KSCE Journal of Civil Engineering (2021) 25(9):3306-3318
DOI 10.1007/s12205-021-2154-7

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Geotechnical Engineering

Experimental Study on Endurance Performance of Lime and Cement-Treated Cohesive Soil

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ARTICLE HISTORY

Received 10 December 2020
Revised 17 March 2021
Accepted 29 March 2021
Published Online 24 May 2021

KEYWORDS

Fine-grained soil
Soil stabilization
Durability
Wetting-drying
Compressive strength
Volume stability
Loss of mass

ABSTRACT

An earthwork design requires to consider the influence of severe climatic conditions on enduring performance of soils treated with chemical additives. This study was focused on investigating the mechanical behavior of a lime and cement-treated cohesive soil under the effects of repeated cycles of wetting and drying. The soil samples were prepared by adding different concentrations of cement (2, 6, 10, 12, 16, 20%) and quicklime (2, 4, 6, 8, 10%). Due to low-plastic nature of the host soil, the effectiveness of cement to reduce the plasticity of soil was relatively higher compared to lime-treatment. Likewise, an increase in optimum moisture and decrease in maximum dry unit weight was observed for both the additives and these effects were significant for lime treated soil compared to cement. Moreover, an increase in strength from 0.57 MPa to 12.9 MPa at 20% cement and from 0.57 MPa to 2.03 MPa at 2% lime was observed in unconfined compressive strengths (UCS) tests on soil samples. To investigate the durability characteristics of the treated soil, the samples were subjected to 12 cycles of wetting and drying with each cycle consisting of 5 hours of immersion in potable water and subsequent drying in oven for 43 hours. The compressive strength, volume change and weight loss of soil samples were determined at the 1st, 3rd, 6th, 9th and 12th cycle. It is observed that the durability behaviour of treated soil is multipart due to parallel processes of positive aging (hydration process associated with binding agents) and negative aging (induced weathering). For a sustainable mechanical performance of the treated soil, an optimum dose of 6% lime or 16% cement is recommended and some correlations are proposed to quantify the effects of repeated wetting and drying.

1. Introduction

Soil treatment has always been considered as an effective and sustainable approach to make a problematic geomaterial durable against both normal and severe climate conditions (Wang et al., 2015; Zhao et al., 2016). The utilization of a wide variety of stabilizing agents to improve the mechanical performance of problematic clayey soils have been meticulously investigated in several studies. Most commonly used materials in this regard are conventional geotechnical engineering soil binders such as cement or lime (Al-Bared and Marto, 2017; Al-Bared et al., 2019; Chakraborty and Nair, 2020; Kamaruddin et al., 2020). However, using cement or lime as stabilization materials may pose environmental concerns due to greenhouse gasses and hence issues related to sustainability of such materials. More recently, researchers have focused on environment friendly geomaterials such as various ash products (Osinubi et al., 2016; Abdullah et al., 2019), recycled construction materials such as ceramic tiles (Al-Bared et al., 2018a, 2018b), nanomaterials and polypropylene fibers (Abdi and Mirzaeifar, 2016; Tajdini et al., 2018; Tomar et al., 2019; Ali et al., 2020), environmental friendly biopolymers (Lee et al., 2019) and some other industrial wastes

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(Consoli et al., 2017; Zainuddin et al., 2019; Qureshi et al., 2021). Likewise, Al-Bared et al. (2020) observed substantial improvement in mechanical properties of a marine clay treated with cement subjected to cyclic loading such as traffic, wind and earthquake. This is a fact that when used in soil stabilization, both the lime and cement pose environmental threats. Nonetheless, as compared to the other available additives, there are enormous advantages of calcium-based soil stabilization still make them a better choice for ground improvement (Firoozi et al., 2017). It is important to mention that depending on the nature of admixture used, the mechanical behavior of a treated soil is severely affected by weathering due to repeated wetting-drying and freeze-thaw cycles (Nowamooz et al., 2013; Consoli et al., 2018). Changes in groundwater table due to successive evaporation and infiltration of precipitation are the major phenomena that cause moisture variations in shallow soil deposits. Such multiple cycles of wetting and drying result in an irregular settlement, surface cracking, deformation and other failures in the soil. Thus, due to high impact in geotechnical and transportation engineering applications, it is very crucial to consider in design phase the possible effects of hydric cycles on mechanical behavior of treated soils. According to Stoltz et al. (2014) changes in mechanical properties is attributed to progressive accumulation of irreversible strains upon successive wetting and drying of treated soils. Prusinski and Bhattacharja (1999) reported that lime-treatment of cohesive soils is relatively more effective in terms of durability and cost-effectiveness as compared to cement-treatment. They associated this behavior primarily with the chemical nature of the admixture. Nevertheless, relatively higher strength gains have been reported for cement-treated soils compared to those treated with lime. This is due to the fact that an additional product Calcium-Aluminate-Hydrate (C-A-H) is formed during the hydration process which rapidly improves the strength in the early weeks of mixing, noticeably during the first month. This additional product formed in cement-treated admixtures is known as cementitious hydration and such a product is not formed in the case of lime-treated soils.

Calcium Hydroxide $Ca(OH_2)$ is primarily responsible for enhanced flocculation/agglomeration of clay particles in the admixture. Therefore, lime treatment make a relatively durable mixture as it provides 85 – 95% $Ca(OH_2)$ by its weight, whereas, cement provides only 31% of $Ca(OH_2)$. Ahmed and Ugai (2011) have reported that recycled gypsum-stabilized soil with no cement added could not resist the repeated actions of weathering very well. Likewise, Rosone et al. (2021) conducted a study on soil samples retrieved from a lime-stabilized embankment affected by seasonal variations in water content due to successive wetting-drying. With the increase in number cycles of wetting-drying, they observed an increase in incompressibility and swelling deformation, reduction in yield stress and loss of shear strength of the treated soil. According to Consoli et al. (2017), long-term mechanical performance of clays under extreme climatic conditions i.e., freeze/thaw and wetting/drying can be significantly enhanced using industrial byproducts such as carbide-lime and coal fly-ash. Although the mechanical behavior of clayey soils improves due to continued pozzolanic reactions, however, the benefits of such stabilization processes are lost upon intrusion of external water. Similarly, Akcanca and Aytekin (2012) and Starcher et al. (2016) have also reported that repeated cycles of wetting and drying considerably affect the durability, strength and volume change behavior of treated soils.

Considering the abundant availability of lime and cement products as well as widespread soft soils in Pakistan, the utilization of lime/cement to improve engineering properties of problematic grounds are usually considered as a feasible and economical solution. A number of case studies are available where lime and cement-treatment has been successfully employed to improve the strength and deformation behavior of weak subgrades of various projects in Pakistan (Riaz et al., 2014; Mujtaba et al., 2018; Aamir et al., 2019; Khan et al., 2020). Due to extreme weathers in Pakistan, endurance performance of soils treated against freeze-thaw and/or wetting–drying cycles is a serious geotechnical concern. However, no such studies have been done so far to investigated the endurance performance of cement and lime-treated soils considering the local environmental conditions. Therefore, the behavior of treated soils in a specific region and the relevant correlations are of prime importance to quantify the potential impact of repeated hydric-cycles and subsequently the endurance performance of stabilizing admixtures. Therefore, this study aimed at assessing the durability characteristics of a lime and cement-treated fine-grained soil subjected to repeated cycles of wetting and drying (i.e., severe climatic conditions). The effects of lime and cement content on durability of treated soil samples were considered by imparting twelve successive wet-dry cycles and their correlation with the loss of mass, volumetric changes and the unconfined compression strength. Nevertheless, more studies are needed in future to investigate the effects of increased number of weathering cycles and its impact on microstructural behavior of the treated soil.

2. Materials and Methods

2.1 Soil Sample and Additives

The bulk soil sample was obtained from a construction site located in Defense Housing Society (Phase-VI) Lahore, Pakistan (UTM coordinates: Zone 43R, Easting 448571 m and Northing 3483048 m). The stabilizing additives (lime and cement) were procured from a single local source to avoid any inconsistency in the test results. Calcium oxide, commonly known as quicklime or burnt lime and the ordinary Portland cement of Maple Leaf brand was used in this study. Different concentrations of Portland cement (2, 6, 10, 12, 16, 20%) and lime (2, 4, 6, 8, 10%) were added by dry weight of the host soil to prepare the soil specimens. The index properties of the soil sample are presented in Table 1. The soil contained more than 98% fines with inactive clay of medium plasticity. After pulverizing, the soil was placed in oven for 24 hours to eliminate the effects of natural moisture on the subsequent laboratory testing. The particle-size distribution

Table 1. Physical and Index Properties of Host Soil

Property	Value	Standard method
USCS	CL	ASTM D2487
Fine contents (%)	98	ASTM D6913
Clay-size fraction (%)	28	ASTM D7928
Liquid limit (%)	26	ASTM D4318
Plastic limit (%)	18	ASTM D4318
Plasticity index (%)	8	ASTM D4318
Activity	0.21 (Inactive)	
Specific gravity	2.64	ASTM D854
Maximum dry unit weight (kN/m^3)	19.3	ASTM D1557
Optimum water content (%)	10.2	ASTM D1557
Unconfined compressive strength (kPa)		ASTM D2166
(a) At optimum water content	566.5	
(b) After drying at 71°C for 42 hrs.	837.0	

Table 2. Physical and Chemical Properties of Stabilizing Agents

Property	Quick lime (L)	Ordinary portland cement (C)
Color	White	Gray
Texture	Amorphous	Smooth
Form	Lumped	Powdered
Specific gravity	3.3	3.1
Bulk density	950 kg/m^3	1,440 kg/m^3
Heat of hydration	1,140 kJ/kg	250 kJ/kg
Reaction with metals	Not reactive in absence of water	Not reactive in absence of water
Nature	Alkaline, $pH > 12$	Alkaline, $pH = 11$

curve of the soil is shown in Fig. 1(a) which is classified as a low-plasticity clay (CL) as per USCS. The optimum moisture (OWC) and dry density (MDD) as determined from modified Proctor test were 10.2% and 19.3 kN/m^3, respectively. The reference values of unconfined compressive strengths (UCS) were determined for an untreated sample at OWC and for a sample dried at 71°C for 42 hours (Fig. 1(b)). To prepare the lime and cement-treated soil samples, the dried soil was divided into portions as per testing scheme and preserved in polythene bags. Each portion of the soil sample was then thoroughly mixed with pre-defined quantity of stabilizer until uniform color was achieved. The soil-additive mixture was finally compacted in layers in a steel mold to achieve the maximum dry density (as determined earlier through the modified Proctor tests). The diameter and height of remolded specimens were kept as 38 mm and 76 mm, respectively to maintain an aspect ratio of 2. The physical and chemical properties of the additives (lime and cement) used in this study are listed in Table 2.

2.2 Plasticity Limits of Treated Soil

Since the clayey soils in Lahore are prone to change in volume upon wetting and drying, therefore the effects of adding cement and lime on index properties is of great interest to practicing engineers. Atterberg limit tests were conducted (ASTM D4318, 2010) to determine the possible effects of the admixture contents on plasticity limits of the host soil. The variations in Atterberg limits at different concentration of admixtures are shown in Fig. 2. It can be observed that the liquid and plastic limits were initially slightly increased and were relatively constant with increasing in lime content and consequently, the plasticity index (PI) initially decreased followed by an increase afterwards (Fig. 2(a)). Similarly, with increase in cement content, the liquid limit initially increased slightly and then decreased, while no change in the plastic limit was observed. Accordingly, plasticity index initially increased

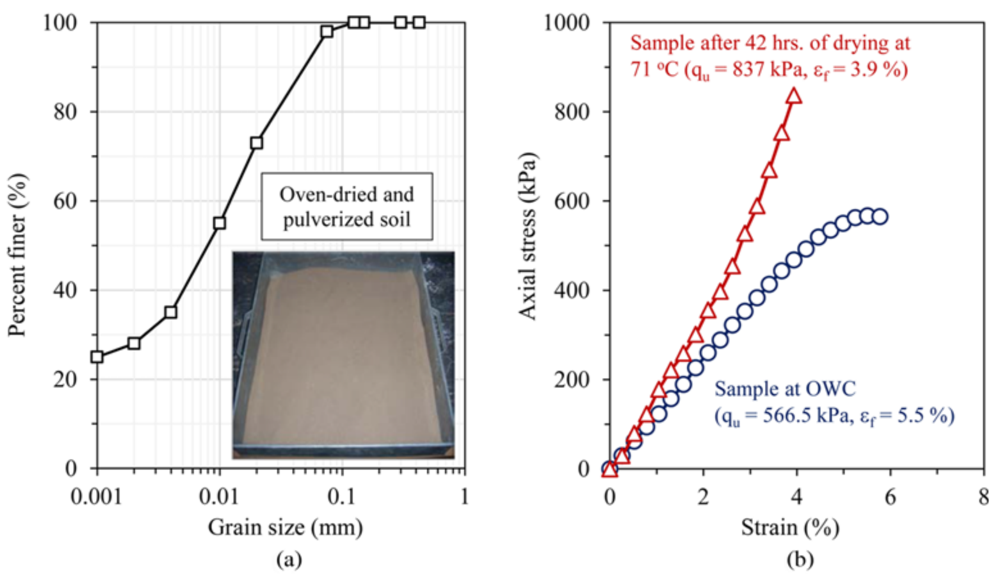


Fig. 1. Host Soil: (a) Particle Size Distribution, (b) UCS Tests on Untreated Soil

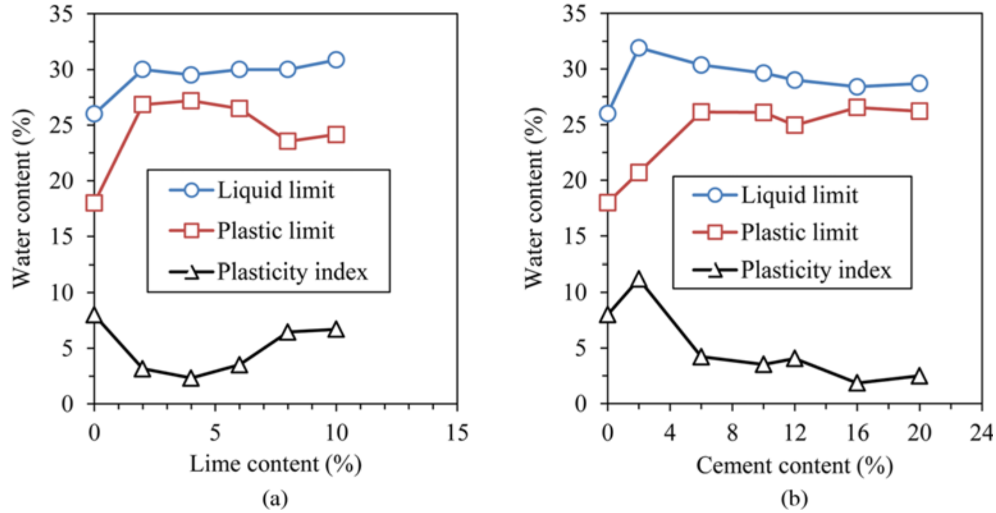


Fig. 2. Plasticity Limits: (a) Lime-Treated Soil, (b) Cement-Treated Soil

which was followed by a subsequent decrease with cement content (Fig. 2(b)). Sariosseiri and Muhunthan (2009) have shown similar results on Aberdeen soil from Washington that the addition of cement and lime improves the workability of fine-grained soils due to the decrease in their plasticity index. In general, the Atterberg limits of the soil stabilized with different concentrations of admixtures (lime and cement) indicated that both the treatments imparted slight impact on the consistency properties. Due to low-plastic nature of the host soil used in this study, the effectiveness of cement to reduce the plasticity of soil was relatively higher as compared to lime-treatment. Nevertheless, the reduction in PI of lime and cement-stabilized soil due to chemical reactions between calcium-based additives (lime and cement) and cohesive soils are well investigated (Parsons et al., 2004).

2.3 Compaction Characteristics of Treated Soil

The compaction properties of host soil treated with admixtures were evaluated by modified Proctor tests (ASTM D1557, 2012). The compaction curves of the treated and untreated soil samples are shown in Fig. 3 and the relationships between optimum water content (OWC) and maximum dry unit weight (MDD) of treated soils are shown in Fig. 4. It can be observed that, generally, the OWC increased whereas MDD decreased as the cement and lime contents were increased. Moreover, the variation in compaction properties are substantial at lower concentrations of the admixtures and it becomes minimal with further increase in admixture content. Similarly, the rate of decrease in MDD and increase in OWC is relatively higher for lime-treated soil compared to the cement-treated soil. The OWC increased due to the exothermic reaction between the additives and water. As a result, this reaction requires additional water to achieve the desired compactness in a relatively moist condition. However, the maximum compactness of the treated soil becomes less, which causes a reduction in the MDD compared to the untreated soil with higher level of OMC.

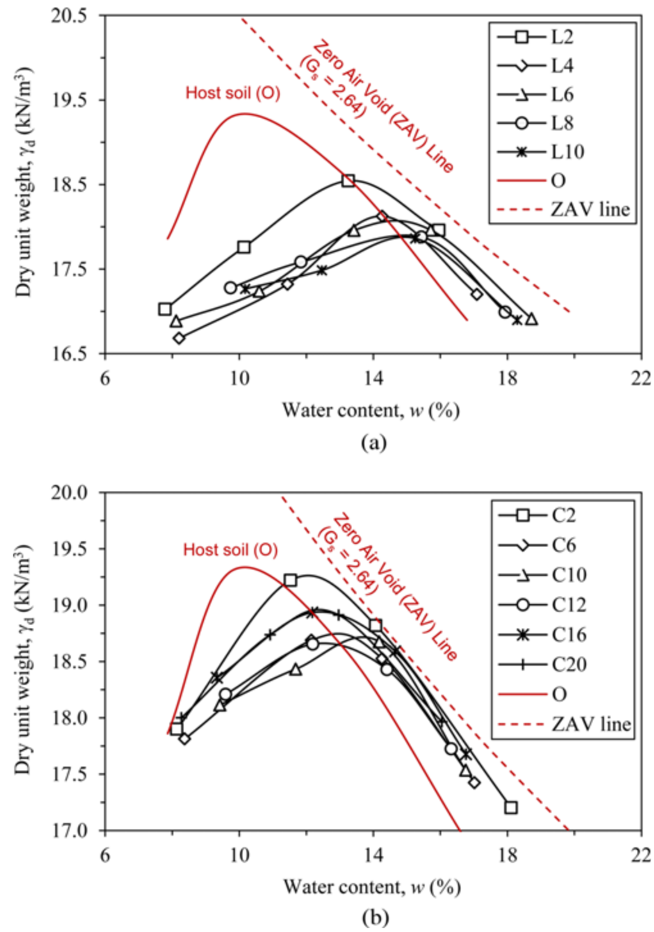


Fig. 3. Compaction Curves of: (a) Lime-Treated, (b) Cement-Treated Soil Samples

As reported by Nabil et al. (2020), this decrease in MDD is attributed to restructuring of soil due to the particles' cementation/aggregation.

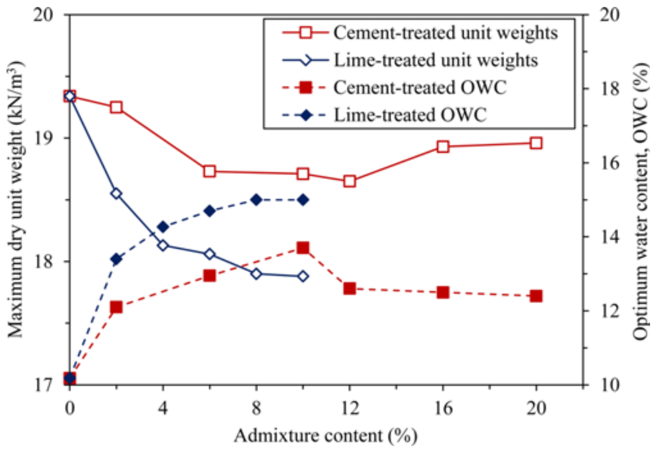


Fig. 4. Effect of Admixtures on Maximum Dry Unit Weight and Optimum Water Content

2.4 Unconfined Compressive Strength (UCS)

Despite of the limitations of reproducing the field conditions, the UCS test is still an extensively used laboratory test amongst many researchers and practitioners across the globe to quantify the degree of improvement of cohesive soils treated with various types of admixtures. The UCS tests were conducted as per ASTM D2166 (2016) on the host soil and the treated soil samples. Axial force was continuously applied (at a strain rate of 1% per minute) until the soil sample failed. The UCS of the host soil at optimum water content and after drying at 71°C for 42 hrs were recorded as 567 and 837 kPa, respectively. The effect of lime and cement treatment on mechanical response of the host soil has been shown in Fig. 5 which shows that with cement content of 20%, the peak axial stress increased significantly (from 0.57 MPa to 12.9 MPa), whereas, the strain at the peak axial stress decreased from 5.8% to 4.9%. Thus, relatively more brittle response was observed for cement-treated soil compared to the non-treated host soil. These results are consistent with the findings of Elkady (2016), Moayedi et al. (2014) and Horpibulsuk et al. (2006). Similarly, with 2% lime added to the host soil, the peak axial stress increased from 0.57 MPa to 2.03 MPa which then decreased to 0.78 MPa with further increase of lime up to 10%. The strains at maximum axial stress initially increased from 5.8% to 13.8% which decreased to 6.8% at lime content of 10%. Thus, lime treated soil exhibited a ductile behavior at low additive content (i.e., 2%) and the behavior changed from ductile to brittle with increase in additive content from 2% to 10%. Khazaei and Moayedi (2019) have also observed that the effect of lime on increasing UCS and other geotechnical properties of an expansive soil is more considerable than the other additives. According to ASTM D7762 (2018), soil treatment is considered to be effective if the increase in UCS value is 345 kPa or more and the slaking of specimens is prevented during water immersion which is true for both the additives used in this study. This increase in strength, especially for cement-treated soil, explains the reaction between soil and calcium-based additives (lime and cement) which eventually forms C-S-A-H and C-S-H (Nabil et al., 2020). The decrease in UCS after 2% lime content is mainly due to the fact that these samples were tested without any curing and the increase in lime content without curing made the treated soil softer as depicted by the sudden drop in failure strain.

3. Durability of Treated Soil against Wetting-Drying Cycles

3.1 Methods and Procedures

Using the respective MDD and OWC as obtained from Proctor tests (Fig. 3), the samples were prepared and cured at constant water content with quicklime content ranging from 0 to 10% and cement content from 0 to 20% by dry weight of the soil. The nomenclature of soil samples used in this study is given in Fig. 5. After curing period of 7 days and in accordance with the ASTM D559 (2015) test procedure, cement and lime-treated samples were subjected to 12 wetting-drying (W-D) cycles with each cycle consisting of 5 hours of immersion in potable water at a

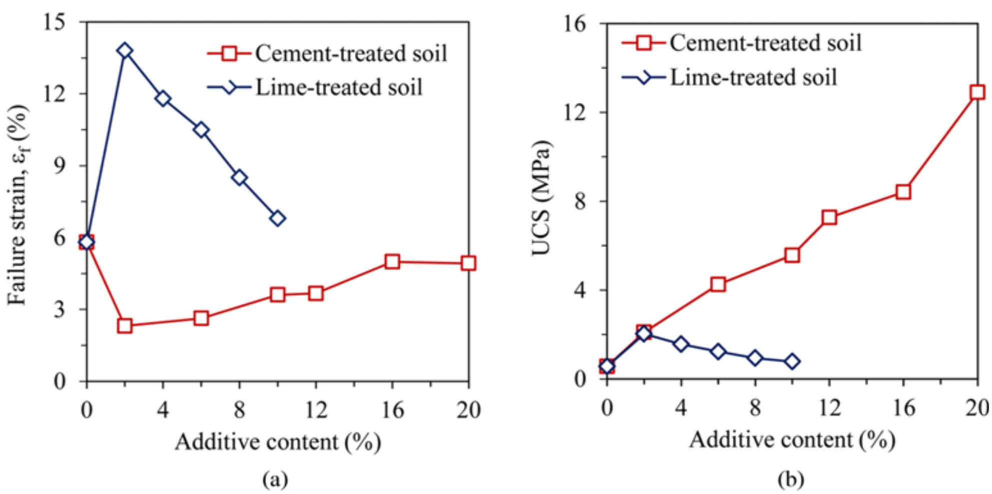


Fig. 5. UCS Tests on Treated Soil Samples with No Wet-Dry Cycles: (a) Effects of Additives on Failure Strain, (b) Effects of Additives on Compressive Strength

Fig. 6. Soil Samples for Durability Tests and Their Nomenclature

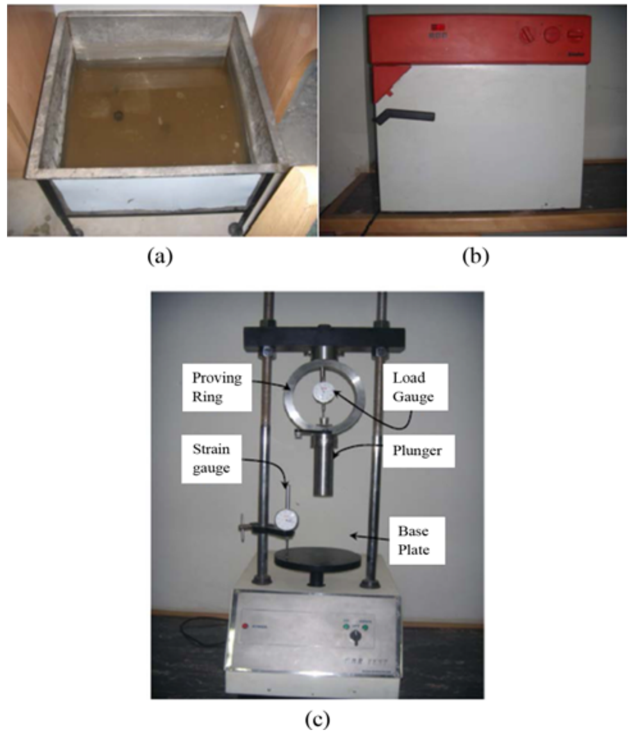


Fig. 7. Experimental Setup Used in This Study: (a) Water Tank for Wetting, (b) Oven for Drying, (c) UCS Test Apparatus

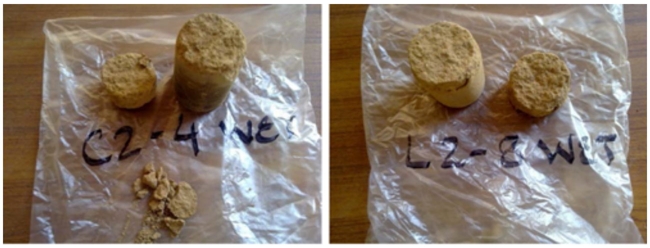
room temperature of 20ºC with subsequent drying in oven at 71ºC for 43 hours. The compressive strength, volume change and weight loss of soil samples were determined at the first, third, sixth, ninth and twelfth W-D cycles (Table 3). The apparatus used for wetting-drying and UCS tests have been shown in Fig. 7 and typical samples disintegrated during successive cycles of wetting-drying have been shown in Fig. 8. The size of soil samples (height and diameter) were carefully measured to assess associated volume changes during each cycle. The weight loss of soil samples due to repeated W-D cycles was also recorded. The samples were buffed with a wire brush to remove the disintegrated (about to detach) particles/lumps from the specimen. It is important to mention here that Nabil et al. (2020), based on their experimental study on durability of lime-treated highly plastic clay (CH), have reported that the positive aging (due to on-going hydration process associated with binding agents) and negative aging (due to induced weathering) acting parallel, in general, make such type of study complex.

3.2 Effects of Wetting-Drying Cycles on Compressive Strength

The mechanical behavior of lime and cement-treated soil samples after the 1st, 3rd, 6th, 9th and 12th W-D cycles was investigated through UCS. However, the soil sample treated with 2% lime was completely disintegrated at the eighth wetting cycle whereas the soil sample treated with 2% cement disintegrated at the fourth wetting (Fig. 8) and for this reason the subsequent W-D cycles and UCS tests could not be performed on these samples. From the stress-strain curves of lime-treated (Fig. 9) and cement-treated (Fig. 10) soil samples at various W-D cycles, the variations

Table 3. Soil Samples Prepared for Durability Tests

Tests	Lime-treated specimens (L)					Cement-treated specimens (C)					
UCS	L2-0	L4-0	L6-0	L8-0	L10-0	C2-0	C6-0	C10-0	C12-0	C16-0	C20-0
	L2-1	L4-1	L6-1	L8-1	L10-1	C2-1	C6-1	C10-1	C12-1	C16-1	C20-1
	L2-3	L4-3	L6-3	L8-3	L10-3	C2-3	C6-3	C10-3	C12-3	C16-3	C20-3
	L2-6	L4-6	L6-6	L8-6	L10-6	C2-6	C6-6	C10-6	C12-6	C16-6	C20-6
	L2-9	L4-9	L6-9	L8-9	L10-9	C2-9	C6-9	C10-9	C12-9	C16-9	C20-9
	L2-12	L4-12	L6-12	L8-12	L10-12	C2-12	C6-12	C10-12	C12-12	C16-12	C20-12
Volume stability	L2-A	L4-A	L6-A	L8-A	L10-A	C2-A	C6-A	C10-A	C12-A	C16-A	C20-A
Weight loss	L2-B	L4-B	L6-B	L8-B	L10-B	C2-B	C6-B	C10-B	C12-B	C16-B	C20-B



(a) (b)

Fig. 8. Disintegrated Soil Samples during Wetting-Drying Cycles: (a) Cement-Treated Soil, (b) Lime-Treated Soil

in peak axial stresses (q_u) and corresponding strains (ε_f) with increase in additive content and number of W-D cycles were computed and are presented in Fig. 11. It is evident that both the lime and cement-treated soil samples had alternate trend of increase and decrease in q_u and ε_f values over the first, third, sixth, ninth and twelfth W-D cycles. However, the q_u and ε_f values increased with an increase in additive contents as depicted by the respective regression models given in Table 4. Knowing the desired additive content, these regression models can be used to predict the average mechanical properties (q_u and ε_f) of treated

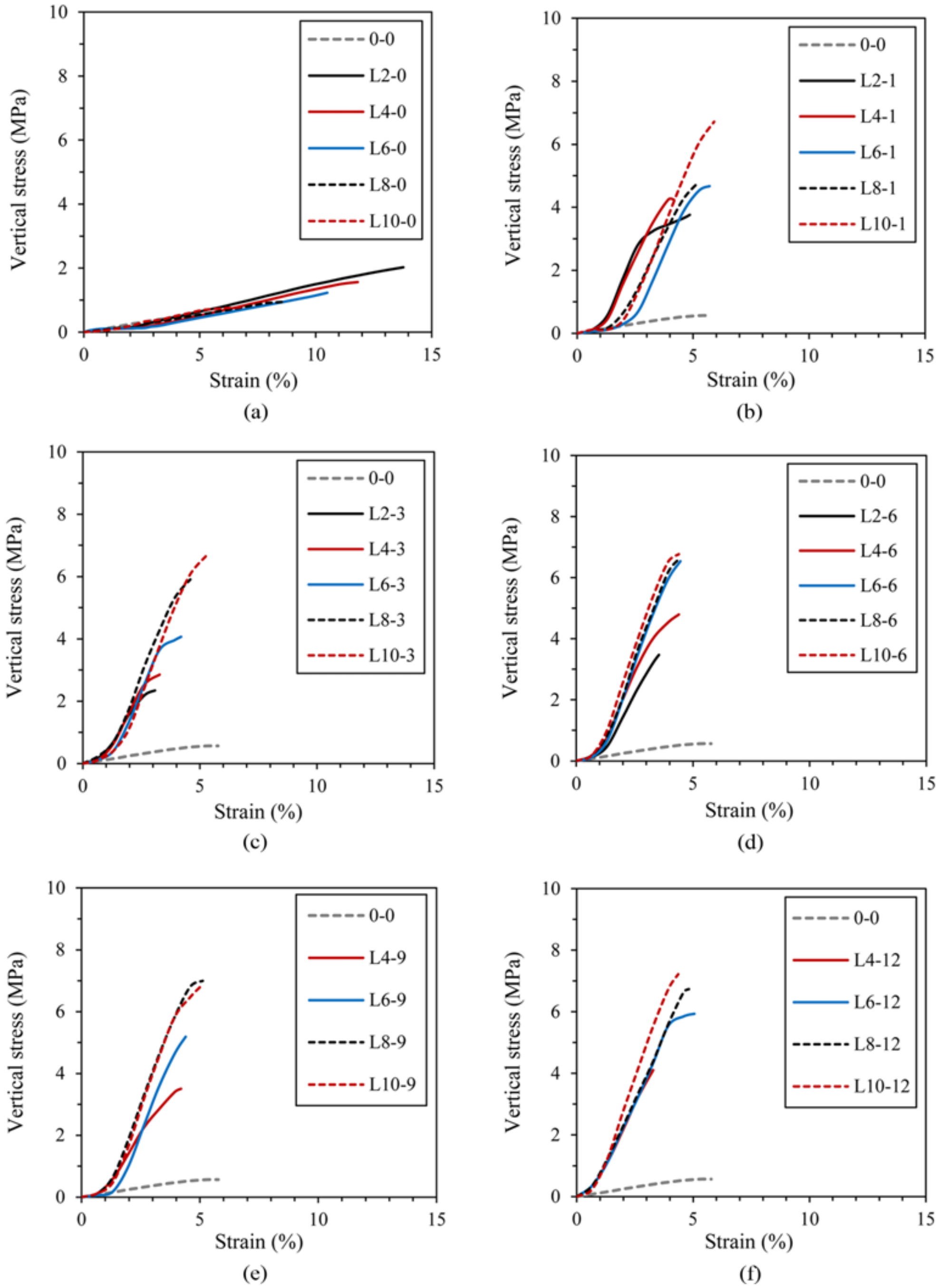


Fig. 9. UCS Tests on Lime-Treated Soil Samples at Different W-D Cycles: (a) W-D Cycles = 0, (b) W-D Cycles = 1, (c) W-D Cycles = 3, (d) W-D Cycles = 6, (e) W-D Cycles = 9, (f) W-D Cycles = 12

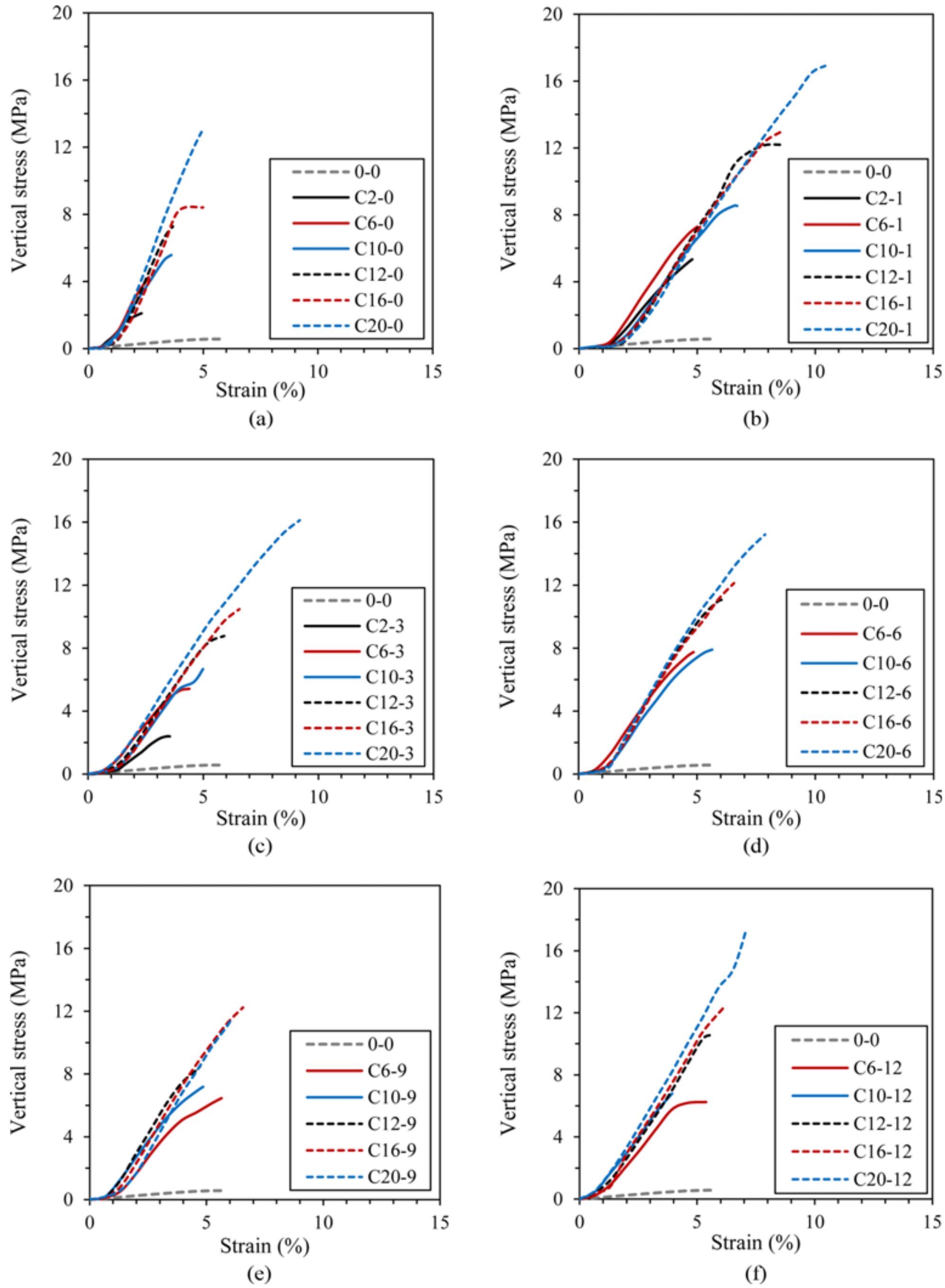


Fig. 10. UCS Tests on Cement-Treated Soil Samples at Different W-D Cycles: (a) W-D Cycles = 0, (b) W-D Cycles = 1, (c) W-D Cycles = 3, (d) W-D Cycles = 6, (e) W-D Cycles = 9, (f) W-D Cycles = 12

soils at 12th cycle of wetting and drying. Moreover, a higher order coefficient of determination (R^2 value) of these models justifies the goodness of data fit. The overall increase in q_u can be attributed to the hydrated products (CSH and/or CAH) formed due to soil-lime and soil-cement reactions. Similar results have also been reported by Aldaood et al. (2014) on the effects of hydric cycles on engineering properties at micro-structure level of a lime stabilized gypseous soils. A significant decrease was reported in UCS of treated soil samples at wetting state with an increase at subsequent drying state. However, an overall increase in q_u was observed after repeated wetting and drying cycles. Fig. 12 shows relative change (increase/decrease) in compressive strength at various wetting-drying cycles. The UCS of both lime and cement-treated soil samples significantly increased during the first W-D cycle with an alternate decrease and increase in UCS for subsequent W-D cycles. The highest increase in UCS after the first cycle was 762% and 153% for soil samples treated with 10% lime and 2% cement, respectively. The greatest

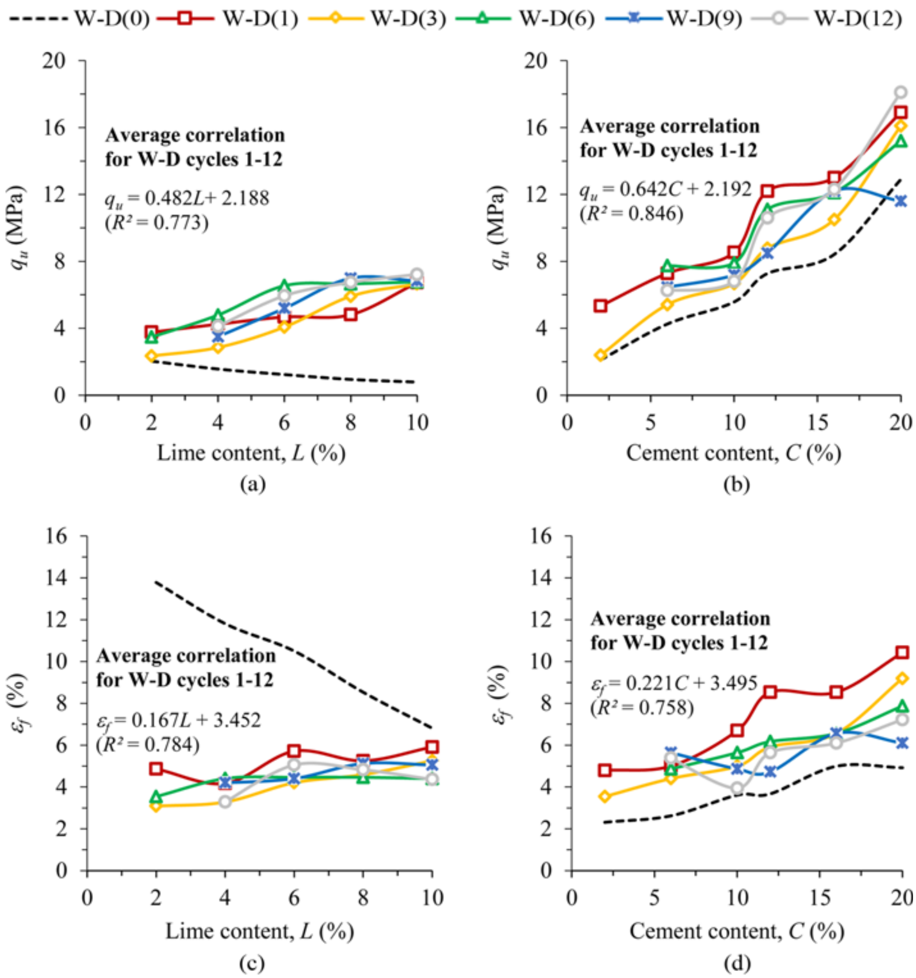


Fig. 11. Effects of Wetting-Drying Cycles on: (a) UCS of Lime-Treated Soil, (b) UCS of Cement-Treated Soil, (c) Failure Strains of Lime-Treated Soil, (d) Failure Strains of Cement-Treated Soil

Table 4. Regression Models for Mechanical Properties of Treated Soils Subjected to Wetting-Drying Cycles

Properties	Lime-treated soil		Cement-treated soil	
	Model	R^2	Model	R^2
Compressive strength, q_u (MPa) =	0.482L+ 2.188	0.773	0.642C + 2.192	0.846
Failure strain, ε_f (%) =	0.167L + 3.452	0.784	0.221C + 3.495	0.758
Volume change, ΔV (cm^3) =	$0.038N^2 - 0.562N + 2.059$	0.898	$0.025N^2 - 0.365N + 1.486$	0.712
Weight loss (%) =	$5.467e^{-0.559L}$	0.925	$1.054e^{-0.205C}$	0.958

L = Lime content (%), C = Cement content (%), N = Number of wetting-drying cycles

reduction in compressive strength (from 762% to -38% for lime-treated soil and from 153% to -55% for cement-treated soil) were recorded at 3rd wetting–drying cycle.

The increase in compressive strength after the 1st cycle is attributed to the hydration of calcium silicates (an ongoing reaction after curing of treated soil samples) which is primarily formed during the initial stages of hydration (Bozbey, 2018). In this study, the samples were tested after completion of each wetting-drying cycle (i.e., drying state only). A point to mention in this regard is that the compressive strength of treated soils in drying state is greater than those samples tested in wetting state which further decreases with increased hydric cycles. The results reveal that the lime-treated soils are much more sensitive to loss of strength upon the wetting-drying cycles, particularly during the 1st cycle compared to a relatively stable behavior of cement-treated soils.

3.3 Volume Change during Wetting-Drying Cycles

Similar to the UCS behavior, relative change in the volume (DV) of lime and cement-treated soil samples were observed at the 1st, 3rd, 6th, 9th and 12th wetting-drying cycle. The diameter and height of the soil samples were measured after the respective W-

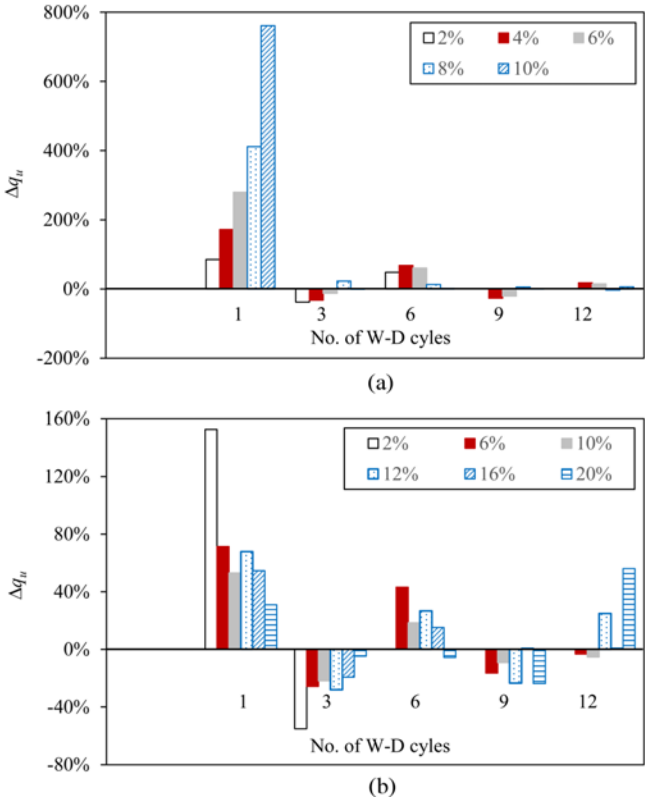


Fig. 12. Relative Change in UCS with Wetting-Drying Cycles: (a) Lime-Treated Soil, (b) Cement-Treated Soil

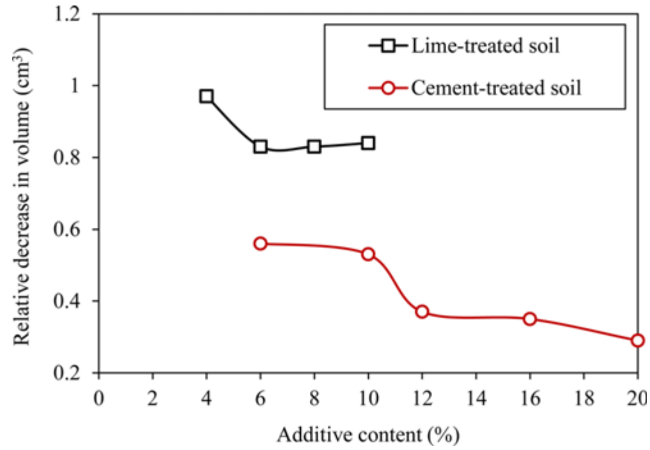


Fig. 14. Overall Decrease in Volume from 1st to 12th Wetting-Drying Cycle

D cycle to determine the volume change variations as shown in Fig. 13. As mentioned earlier that the soil sample treated with 2% lime was completely disintegrated at the 8th wetting cycle and the 2% cement-treated sample disintegrated at the 4th wetting and that is why the subsequent W-D cycles and volume change measurements could not be done. It can be observed in Fig. 13 that with both the additives (i.e., cement and lime) there is a sudden and significant decrease in the volume of soil specimens until the 6th W-D cycle and volumetric expansion takes place after the 6th cycle for all concentrations of the additives. Moreover, there is a net reduction in volume at the 12th cycle when compared to the 1st cycle (Fig. 14) which is relatively higher for cement-treated soil samples. The volumetric shrinkage of soil specimens during the initial cycles of wetting and drying is attributed to continued hydration of lime and cement and subsequent reduction in voids due to the agglomeration of soil particles during this phase. However, after certain number of W-D cycles, the disintegration process dominates which creates large voids with an overall increase in the volume of soil specimens. The regression models of this behavior have been presented in Table 4. The average regression model has been developed for cement-treated soil and likewise for lime-treated soil because each concentration of the additive induced quite a similar volume change behavior over the repeated cycles of wetting and drying. These models (with a significantly high

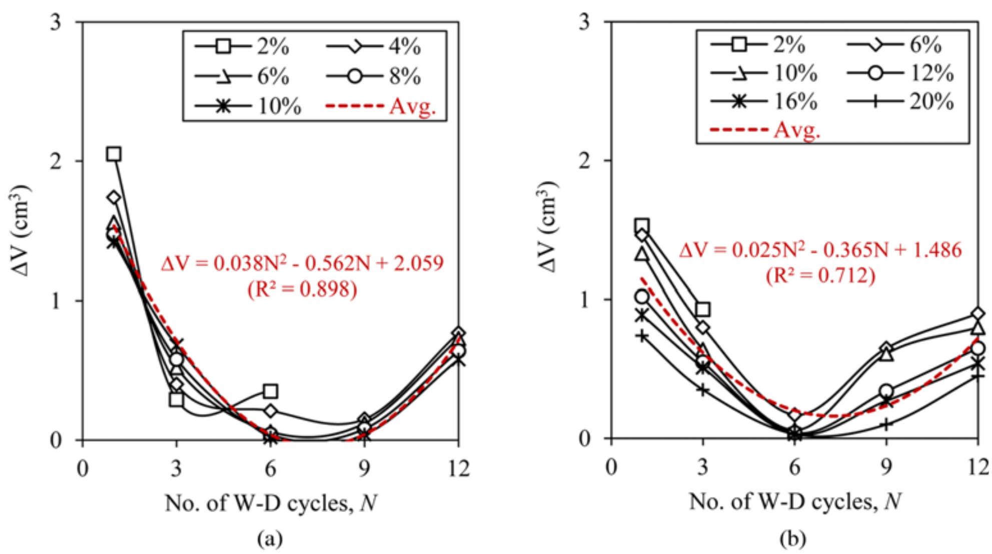


Fig. 13. Effects of Wetting-Drying Cycles on Volume Change: (a) Lime-Treated Soil, (b) Cement-Treated Soil

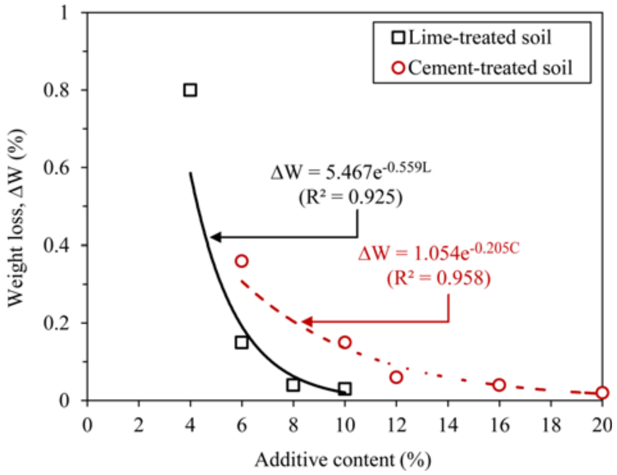


Fig. 15. Cumulative Weight Loss after 12th Wetting-Drying Cycle

value of R^2) can be used to estimate the change in volume of a treated soil for a given number of hydric cycle.

3.4 Weight Loss during Wetting-Drying Cycles

The cumulative weight loss of soil samples at 12th wetting and drying cycle were also recorded. The soil samples were buffed with a wire brush to remove the disintegrated (about to detach) particles/lumps. With the increased number of hydric cycles for each specimen, it was observed that the weight loss increased at a relatively constant rate. However, as shown by the relationships in Fig. 15, the increase in additive content made the soil samples relatively more agglomerated and hence improved their endurance against the loss of weight due to repeated wetting and drying. Hoy et al. (2017) and Consoli et al. (2018) established similar correlations between cumulative loss of mass and the imparted W-D cycles on fly ash and geopolymer-mixed reclaimed asphalt pavement and cement-treated fine grained soils, respectively. From the respective regression models for lime and cemented treated soil specimens presented in Table 4, it can be noted that the cement-treated soil showed more endurance with a gradual but lesser weight loss relative to lime-treated soil samples showing an abrupt and greater loss of weight upon wetting and drying. Knowing the desired additive contents, these models can be used to estimate the weight loss of a treated soil at 12th cycle of wetting and drying. According to Stoltz et al. (2014), a physio-chemical analysis should be carried out to supplement the understanding of the loss of bonding in treated soils subjected to repeated W-D cycles.

4. Conclusions

Considering the abundant availability of lime and cement products as well as widespread soft soils in Pakistan, the utilization of such admixtures to enhance mechanical performance of problematic grounds has been considered a sustainable solution by the construction industry. However, due to severe local climatic conditions, there are geotechnical concerns related to how to quantify the endurance performance of a treated soil against freeze-thaw and/or wetting–drying. An experimental study was conducted to assess mechanical properties of a lime and cement-treated cohesive soil undergoing repeated wetting-drying cycles, and to propose possible correlations of such hydric cycles with the loss of mass, volume change and unconfined compressive strength. Regarding the effects of admixtures on index properties and compression behaviour, it is observed that:

1. The effectiveness of cement to reduce soil plasticity was relatively higher as compared to lime mainly due to the low-plastic nature of the host soil. Nevertheless, this decrease in plasticity index has an advantage of better workability of such soils in the field.
2. The effects of lime and cement on compaction properties are significant at lower percentages (i.e., 4% lime, 10% cement) which becomes minimal with further increase in additive content. Similarly, it has been shown that for lime-treated soil, the rate of increase in OWC and decrease in MDD is relatively higher as compared to cement-treatment.
3. An increase in strength from 0.57 MPa to 12.9 MPa at 20% cement and from 0.57 MPa to 2.03 MPa at 2% lime was observed in UCS tests on soil samples. Compared to the non-treated soil, cement-treatment indicated relatively brittle response, whereas, lime-treated soil showed a ductile response at low additive content (i.e., 2%) and the behavior changed to brittle with further increase in its concentration up to 10%.

Regarding the effects of repeated cycles of wetting-drying on the endurance performance of treated soil samples, the following conclusions are drawn:

1. Compressive strength of both lime and cement-treated soil samples significantly increased during the first wetting and drying cycle with an alternate decrease and increase in strength in the subsequent cycles. The highest increase in compressive strength after the first cycle was 762% and 153% for soil treated with 10% lime and 2% cement, respectively. The greatest reduction in compressive strength (from 762% to -38% for lime-treated soil and from 153% to -55% for cement-treated soil) were recorded after third wetting–drying cycle.
2. An abrupt and significant decrease in the volume of both lime and cement-treated soil specimens was observed until the 6th wetting-drying cycle with subsequent volume expansion for all concentrations of the additives. However, there is a net reduction in volume at the 12th cycle when compared with the 1st cycle and this phenomenon is more prominent for cement-treated soil compared with the soil treated with lime.
3. With the number of W-D cycles for each specimen, it was observed that the weight loss increased at a relatively constant rate. However, the increase in additive content made the soil relatively more agglomerated and hence improved its endurance against the loss of weight due to successive hydric cycles.

4. For a sustainable mechanical performance of the treated soil, an optimum dose of 6% lime or 16% cement is recommended and some correlations are proposed to quantify the effects of repeated wetting and drying. However, further studies are recommended to assess the effects of prolonged curing of soil specimens and increased number of weathering cycles along with their impact on microstructural behavior of the treated soil.

Acknowledgments

The laboratory facilities provided by the Geotechnical Engineering Laboratory at the Department of Civil Engineering, UET Lahore Pakistan is gratefully acknowledged.

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