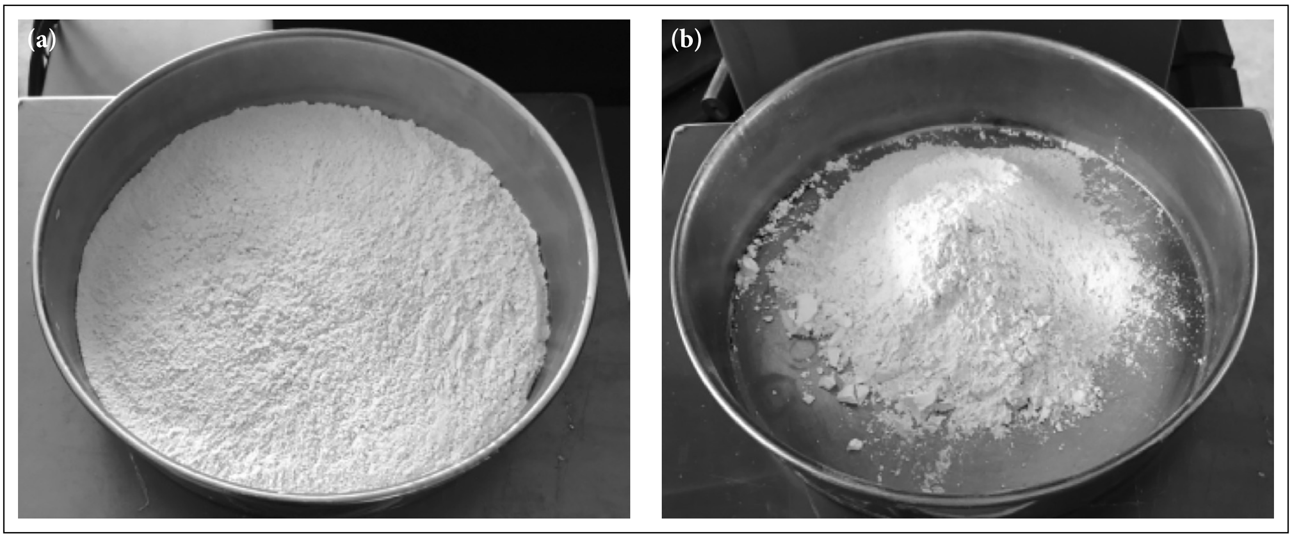

Figure 1. **(a)** Clay (Bentonite). **(b)** Lime.

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 [5]. As such, the mineral particles re-arrange in the flocculated/aggregated structure, giving rise to an intra-aggregate porosity and an apparent change in texture, with clay particles clumping together into larger-sized aggregates [6]. The above-described reactions are commonly identified as short-term reactions and they reduce the soil plasticity index (PI) and its water affinity [7]. The swelling potential decreases while hydraulic conductivity usually increases [8]. In the long-term, pozzolanic reactions develop between calcium ions and the silica or alumina of the lattices of clay minerals, improving strength and compressibility of the soil [6–8].

The clayey soils mostly have soft and sensitive nature that is related to and controlled by depositional and post-depositional factors [9]. As such, the main depositional factor is the inter-particle flocculation that creates an open micro-structure in such soils. As a consequence of different environmental depositional conditions, the soft, sensitive nature clay deposits located worldwide are characterized by different mineralogical and mechanical characteristics [10]. In this regard, lime is a stabilizing agent capable of improving properties of fine-grained soils to obtain proper hydraulic and mechanical characteristics for earthen structures (e.g., dikes, road embankments) [11]. Lime stabilization is acknowledged as an environmentally sound and cost-effective application because costs of high-quality material from quarries and of disposal of the unsuitable in situ soil are eliminated, and therefore, it is widely applied worldwide [12]. In this regard, the soil stabilization utilizing lime has also been practically applied in the field for important infrastructural projects in Turkey including roadway constructions conducted by General Directorate of Highways (i.e. KGM) in Marmara Region (Tekirdag), Central Anatolia (Konya). To this end, this paper will extend the understanding regarding the effect of lime stabilization on the consolidation behavior, mechanical characteristics and hydraulic properties of soils.

MATERIAL PROPERTIES AND TESTING PROGRAM

In this section, the experimental method followed in the laboratory for performing the comprehensive testing program will be explained along with the information provided on the engineering properties of the testing materials as well as the description given regarding the testing device and the experimental procedures conducted for the preparation of test specimens, installation of the equipment and the placement of the specimen in the experimental set-up.

Materials

The clayey soil selected to be used throughout the entire experimental program was the natural calcium Bentonite (i.e. has a very high proportion of exchangeable calcium whereas including a very low proportion of exchangeable sodium) (Fig. 1a) that is industrial clay for which the physical, chemical and index properties are suitable for the engineering standards. The lime (Fig. 1b) admixed into clay 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 as shown in Figure 1b.

Testing Equipment

A floating ring cell consolidometer (UTS – 0300 Oedometer) 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 – lime admixture

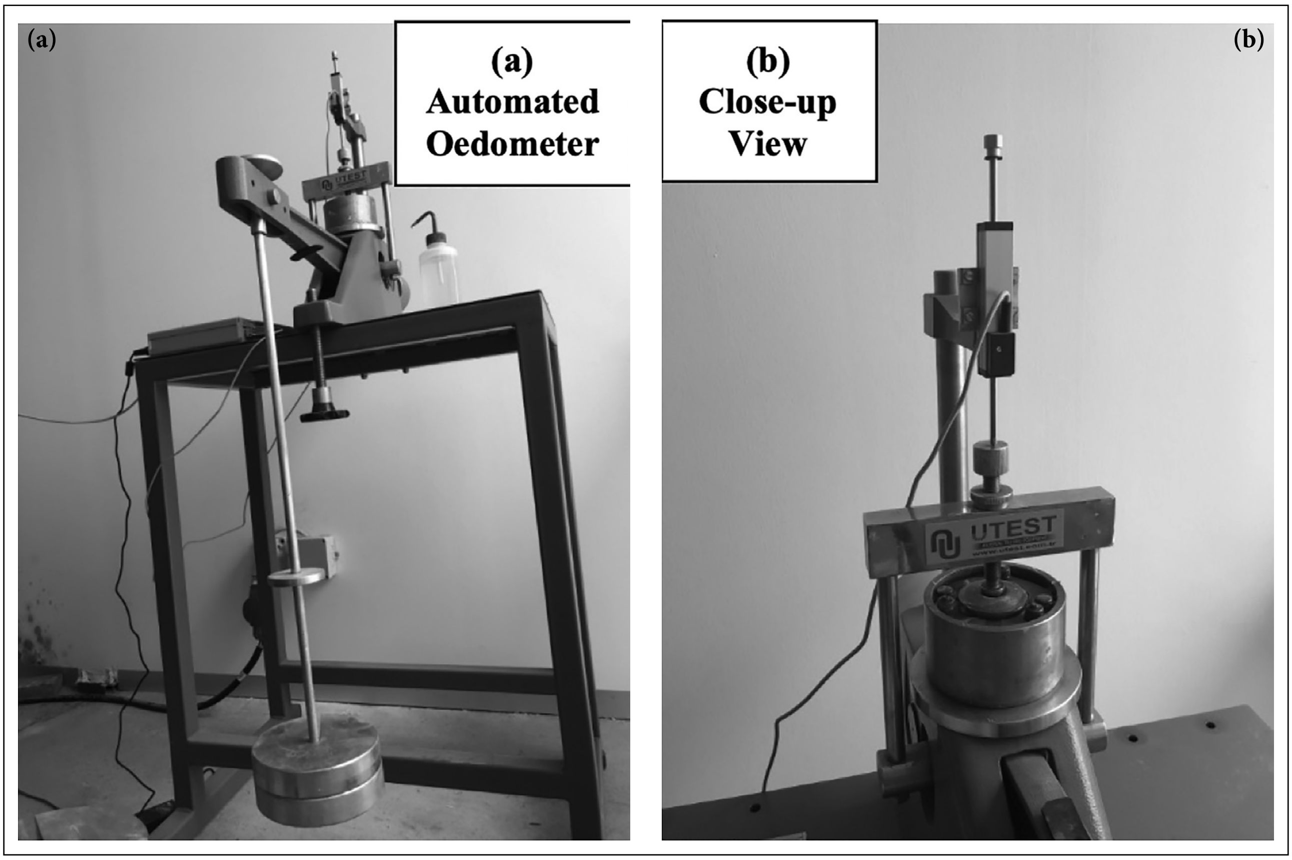

Figure 2. **(a)** Automated consolidation device. **(b)** Close up view of consolidation device.

Table 1. Laboratory testing program and dry mass proportions of different test specimens

Samples	Test specimen I	Test specimen II	Test specimen III
Mass proportions	100% Clay – 0% Lime	90% Clay – 10% Lime	%80 Clay 20% Lime

specimens (Fig. 2). A linear variable differential transformer (LVDT) was employed in the system to measure vertical displacement in evaluating the deformations developing in the soil specimen under the application of load during the tests. 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.

Testing Program

In this study, a series of consolidation tests [13] were performed in the laboratory at different lime contents (lime: lime-clay-mixture proportions by dry weight: 0%, 10%, and 20%) on the test specimens prepared in the laboratory to investigate the lime-stabilization (Table 1). Those different lime contents were mixed with clayey soil specimens such that the required weights of slaked lime were properly and completely admixed with batches of air-dried clay soil specimens to achieve lime-soil admixtures containing 0%, 10%, 20% lime contents on a dry weight basis. Further, the reconstituted consolidation test specimens were prepared at a dry unit weight of 13 kN/m^3 with a optimum moisture content of 30%. The results of consolidation tests conducted were used to determine the engineering consolidation parameters including; coefficient of consolidation (c_v), compression index (C_c), recompression index (C_r) for evaluating strength-deformation characteristics as well as to identify an important hydraulic property such as coefficient of permeability (k) for assessing hydraulic characteristics. The test specimens (cylindrical: 6.0 cm in diameter and 2.5 cm in height) were prepared by admixing lime into clay at different dry mass proportions, and then, by enclosing in a stiff metal ring and placing between two porous stones in a cylindrical container filled with water. Later, A metal load platen mounted on top of the upper porous stone transmits the applied vertical stress (vertical total stress) to the soil sample. Both the metal platen and the upper porous stone can move vertically inside the ring as the soil settles under the applied vertical stress.

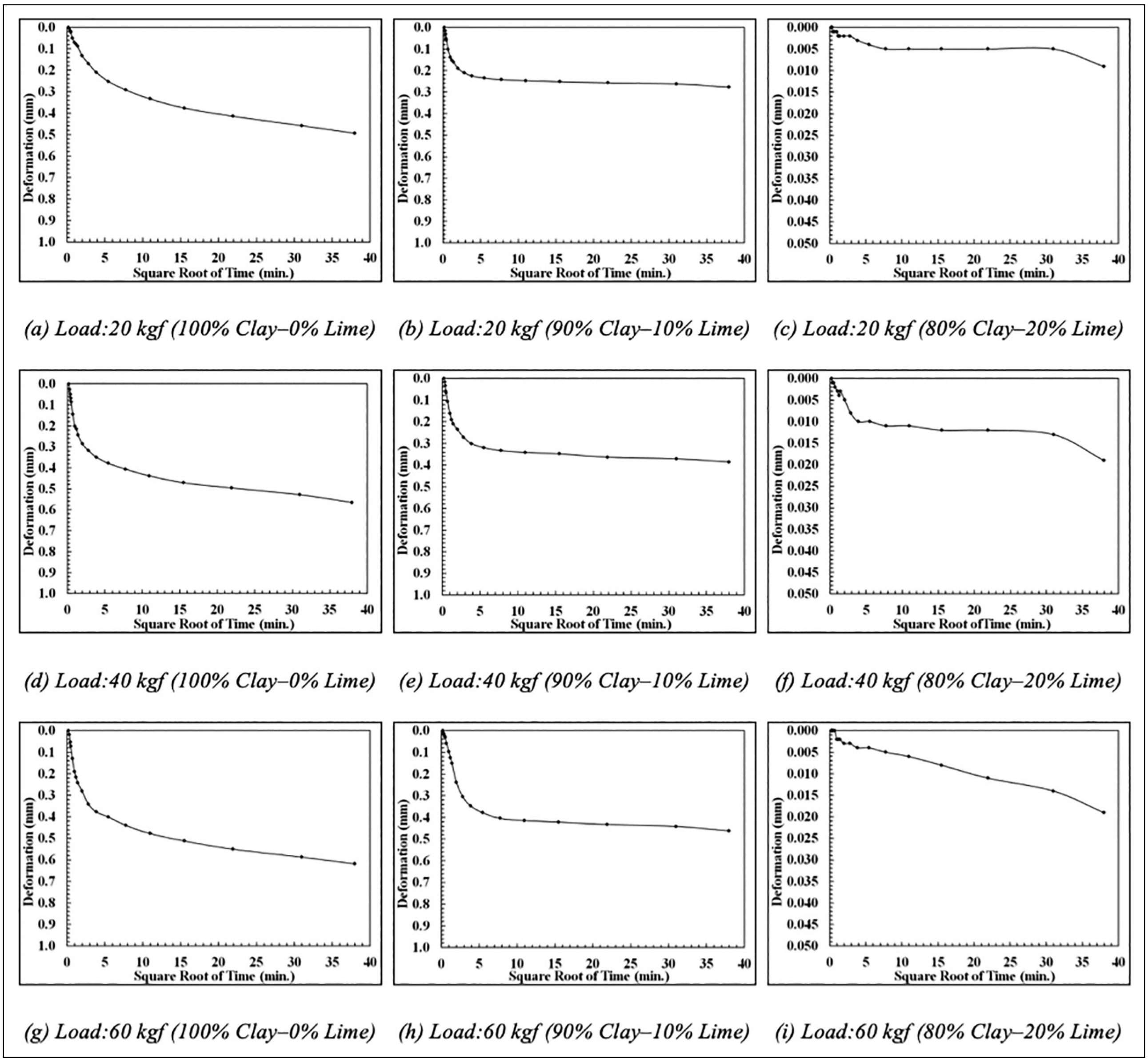

Figure 3. Deformation versus square root of time curves.

Incremental loads are applied to the platen, and the settlement of the soil at various fixed times under each load increment is measured by the transducer (LVDT) described in Testing Equipment Section. Each test continued six days with sequential incremental loads of 5, 10, 20, 40, 60, and 80 kgf, 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 [14]. Therefore, the vertical displacements (i.e. 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. Similarly, the measurement time interval for reading the deformations develeoped in the specimen under loading were also selected as two purposefully to examine consolidation behavior in a comprehensive manner.

RESULTS

The experimental findings of consolidation tests performed at different lime contents (0%, 10%, and 20%) on the test specimens prepared in the laboratory to investigate the lime-stabilization will be presented in this Section along with supplementary theoretical descriptions and technical

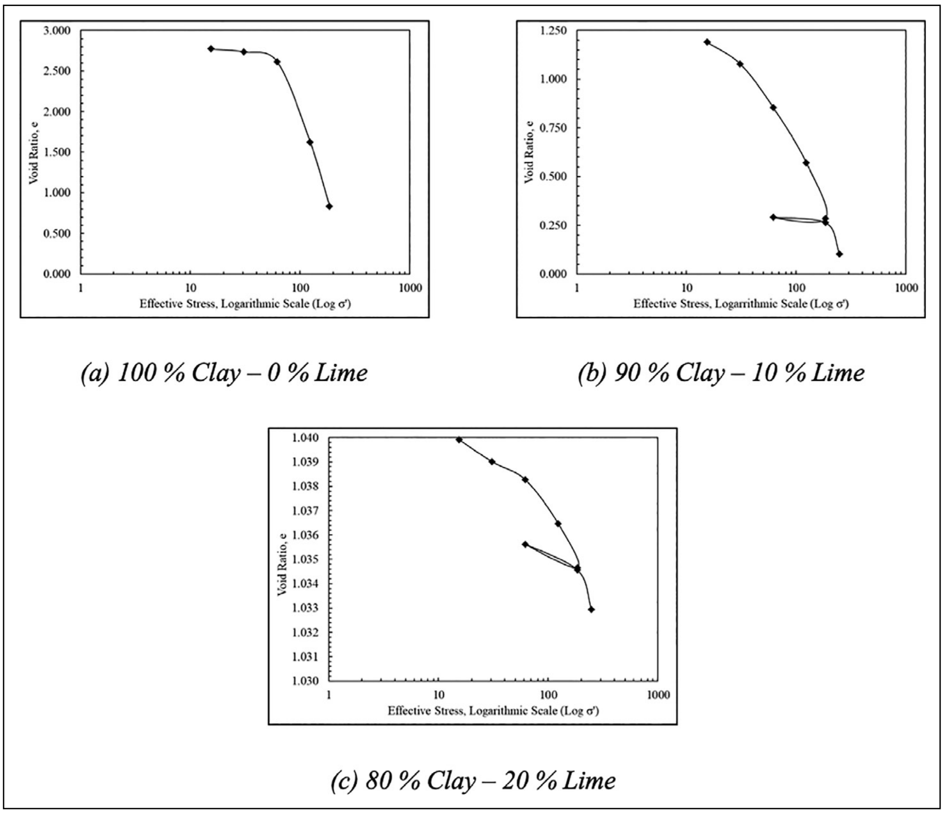

Figure 4. Void ratio (e) versus effective stress, logarithmic scale (Log σ') curves.

explanations. One purpose for changing lime content (i.e. dry mass percentage) in clay soil is 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 and engineering properties.

Deformation Readings with Time

Three different loading conditions (20, 40 and 60 kgf) among distinct loads ranging 5 kgf up to 80 kgf incrementally applied during the course of each consolidation test were selected representatively to show the deformation readings with time, that is to say, the developed displacements measured in the tests with time for different clay – lime admixtures. As such, the generated displacement versus square root of time curves based on experimental measurements are presented in Figure 3 in the sequence of incremental loads successively.

Volumetric Compression and Loading

Soil is a multiphase material that consists of solid soil particles and void space filled by fluid and/or occupied by air exhangeably. The relative proportion of the volume of void space with respect to the volume of the solid soil particles is called void ratio (e) [15]. This engineering parameter is used very commonly to examine the change in volume of soil (i.e. volumetric compression) because of loading. 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, that is to say, an increase in the effective stress (applied load/specimen area) are presented in Figure 4. The compression and the recompression stages are 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 quantized through an engineering design parameter called recompression index (C_r), while the other part is permanent quantized through a consolidation property called compression index (C_c). Additionally, the unloading-reloading cycle has been performed in the tests of the 90% Clay-10% Lime and the 80% Clay-20% Lime specimens to clearly detect and evidently reveal recompression stage, and thus, accurately determine the important consolidation parameter; recompression index (C_r).

Both C_c and C_r consolidation parameters (from Fig. 4) helps us extend the understanding on the estimation of the amount of consolidatiton settlement the soil will undergo due to application of overburden in the field, and thus, the bearing capacity of the soil under loading. As such, the load-deformation behavior of the clayey soil is assessed through these important engineering parameters; C_c and C_r. Further, the coefficient of consolidation (c_v) (from Fig. 3) aids in the evaluation of the rate of consolidation settlement, and thus, time characteristics of the soil subjected

Table 2. Consolidation strength and deformation as well as hydraulic properties

Engineering Design Parameters (Consolidation Strength, Deformation, Hydraulic Properties)				
Clay - Lime Admixture	Compression Index (C_c), [ ]	Recompression Index (C_r), [ ]	Coefficient of Consolidation (C_v), [cm^2/min]	Coefficient of Permeability (k), [cm/min]
100% Clay - 0% Lime	1.439E-02	3.364E-03	0.19781	3.920E-04
90% Clay - 10% Lime	5.122E-03	4.787E-05	0.12036	1.151E-04
80% Clay - 20% Lime	3.085E-05	7.776E-06	0.03565	2.229E-06

to loading in the field as leading to comprehend strength performance of the clayey soil under loading.

Determination of Consolidation Engineering Design Parameters

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

(i) The compression index (Equation 1) that is the average slope of compression stage in the e versus log(σ') plots – was determined using the void ratio and effective stress curves as presented in Figure 4 for different clay – lime admixtures.

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

Where:

Δe: Change in void ratio

$\log(\sigma'_2 / \sigma'_1)$: Change in vertical effective stress

(ii) Similarly, the recompression index (Equation 2) that is the average slope of recompression stage in the e versus log(σ') plots – was determined using the void ratio and effective stress curves as presented in Figure 4 for different clay – lime admixtures.

$$(C_r = \Delta e / (\log \sigma'_2 / \sigma'_1)) \tag{2}$$

Where:

Δe: Change in void ratio

$\log(\sigma'_2 / \sigma'_1)$: Change in vertical effective stress

(iii) 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 3 at distinct loads for different clay – lime admixtures. According to Taylor's method, the cv can be calculated as follows:

$$c_v = \frac{T_v.(H/2)^2}{t_{90}} \tag{3}$$

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

Determination of 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 as follows:

$$k = c_v . m_v . \gamma_w \tag{4}$$

Where:

c_v: Coefficient of consolidation

m_v: Coefficient of volume change or compressibility

γ_w: Unit weight of water

Using Equation 4, the important engineering parameter that is coefficient of permeability (k) employed to assess hydraulic properties of clayey soils was calculated for different clay – lime admixtures.

COMPARATIVE ANALYSIS ON EXPERIMENTAL FINDINGS

The engineering design parameters for clayey soils aiding in quantification and qualification of consolidation strength, deformation and hydraulic properties are listed in Table 2 to explore, and thus, to evaluate their values as well as to gauge the changes in clayey soil as a result of adding lime content on a purpose for stabilization. Substantial variations in the values of compression index (C_c), recompression index (C_r), coefficient of consolidation (c_v) and coefficient of permeability (k) have been investigated positively such that the consolidation strength-deformation characteristics have been enhanced as well as the hydraulic properties of the clayey soil have been improved owing to the contribution (favorable influence) of lime addition to the soil.

Moreover, a comparative analysis was performed on the computed values of engineering design parameters regarding consolidation strength-deformation characteristics (C_c, C_r, c_v) assisting in evaluating load bearing capacity of clayey soil (i.e. load resistance performance), and additionally, regarding hydraulic properties (k) assisting in assessing imperviousness features of clayey soil layer in the field

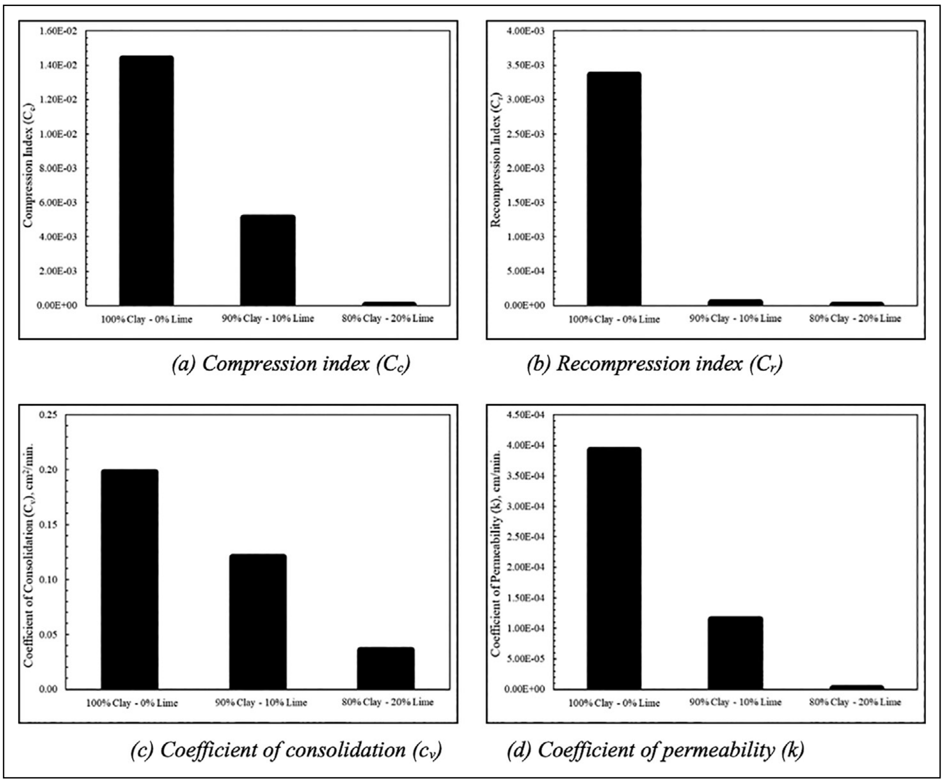

Figure 5. Comparative analysis on engineering design parameters.

(Fig. 5). The decrease in both compression index (C_c) and recompression index (C_r) (Fig. 5a, b, respectively) with an increase in lime content shows that the strength of clay becomes greater exhibiting smaller amount of deformation (consolidation settlement) against loading, and hence, displaying higher bearing capacity (greater load-carrying resistance). This is attributed to the lime treatment of the clay resulting in stabilization of soft soil through possible reactions including base-exchange, coagulation, and flocculation, reduction in thickness of water film around clay particles, cementing action and carbonation. As such, fine platy-like clay particles react with lime, and thus, get flocculated or aggregated into larger particle groups that are moderately stable even under subsequent soaking.

Since the bentonite clay used throughout the experimental program possesses inherent plastic constitution, the higher the agglomeration, the larger the strength increment was investigated compared to the other soil types such as sandy or silty soils. Therefore, lime treatment on clay specimens has shown as a result of the experimental program that the strength of clay against loading enhances, and further, exhibits less vertical deformation (settlement) under the load owing to an increase in lime content.

As per hydraulic properties, the values of coefficient of permeability (k) (Fig. 5d) have decreased such that the clay has become highly impermeable and displayed substantially improved water-resistant properties because of the increased lime content of the clayey soil. On the other hand, the coefficient of consolidation (c_v) (Fig. 5c) – showing quantitatively the time rate of consolidation deformation process (i.e. time rate of consolidation settlement in the field) – has decreased with an increase in lime content in soil. This results in extension of time duration required for the completion of consolidation settlement process of the clayey soil when subjected to loading that could be overcome by inserting wick drains in the constrcution area to facilitate and accelerate the expulsion (i.e. escape) of pore water from void space so that the progress of consolidation settlement has been eased and sped up to normal level. Similar results regarding the change in consolidation design parameters (Fig. 5) owing to the addition of lime into fine grained soils were also shown by the Reference [16] such that there observed a general increase in hydraulic conductivity (k), an evident decrease in consolidation engineering properties including coefficient of consolidation (c_V), compression as well as recompresion indices (C_c, C_r, respectively). Such finding for lime-treated soils is attributed to the aggregation of clay particles due to lime addition [6, 11, 12]. Further, as previously investigated and revealed by the Reference [6, 8], the reduction in hydraulic conductivity (i.e. k) as well as the enhancement in compressive strength properties against loading (i.e. C_c, C_r) are related and governed by the growth of pozzolanic products that are capable of partially filling the inter-aggregate porosity. As such, the significant reduction in compressibility of the tested clayey soil owing to the lime-treatment as evidently detected from the decrease in the values of C_c, C_r (Fig. 5a, b) confirms the eaerlier findings of the References [7, 8,]. Moreover, as already indicated by the References [12, 16] and verified through the experimental results of the testing program as reported in this paper, the clayey soil – lime admixtures exhibit similar behavior analogous to over-consolidated soils attributed to and associated with the cementation characteristics induced by pozzolanic reactions being able to create a more rigid structure. Therefore, low deformations in the range of pressure typical of geo-environmental earthworks including landfills, embankments could be deemed to be ensured when soil–lime mixtures are selected to be utilized in their construction [11, 12].

The effectiveness of lime treatment can evidently be observed from the improvement of the consolidation engineering properties as shown in Figure 5. This type of enhancements in the consolidation design parameters were also reported by the References [17, 18]. In particular, for the case of soils characterized by high water contents (i.e. sensitive clayey soils), a proper design of soil–lime mixtures is based on a preliminary investigation of the soil to be used to verify its suitability to lime treatment as earlier indicated by the References [18–20]. The extensive laboratory testing program carried out on the soil–lime admixtures in the current study revealed the effect of mix proportion taking into account the specific in situ construction procedures and curing conditions in order to verify the effectiveness of quicklime treatment on a typical soft, sensitive, clayey soil for assessment at a laboratory scale.

CONCLUSION

On a purpose to address the two most important design concerns (i.e. Consolidation and Hydraulic Properties of Clay) as well as to in an attempt to develop an enhanced clay layer barrier system for landfill base liners that has enhanced bearing capacity (i.e. load carrying resistance), and hence, being robust, stable and durable against settlements, and additionaly, possesing improved hydraulic properties by being relatively more water-resistant and highly and favorably impermeable, a series of consolidation tests were performed in the laboratory at different lime contents on clay specimens to investigate the stabilization and improvement of clayey landfill base liners. The test results showed that the detected values of C_c, C_r, k decreased approximately 1/10 of the original value of the pure clayey soil, while the measured values of c_V decreased roughly 1/4 of the original magnitude as a result of an increase in lime content up to 20% by dry weight. As such, the findings of the experimental program demonstrates that lime stabilization of the clayey soils in landfill base liners will benefit the bearing capacity and the imperviousness (watertightness) engineering design properties as compared to standard compostite multi-layered landfill base liner systems. For sake of safe and stable design of base liners, containing clay layer barriers, under the landfills, the reduction of consolidation settlement in clay by enabling more stability, and thus, larger bearing capacity (i.e. greater load-carrying resistance) when subjected to the accumulated waste load (i.e. superposed action) during landfill operation could be achieved by lime stabilization. Furthermore, the accomplishment for ensuring the waterproof of those composite base liners (comprised of multiple different layers) not to allow the penetration of the contaminated water - produced as a result of exothermic reactions occurring in the waste body in landfills – by enabling enhanced isolation from natural ground could be realized in design. To this end, lime-treatment, filling voids, leads to reduction of porosity, and consequently, the reduction of permeability and the improvement of the imperviousness of clay layer. Further, the increase in bonding between soil grains as a result of lime-treatment produces mechanical strength increase, and hence, the enhancement of bearing capacity to demonstrate higher load-resistant performance of clayey soil layers in the field when employed in geo-environmental infrastructural projects.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

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

ETHICS

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

REFERENCES

[1] F. G. Bell, "Lime stabilization of clay minerals and soils," Engineering Geology,Vol. 42, pp. 223–237, 1996.

[2] S. K. Dash and M. Hussain, "Lime stabilization of soils: reappraisal," Journal of Materials in Civil Engineering, Vol. 24, pp. 707–714, 2012. [CrossRef]

[3] M. R. Abdi and S. Wild, "Sulphate expansion of lime-stabilized kaolinite: Physical characteristics," Clay Minerology, Vol. 28, pp. 555–567, 1993. [CrossRef]

[4] C. M. Geiman, "Stabilization of soft clay subgrades in Virginia; Phase I laboratory study," Master thesis, Virginia Polytechnic Institute and State University, Blacksburg, 2005. [CrossRef]

[5] J. E. Barker, C. D. F. Rogers, and D. I. Boardman,

"Physiochemical changes in clay caused by ion migration from lime piles," Journal of Materials in Civil Engineering, Vol. 18, pp. 182-189, 2006. [CrossRef]

[6] M. Di Sante, E. Fratalocchi, F. Mazzieri, and E. Pasqualini, "Time of reaction in a lime treated clayey soil and influence of curing conditions on its microstructure and behaviour," Applied Clay Science Vol. 99, pp. 100–109, 2014. [CrossRef]

[7] T. C. De Brito Galvão, A. Elsharief, and F. Simões, "Effects of lime on permeability and compressibility of two tropical residual soils," Journal of Environmental Engineering, Vol. 130, pp. 881–885, 2004. [CrossRef]

[8] N. C. Consoli, L. S. Lopes, Jr., and K. S. Heineck, "Key parameters for the strength control of lime stabilized soils," Journal of Materials in Civil Engineering, Vol. 21, pp. 210–216, 2009. [CrossRef]

[9] M. D'Ignazio, T. Lunne, K.H. Andersen, S. Yang, B. Di Buò, and T. Länsivaara, "Estimation of preconsolidation stress of clays from piezocone by means of high-quality calibration data," AIMS Geoscience Vol. 5, pp. 104–116, 2019. [CrossRef]

[10] H. F. Winterkorn, S. Pamukcu, "Soil stabilization and grouting," In Foundation Engineering Handbook, F. Hsai-Yang, editors, Van Nostrand Reinhold: New York, NY, USA, pp. 317–378, 1991. [CrossRef]

[11] H. M. Greaves, "An introduction to lime stabilization," In Lime Stabilisation; Roger, C.D.F., Glendinning, S., Dixon, N., editors, Thomas Telford: London, UK, pp. 5–12, 1996.

[12] P. Beetham, T. Dijkstra, N. Dixon, P. Fleming, R. Hutchinson, J. Bateman, "Lime stabilisation for earthworks: A UK perspective," ICE Proc. Ground Improvising, Vol. 168, pp. 81–95, 2014. [CrossRef]

[13] ASTM 2435, "Standard test method for one-dimensional consolidation properties of soils," ASTM International, West Conshohocken, PA, USA, 2003.

[14] R. D. Holtz, W. D. Kovacs, and T. C. Sheahan, "An Introduction to Geotechnical Engineering," 2nd ed., Pearson Prentice Hall, Upper Saddle River, NJ, USA, 863p, 2011.

[15] M. Budhu, "Soil Mechanics and Foundations," 3rd ed., John Wiley & Sons, Inc., New York, NY, USA, p. 761, 2011.

[16] M. R. A. Asgari, D. Baghebanzadeh, and M. Bayat, "Experimental study on stabilization of a low plasticity clayey soil with cement/lime," Arabian Journal of Geosciences, Vol. 8, pp. 1439–1452, 2015. [CrossRef]

[17] M. Di Sante, E. Fratalocchi, and F. Mazzieri, "Effects of variation in compaction water content on geotechnical properties of lime-treated clayey soil," Procedia Engineering, Vol. 158, pp. 63–68, 2016. [CrossRef]

[18] E. Fratalocchi, I. Bellezza, M. Di Sante, and E. Pasqualini, "Mix-design, construction and controls of lime stabilized embankments," In Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt, Vol. 3, pp. 2248–2251, 5–9 October 2009.

[19] M. Di Sante, "The Contribution of Microstructural Investigation to the Study of Lime-Treated Soils," In Proceedings of the 1st International Workshop on Metrology for Geotechnics, IMEKO TC-4, Benevento, Italy, pp. 16–21, 17–18 March 2016.

[20] M. D'Ignazio, B. Di Buò, and T. Länsivaara, "A study on the behaviour of the weathered crust in the Perniö failure test," In Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, XVI ECSMGE, Edinburgh, Scotland, UK, ICE Publishing: London, UK, pp. 3639–3644, 13–17 September 2015.

[21] M. Di Sante, "On the compaction characteristics of soil-lime mixtures," Geotechnichal Geological Engineering Vol. 38, pp. 2335–2344, 2020. [CrossRef]

[22] I. Bellezza, E. Fratalocchi, "Effectiveness of cement on hydraulic conductivity of compacted soil-cement mixtures," ICE Proc Ground Improv Vol. 10, 77–90, 2006. [CrossRef]