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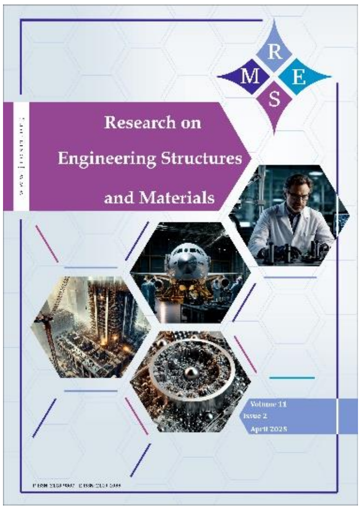

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Research Article

Strength and deformation characteristics of stabilized fine-grained soil cured under overburden stress

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Abstract

This study investigates the effects of overburden stress on the physical and mechanical properties of stabilized fine-grained soil. Unconfined compressive strength (UCS) tests were conducted to evaluate the influence of overburden stress on stabilized soil specimens cured for 7, 14, 28, 60, and 90 days. The soil was treated with various binder contents of 1%, 2%, 4%, and 7% by soil dry weight. Two sets of stabilized soil specimens were prepared: one cured under atmospheric pressure and the other cured under stress of 10.5 kPa. The results indicate that the specimen density increased with both binder content and curing stress. The applied stress had the effect of increasing the unconfined compressive strength and stiffness, while a reduction in failure strain was observed compared to stabilized soil specimens cured without stress. The failure behavior is more brittle in stabilized soil with 7% binder content compared to soils with lower binder contents and natural soil, which exhibit more ductile behavior.

1. Introduction

Chemical soil stabilization involves adding different stabilizing agents to enhance the properties of weak soils, which exhibit low shear strength and stiffness. Generally, such soils are unsuitable for construction and are therefore excavated and replaced with good-quality geomaterials from quarries. Excavation and transportation generate large volumes of waste soil and contribute significantly to CO_2 emissions. In recent years, the lack of good-quality geomaterials and limited disposal options due to stricter environmental restrictions has made this approach increasingly impractical. Therefore, the use of stabilized soil in various construction projects has become widespread, as it improves soil performance while reducing environmental impact [1].

The use of hydraulic binders, such as cement, cement kiln dust, and their combinations, has been extensively studied for improving the physical and mechanical properties of fine-grained soils [2–11]. Moreover, the influence of other factors such as binder type and dosage, soil properties, mixing procedure, and curing time and conditions on the behavior of stabilized soils has been widely studied [12–17]. Previous studies have shown that improvements in cement stabilized soils are primarily attributed to the hydration and pozzolanic reactions of cement-based stabilizers, which produce primary and secondary cementitious materials. Hydration reactions start immediately after cement is mixed with moist soil, generating three types of primary cementitious products: calcium-silicate hydrate (CSH; C_2SH_x and $C_3S_2H_x$), calcium-aluminate hydrate (CAH; C_3AH_x and

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C_4AH_x), and calcium hydroxide (Ca $(OH)_2$). The symbols, C, S, A and H refer to calcium (CaO), silicate (SiO_2), aluminate (Al_2O_3) and water (H_2O) respectively. CSH and CAH gel bind soil particles together to form a strong, hard matrix over time, while $Ca(OH)_2$ deposited on the surface of soil particles increases the pH of the mixture. Under certain conditions, when the pH rises to around 12, calcium hydroxide can react with components of the soil, such as silica and alumina from clay minerals, through pozzolanic reactions, leading to the formation of additional of CSH and CAH gel over time (secondary cementitious materials).

To predict the improvement in the engineering properties of stabilized soil, a series of experimental tests are typically conducted in a laboratory under certain conditions, which in principle should simulate the in-situ conditions as much as possible. In a laboratory, the experimental testing program is carried out according to the standard protocols, starting from specimen preparation, curing conditions and period until testing of stabilized soil specimens [18]. Almost all standards recommend that the specimens of stabilized soils be cured under controlled conditions such as at temperatures around 20 °C, relative humidity exceeding 95%, and atmospheric pressure. However, in the field, stabilized soil layers are typically subjected to overburden stress immediately after treatment due to the placement of a cover layer 0.5–1.0 m thick. This loading contributes to densification and improved homogeneity of the treated soil by expelling some of the air entrapped during the mixing process. Moreover, the initial loading is considered a necessary step to create a leveled and more homogenized stabilized mass which can improve the physical and mechanical characteristics of stabilized soil [19].

Several researchers have reported differences between laboratory-cured specimens and field specimens taken from deeper depths for cemented paste backfill, cemented sand, and stabilized peat [20–22]. A few studies have pointed out that the mechanical behavior of stabilized soils cured under overburden stress can be altered due to the compression effect during the formation of cementitious products. The effect of the application of various vertical stresses (9 and 18 kPa) on top of stabilized peat specimens during curing was investigated by [19]. The UCS specimens were prepared by pouring the stabilized peats by hand inside the specimens. The results indicated that stabilized soil specimens cured under vertical stress showed a significant increase in strength compared to specimens cured without vertical stress. Moreover, the results show that the compression of stabilized peat during curing decreases with increasing binder content. Reference [23] pointed out that the pre-consolidation pressure of stabilized soils was highly affected by large cementation materials generated due to the use of higher binder content. Reference [24] investigated the effect of overburden stress (7.5 kPa) applied during curing on the strength behavior of silt soil treated with cement. Cement content ranged between 5%, 7% and 9%, and the specimens were cured for 7,14 and 28 days. The UCS specimens were prepared by pouring the stabilized soil in five layers and tapping each layer with a rubber hammer to remove any air bubbles. The strength of stabilized soil increased due to the application of overburden stress.

The effect of applying 5 kPa overburden stress on stabilized silty clay soil treated with 8%, 10%, and 12% Portland pozzolanic cement has been investigated by [25]. The specimen was prepared and compacted at the optimum water content and cured for 56 days. The results indicated that the specimens cured under stress show an increase in soil strength compared to specimens cured without stress. A recent study investigated the effect of curing stress on low-plasticity silty soil treated with a mixture of 1% lime (90% quicklime (CaO)) and 5% hydraulic binder (35% Portland cement clinker and 65% blast furnace slag). The testing program was limited to only nine prepared specimens, which were compacted using an isotropic confining pressure of 500 kPa at optimum water content, and only one specimen was cured under 500 kPa curing stress for 70 days. The results showed that curing stress has an effect on further increasing the shear modulus of stabilized soil compared to specimens cured without stress [1]. As clarified by previous studies, higher binder content generates more cementitious materials compared to lower binder content, which subsequently results in greater improvement in soil strength and a lower compression effect under overburden stress during curing period. Despite these findings, most previous studies have not explicitly considered the combined influence of curing stress and standard compaction effort applied during specimen preparation. In addition, the majority of previous studies used higher binder contents, shorter curing periods, and did not compare the effect of overburden stress on the natural soil. To address this limitation, laboratory tests were conducted to evaluate the effects of initial stress over time on the strength and stiffness of compacted natural and stabilized soil specimens.

This study aimed to investigate the effect of overburden stress on the strength and deformation characteristics of natural and stabilized soil specimens treated with various binder contents (from 1% to 7%) and compacted specimens using a Proctor hammer to achieve a compaction effort of 600 kJ/m^3. The combined effects of binder amount, curing time and applied stress are evaluated using unconfined compressive strength tests.

2. Experimental Program

2.1. Materials

The natural soil used in this study was collected from a construction site in the southwestern part of Sweden. The standard identification laboratory tests were performed on the natural soil to determine its properties. The basic soil characteristics are illustrated in Table 1. The soil was classified as lean clay (CL) according to the Unified Classification System ASTM D 2487-11 [26].

The binder used in this study, named Multicem, was sourced from Cementa AB, Sweden. It is a mixture of Portland cement and cement kiln dust (CKD) in a 50:50 proportion at the plant site, where the CKD replaces limestone as a raw material during cement production. The chemical composition of the binder is presented in Table 2.

Table 1. The basic characteristics of studied soil

Description	Value
Specific Gravity	2.69
Liquid limit (%)	38
Plastic limit (%)	19
Plasticity index (%)	19
Sand content (%)	29
Silt content (%)	54
Clay content (%)	17
Optimum moisture content (%)	13
Maximum dry density (g/cm3)	1.96
Organic content (Loss of ignition) (%)	4

Table 2. Chemical composition of the binder used in this study

Description	Value
Alkalis, Sodium oxide (Na_2O) (%)	3
Free lime, (CaO) (%)	14
Calcium oxide (CaO) total (%)	50
Magnesium oxide (MgO) (%)	2.1
Potassium oxide (K_2O) (%)	7.5
Silicon oxide (SiO_2) (%)	19
Aluminum oxide (Al_2O_3) (%)	4.5
Iron oxide (Fe_2O_3) (%)	2.8
Sulfur trioxide (SO_3) (%)	5
Loss of Ignition (%)	4.8

2.2. Preparation of Specimens

The unconfined compressive strength (UCS) specimens of the natural soil were prepared by homogenizing the natural soil using a laboratory mixer for 15 to 18 seconds [27]. After that, the homogenized soil was placed inside cylindrical plastic tubes in five compacted layers to achieve a height of 10 cm. The inner diameter of the tubes was 50 mm and the height was 170 mm. The standard compaction procedure was followed for preparing all specimens by compacting each layer with 15 blows using a design hammer which provides energy per volume 600 kJ/m³ as compaction effort. According to the curing conditions, the prepared specimens were divided into two sets: one cured under atmospheric pressure (without stress), and the other cured under a stress of 10.5 kPa. The applied curing stress of 10.5 kPa corresponds to an equivalent soil depth of about 0.6 m representing a low overburden stress near-surface soil.

For specimens cured under atmospheric pressure, the prepared specimens were sealed on both sides using covers to prevent water from entering. For the other specimens that were cured under overburden stress, the prepared specimens were subjected to loads on the top of each soil specimen. The load was applied using a filter plug as shown in Fig. (1). The filter plug was inserted from the top end of the PVC tube until it made contact with the upper surface of the specimen. The filter plug has a cylindrical shape with an outside diameter of 49 mm and contains a circular hole in the middle of both ends. The lower end (which makes contact with the upper surface of the specimen) contains a thick filter to allow water to drain through the hole during the compression period (application of overburden stress). The upper end is used to apply the vertical load. The main purpose of the filter plug was to transfer the applied stress to the soil specimens and allow drainage from the top surface during the curing period. Before inserting the plug and soil, the inner surfaces of the polyvinyl chloride (PVC) tubes used for specimen preparation were manufactured with a smooth finish layer to ensure very smooth surfaces and were also greased prior to testing to minimize side friction during the consolidation and extrusion of the soil specimens. The bottom end of the specimen was sealed with plastic covers and rubber lids. All prepared specimens were cured in glass containers partially filled with water to a certain level (cover half of the specimen height) and stored at a controlled room temperature of 20 °C, as illustrated in Fig. 2. A load of 2 to 2.1 kg was placed on top of each filter plug for natural and stabilized soil specimens immediately after preparation. All prepared specimens were cured for 7, 14, 28, 60 and 90 days.

The stabilized soil specimens were prepared by mixing the homogenized soil with the binder for ten minutes using a laboratory mixer until a visually homogeneous consistency was achieved. The binder was added in various proportions of 1%, 2%, 4%, and 7% based on the dry weight of the soil. The mixtures were then placed by hand inside the plastic tubes. The preparation of UCS specimens of stabilized soil followed the same protocol and procedure described above for preparing and curing the UCS specimens of natural soil.

All prepared specimens (both cured under atmospheric and overburden pressures) were tested after 7, 14, 28, 60 and 90 days of curing. The filter plug was removed from the loaded specimens. The soil specimens were removed from the tubes and carefully trimmed to obtain parallel end surfaces. The specimen density was measured which can give an indication about the homogeneity of the specimens.

2.3. Testing of Specimens

Unconfined compression strength (UCS) tests were conducted according to the ASTM D2166/D2166M-16 standard [28] to evaluate the development of soil strength for various specimens. The UCS tests were performed on cylindrical specimens placed on the UCS apparatus without constraints with a constant height to diameter ratio of 2. Each specimen was axially loaded at a strain rate of 1 mm/minute until failure. During the test, the load and deformation of each specimen were continuously measured until failure occurred. The stress- strain curves were calculated by dividing the load by the specimen's cross-sectional area. The unconfined compressive strength was defined as the maximum peak stress causing failure and corresponding to the failure strain. The water content of the specimens was determined using the broken parts collected after the UCS test.

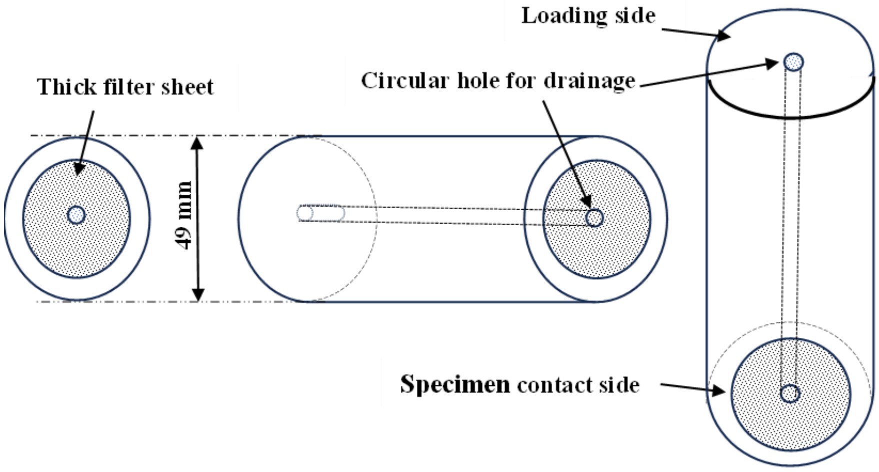
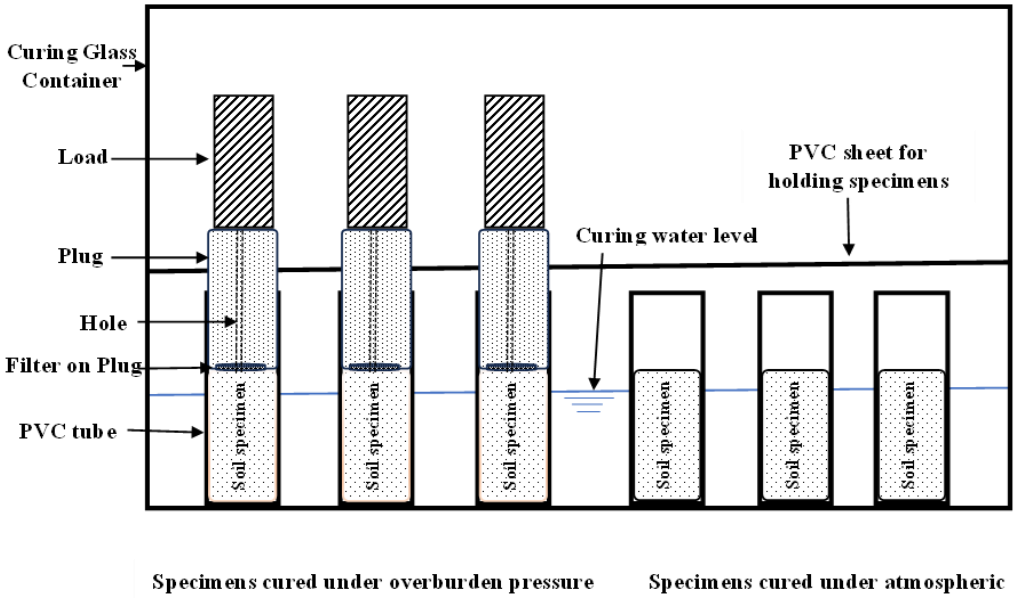


Fig. 1. Filter plug used in this study (schematic)



(a)

(b)

Fig. 2. Shown two diffrent curing conditions (a) Schematic sketch and (b) Two specimens sets cured under different conditions

3. Results and Discussion

3.1 Statistical Analysis

The unconfined compressive strength tests were conducted on specimens prepared in a similar manner and cured under either overburden or atmospheric pressure conditions. The specimen density after preparation was used to compare the two different curing conditions. A t-test was conducted to examine differences in specimen density for different binder contents. Table 3 presents the results of the t-tests, the ratio of standard deviation (SD) to the 95% confidence interval (CI), and the number of specimens (n) for all prepared specimens. The values of the t-test ranged between 0.029 and 0.444, and the p-values ranged between 0.661 and 0.977. The low values of the t-test, as well as all p-values being greater than 0.05 and close to one, indicate no significant differences in specimen density after preparation. The SD/CI ratios for both curing conditions also support this observation. For natural soil, the SD/CI values are highly consistent, whereas for stabilized soil, only small differences in SD/CI are observed. Generally, the similarity in SD/CI values indicates that specimen density after preparation is uniform under both curing conditions, and the process of specimen preparation was well controlled.

Table 3. Presents the results of the t-test analysis of specimen's density after preparation, binder content, and the values of SD/CI or all prepared specimens

Binder content %	Atmospheric Pressure Specimens			Overburden Pressure Specimens			T- test	
	n	Density (Mean Values)	Values of SD/CI	n	Density (Mean Values)	Values of SD/CI	T-value	P-value
0	11	1.94	1.48	13	1.96	1.49	0.406	0.688
1	10	1.98	0.96	10	1.99	1.19	0.359	0.725
2	10	2.01	1.04	10	2.02	1.21	0.268	0.792
4	12	2.02	1.57	11	2.02	1.48	0.444	0.661
7	12	2.02	1.53	10	2.02	1.41	0.029	0.977

Tables 4 and 5 present the ratio between the standard deviation (SD) and the 95% confidence interval (CI), and the number of specimens (n), for UCS, failure strain, density, and soil water content for two different curing conditions. The results shows that the majority of SD/CI values are around 0.1175 for both curing conditions. In contrast, slightly higher SD/CI values of around 0.4034 were noted in a few cases. These differences are infrequent and can be explained by minor experimental uncertainties; therefore, they do not significantly influence the overall trend. The consistency of the SD/CI values under the two curing conditions indicates that the experimental procedure was reliable, with only minimal variation in the measured results.

Table 4. presents the ratio between SD/CI and specimens' number for UCS, failure strain, density and soil water content for atmospheric pressure specimens

Binder content, %	Curing time, Days	n	Values of SD/CI					
			UCS	Strain	Density	Water Content		
						n	Before curing	After curing
0	7	2	0.1175	0.1175	0.1175	2	0.1175	0.1175
	14	3	0.4034	0.4034	0.4034	2	0.1175	0.1175
	28	3	0.1179	0.4034	0.1175	3	0.4034	0.4034
	60	2	0.1175	0.1175	0.1174	2	0.1175	0.1175
	90	2	0.1175	0.1175	0.1174	2	0.1175	0.1175
1	7	2	0.1175	0.1175	0.1175	2	0.1175	0.1175
	14	2	0.1175	0.1175	0.1178	2	0.1175	0.1175
	28	2	0.1175	0.1175	0.1174	1	-	-
	60	2	0.1175	0.1175	0.1179	0	-	-
	98	2	0.1175	0.1175	0.1174	1	-	-

Binder content, %	Curing time, Days	n	Values of SD/CI					
			UCS	Strain	Density	Water Content		
						n	Before curing	After curing
2	7	2	0.1175	0.1175	0.1178	2	0.1176	0.1175
	14	2	0.1175	0.1175	0.1175	2	0.1175	0.1175
	28	2	0.1175	0.1175	0.1176	1	-	-
	60	2	0.1175	0.1175	0.1172	2	0.1175	0.1175
	98	2	0.1175	0.1176	0.1175	2	0.1175	0.1175
4	7	2	0.1175	0.1175	0.1174	2	0.1175	0.1175
	14	2	0.1175	0.1175	0.1175	2	0.1175	0.1175
	28	2	0.4034	0.1175	0.1175	4	0.6285	0.6286
	60	2	0.1175	0.1175	0.1174	2	0.1175	0.1175
	90	2	0.1175	0.1175	0.1176	2	0.1175	0.1175
7	7	2	0.1175	0.1175	0.1175	2	0.1175	0.1175
	14	2	0.1175	0.1175	0.1175	1	-	-
	28	2	0.4034	0.1175	0.1170	5	0.8054	0.8054
	60	2	0.1175	0.1175	0.1175	2	0.1175	0.0831
	90	2	0.1175	0.1175	0.1176	2	0.1175	0.0831

Table 5. presents the values of SD/CI and specimens' number for UCS, failure strain, density and soil water content for overburden pressure specimens

Binder content, %	Curing time, Days	n	Values of SD/CI					
			UCS	Strain	Density	Water Content		
						n	Before curing	After curing
0	7	2	0.1175	0.1175	0.1175	3	0.4034	0.4034
	14	4	0.4034	0.4034	0.4029	4	0.4034	0.4034
	28	3	0.1175	0.4034	0.1175	3	0.4034	0.4034
	60	2	0.1175	0.1175	0.1174	2	0.1175	0.1175
	90	2	0.1175	0.1175	0.1175	2	0.1174	0.1175
1	7	2	0.1175	0.1175	0.1174	2	0.1175	0.1175
	14	2	0.1175	0.1175	0.1178	2	0.1175	0.1174
	28	2	0.4034	0.1175	0.1177	2	0.1175	0.1175
	60	2	0.1175	0.1177	0.1172	0	-	-
	98	2	0.1175	0.1175	0.1178	2	0.1175	0.1175
2	7	2	0.1175	0.1175	0.1175	2	0.1174	0.1174
	14	2	0.1175	0.1175	0.1176	2	0.1175	0.1176
	28	2	0.1175	0.1175	0.1173	2	0.1176	0.1175
	60	2	0.1175	0.1175	0.1177	2	0.1175	0.1175
	98	2	0.1175	0.1175	0.1176	2	0.1175	0.1175
4	7	2	0.1175	0.1174	0.1173	2	0.1174	0.1175
	14	2	0.1175	0.1175	0.1175	0	-	-
	28	3	0.4034	0.1175	0.1171	5	0.8054	0.8056
	60	2	0.1175	0.1175	0.1179	2	0.1175	0.1175
	90	2	0.1175	0.1175	0.1243	2	0.1175	0.1175
7	7	2	0.1175	0.1175	0.1174	2	0.1177	0.1177
	14	2	0.1175	0.1175	0.1177	0	-	-
	28	3	0.1175	0.1175	0.1175	4	0.6286	0.6286
	60	2	0.1175	0.1175	0.1175	2	0.1175	0.1175
	90	2	0.1175	0.1175	0.1172	2	0.1175	0.1175

3.2 Specimens cured under atmospheric pressure

3.2.1 Effect of Binder Content and Curing Time on the UCS

Fig. 3 shows the effect of curing time on the unconfined compressive strength (UCS) of natural soil specimens cured under two different conditions. For specimens cured under atmospheric pressure, the natural soil exhibits low shear strength with an average value of 22 kPa.

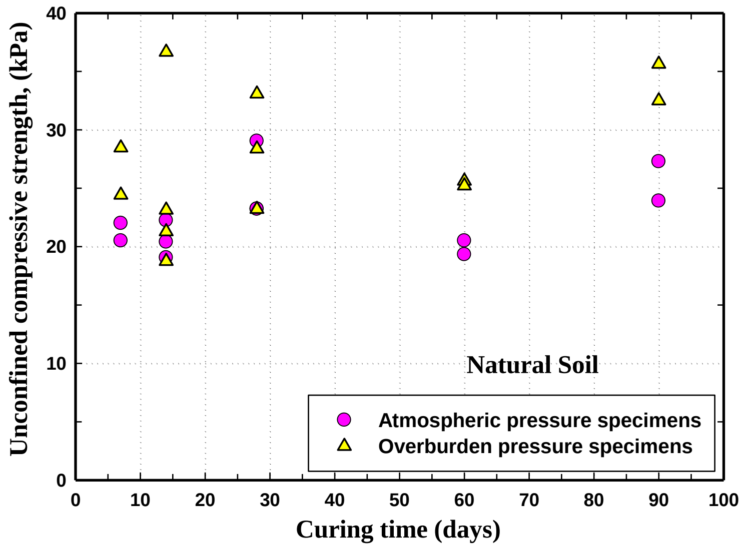


Fig. 3. Unconfined compressive strength of natural soil specimens for different curing times and conditions

Figs. 4 and 5 show the development of the unconfined compressive strength (UCS) over time for stabilized soil specimens treated with various binder contents. Table 6 summarizes the enhancement of soil strength for two curing conditions. Compared to natural soil, the increase in UCS of stabilized soil can be expressed as the UCS ratio, defined as the ratio of the UCS of stabilized soil to the average UCS of natural soil. For specimens cured under atmospheric pressure, the addition of 1% binder improved soil strength up to 5.6 times during the 28 days of curing, with only slight increases observed (6.2 times) at longer curing times of 60 and 98 days as illustrated in Fig. 4 and Table 6. Increasing the binder content to 2% further enhanced soil strength up to 8.5 times during the 28 days of curing, with a slight increase observed at longer curing times (9.5 time). Further increases in binder content to 4% and 7% (Fig. 5) resulted in higher soil strength due to the combined effects of increased binder content and curing time. For 4% binder content, UCS increased during the 28 days of curing up to 12.4 times, with a slight improvement to 15.5 times at 90 days of curing. A similar observation was found for 7% binder content, which showed rapid improvement in soil strength during 28 days (18.1 times) compare a slight increase up to 19.7 times at longer curing times.

In general, the addition of binder at different dosages improves the shear strength of the soil. The strength increases as both binder content and curing time increase. The dominant gain in soil strength was observed after 28 days of curing, compared to only slight improvement at longer curing times. This improvement was attributed to the formation of cementitious hydration products, primarily calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) gels, produced through hydration and pozzolanic reactions. A similar trend of increasing soil strength after treatment and over time is consistent with previous studies that used cement-based stabilizer to improve different soil types [7–15, 29–30, 48].

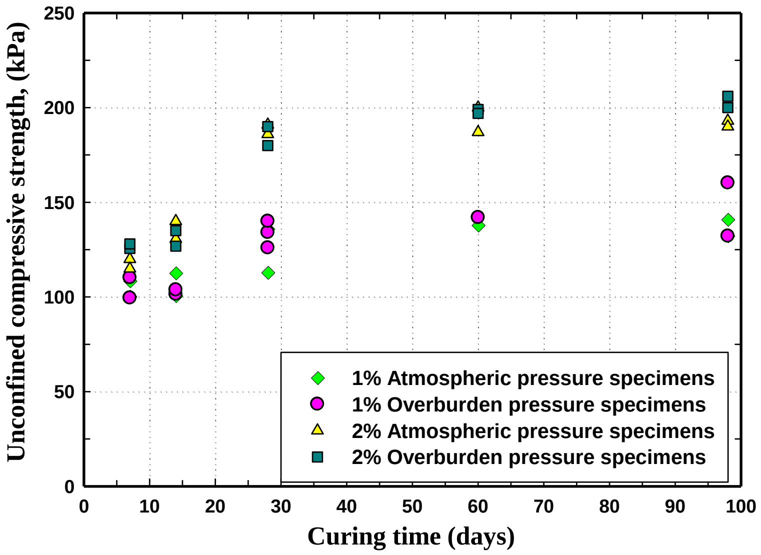


Fig. 4. Unconfined compressive strength of stabilized soil specimens treated with 1% and 2% binder content for different curing times and conditions.

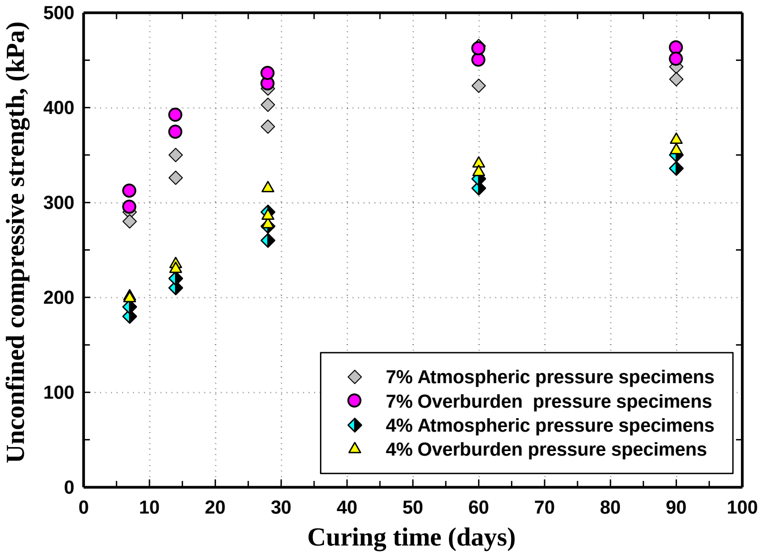


Fig. 5. Unconfined compressive strength of stabilized soil specimens treated with 4% and 7% binder content for different curing times and conditions

Table 6. Summarizes the increases in soil strength due to the addition of various binder content, curing time, and applied overburden pressure

Binder content %	Curing time, Days	Atmospheric Pressure Specimens		Overburden Pressure Specimens		Effect of Applying Overburden Stress on percentage increases in the UCS
		Unconfined compressive strength (UCS), KPa				
		Mean value	UCS ratio	Mean value	UCS ratio	
0	7	21.3	1	23.7	1.1	12
	14	20.6	1	25.0	1.2	21
	28	23.2	1	28.2	1.3	22
	60	20.5	1	25.4	1.2	28
	90	25.6	1	34.1	1.6	33
1	7	104.5	4.7	105.5	4.8	1
	14	106.7	4.8	108.7	4.9	4
	28	124.5	5.6	133.4	6.0	7
	60	136.5	6.2	145.3	6.6	6
	98	136.7	6.2	146.2	6.6	7

Binder content %	Curing time, Days	Atmospheric Pressure Specimens		Overburden Pressure Specimens		Effect of Applying Overburden Stress on percentage increases in the UCS
		Unconfined compressive strength (UCS), KPa				
		Mean value	UCS ratio	Mean value	UCS ratio	
2	7	117.5	5.3	122.0	5.5	4
	14	135.3	6.1	142.0	6.4	5
	28	188.5	8.5	196.0	8.9	4
	60	189.0	8.5	197.0	8.9	7
	98	190.0	8.5	199.0	9.0	5
4	7	185.0	8.5	196.0	8.9	6
	14	215.0	9.7	228.0	10.3	6
	28	275.0	12.4	292.7	13.2	6
	60	320.0	14.5	340.0	15.4	6
	90	343.0	15.5	366.0	16.6	7
7	7	285.0	12.9	303.5	13.7	6
	14	347.0	15.7	371.0	16.8	7
	28	401.0	18.1	430.5	19.5	7
	60	444.0	20.1	466.0	21.1	5
	90	436.5	19.7	457.0	20.7	5

3.2.2 Strain at Failure

The strain at failure, obtained from the stress–strain curves at peak UCS, is presented in Table 7. The failure strain ratio is defined as the ratio of stabilized soil failure strain to that of natural soil. For specimens cured under atmospheric pressure, the natural soil shows a high failure strain, with an average value of 28%. The quantitative analysis indicates that the addition of various binder amounts significantly reduces failure strain, particularly at lower binder contents (1%, 2%, and 4%). Further increases in binder content up to 7% have less impact on reducing the failure strain. The reduction in failure strain becomes less pronounced at 7% binder content compared to 4%. Moreover, the failure strain decreases over time.

The reduction in failure strain can be attributed to the increased formation of cementing products. In general, for soil treated with 7% binder content, the average failure strain at 90 days is lower than that at 7 days. The decrease in failure strain leads to more brittle behaviour in specimens treated with 7% binder content compared to those with lower binder contents, which exhibit more ductile behavior. Consequently, the mode of failure gradually transitions from ductile to brittle as the binder content and curing time increase. The general trends of reduction in failure strain due to the addition of different binder types and over time for stabilizing different soil types are consistent with previous studies [7–15, 30, 48].

Table 7. Summarizes the strain at versus binder content and curing time for two different curing conditions

Binder content %	Curing time, Days	Atmospheric Pressure Specimens		Overburden Pressure Specimens		Effect of Applying Overburden Stress on reduction in failure strain, %
		Strain at failure %				
		Mean value	Failure strain ratio	Mean value	Failure strain ratio	
0	7	28.15	1	24.87	0.88	11.6
	14	27.90	1	23.48	0.83	15.8
	28	27.62	1	23.60	0.84	14.6
	60	28.67	1	22.50	0.80	21.5
	90	27.52	1	22.01	0.78	20.0
1	7	17.00	0.61	16.00	0.57	5.9
	14	14.00	0.50	13.00	0.46	7.1
	28	12.37	0.44	11.29	0.40	8.8
	60	11.78	0.42	11.19	0.40	5.1
	98	11.24	0.40	10.01	0.36	10.9

Binder content %	Curing time, Days	Atmospheric Pressure Specimens		Overburden Pressure Specimens		Effect of Applying Overburden Stress on reduction in failure strain, %
		Strain at failure %				
		Mean value	Failure strain ratio	Mean value	Failure strain ratio	
	98	11.24	0.40	10.01	0.36	10.9
2	7	9.13	0.33	9.02	0.32	1.2
	14	8.58	0.31	8.51	0.30	0.7
	28	8.65	0.31	8.61	0.31	0.5
	60	8.05	0.29	7.50	0.27	6.8
	98	7.46	0.27	7.07	0.25	5.2
4	7	4.72	0.17	4.52	0.16	4.3
	14	4.56	0.16	4.40	0.16	3.5
	28	4.25	0.15	4.04	0.14	5.0
	60	3.93	0.14	3.67	0.13	6.7
	90	3.61	0.13	3.32	0.12	8.1
7	7	4.54	0.16	4.54	0.16	0.0
	14	4.12	0.15	4.01	0.14	2.6
	28	4.01	0.14	3.87	0.14	3.4
	60	3.97	0.14	3.57	0.13	10.0
	90	2.66	0.10	2.39	0.09	10.0

3.2.3 Water Content and Density

For the natural soil, Fig. 6 shows the variation in soil water content with curing time for specimens cured under two different conditions. The water content of the specimens was measured for the natural soil after specimen preparation (before curing) and after curing (after UCS testing). For specimens cured under atmospheric pressure, almost no change in soil water content was observed for before and after curing (Fig. 6A).

For stabilized soil specimens cured under two different curing conditions, Figs. 7, 8, 9 and 10 show the variation in soil water content with curing time for specimens stabilized with 1%, 2%, 4% and 7% binder content, respectively. The soil water content was measured before treatment (prior to binder addition), after specimen preparation (before curing), and after curing (after UCS testing). Table 8 summarizes the impact of binder amounts and curing time on the soil water content under different curing conditions. The addition of various binder contents of 1%, 2%, 4%, and 7% immediately reduces the soil water content to 2%, 3.3%, 4.5%, and 6%, respectively. This effect was measured one hour after treatment. The percentage reduction in soil water content over time was calculated as the difference between the water content before and after curing, divided by the water content before curing. For specimens cured under atmospheric pressure, the results indicate that there is no significant reduction in soil water content over time (the percentage reduction less than 1%) as illustrated in Table 8. Since all prepared specimens were cured in a moist environment, the small variation in the water content of the prepared specimens before and after curing can be attributed to small evaporation that occurred during the UCS testing. The water content in the soil–binder mixture is primarily derived from the natural soil. Therefore, the initial reduction in soil water content can be attributed to the addition of dry binder, as well as hydration reactions between the binder and water [11-15].

The density of stabilized soil gradually increased with increasing binder content from 1% to 4%, with a slight increase observed when the binder content increased to 7% as shown in Fig. 11. The consumption of water during hydration and pozzolanic reactions results in the formation of a significant number of solid products within the soil matrix, thereby increasing the soil density after treatment. This densification is primarily attributed to the formation and deposition of CSH (calcium silicate hydrate) and CAH (calcium aluminate hydrate) gels generated during these reactions. These hydration products fill the pore voids, resulting in a denser soil structure. A similar trend of initial reduction in soil moisture content and increase in density for stabilized soils with cement-based stabilizer has been reported in previous studies [29-31].

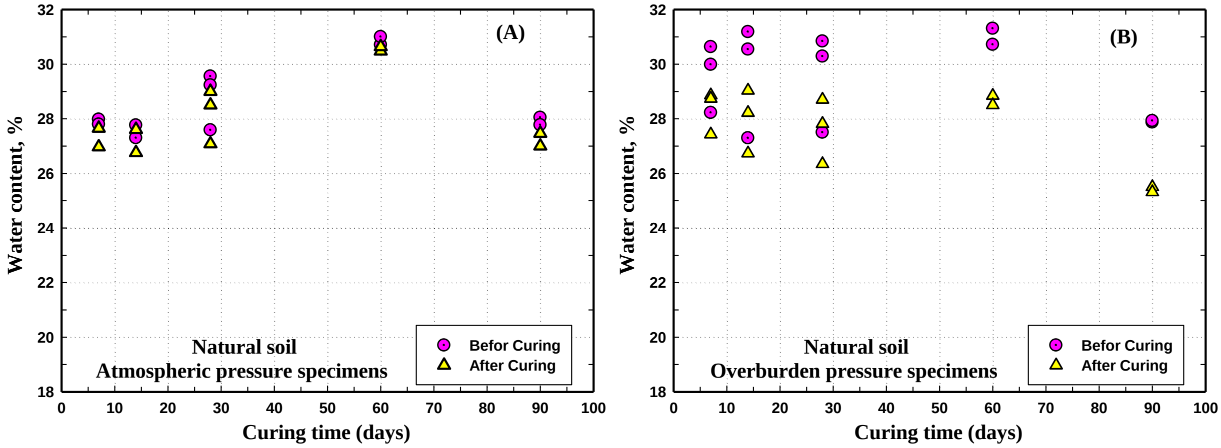


Fig. 6. Water content versus curing time for natural soil specimens under two different curing conditions

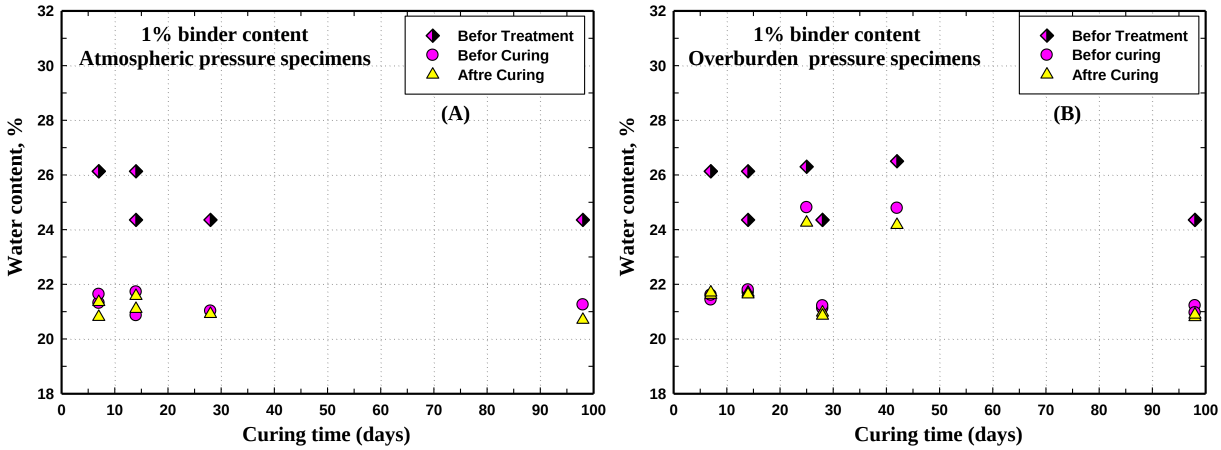


Fig. 7. Water content versus curing time for stabilized soil specimens treated with 1% binder content under two different curing conditions

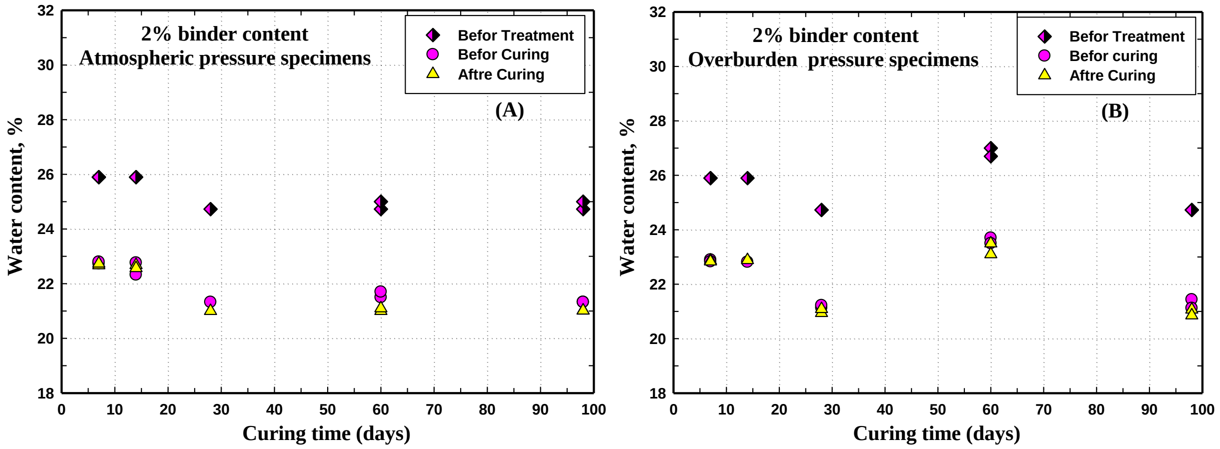


Fig. 8. Water content versus curing time for stabilized soil specimens treated with 2% binder content under two different curing conditions

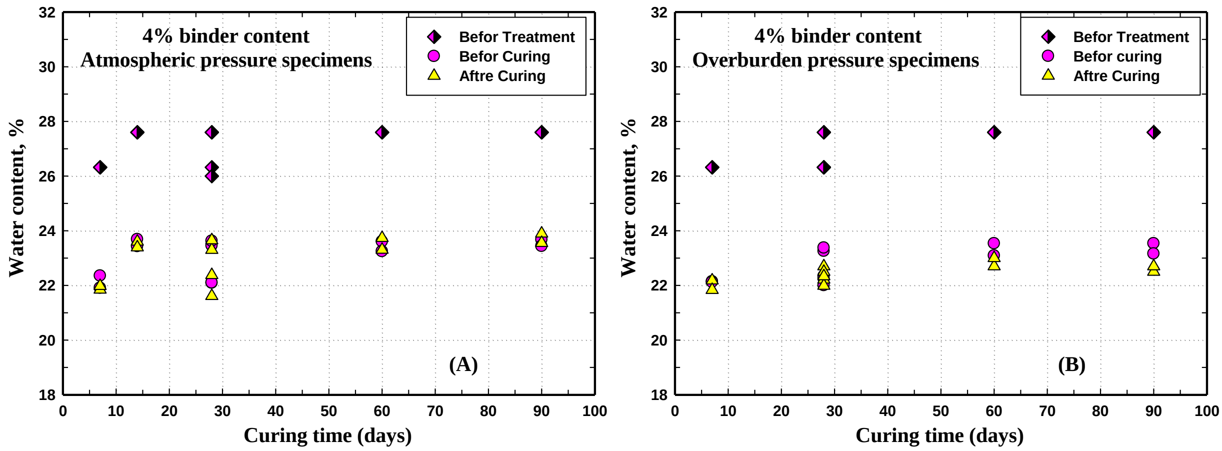


Fig. 9. Water content versus curing time for stabilized soil specimens treated with 4% binder content under two different curing conditions

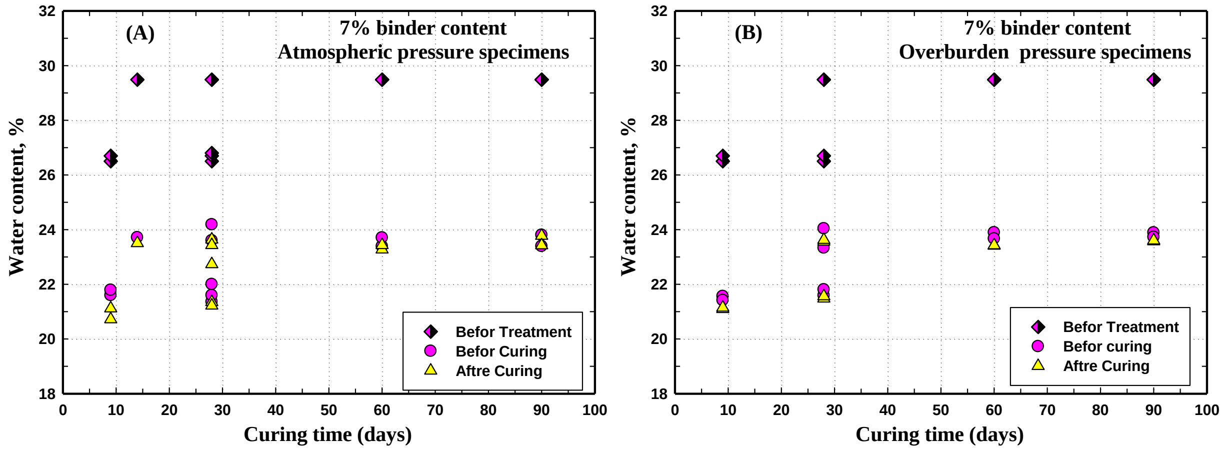


Fig. 10. Water content versus curing time for stabilized soil specimens treated with 7% binder content under two different curing conditions.

Table 8. Summarizes the impact of binder amount and curing time on soil water content for two curing conditions

Binder content, %	Curing time, Days	Atmospheric Pressure Specimens				Overburden Pressure Specimens				Effect of Binder content
		Water content, %								
		Mean value				Mean value				
		Natural soil, ω_n	Before curing	After curing	Percent reduction in Water content	Natural soil, ω_n	Before curing	After curing	Percent reduction in Water content	Initial reduction in Soil Water content, %
0	7	27.9	27.9	27.8	0.4	29.6	29.6	28.3	4	0
	14	27.5	27.5	27.4	0.5	29.7	29.7	28.0	6	
	28	28.8	28.8	28.5	1.0	29.5	29.5	27.6	6	
	60	30.9	30.9	30.6	1.0	31.0	31.0	28.7	8	
	90	27.9	27.8	27.5	1.0	27.9	27.9	25.4	9	
1	7	23.4	21.3	21.1	0.9	21.5	21.8	21.7	1	2
	14	23.7	21.5	21.3	0.7	21.8	21.9	21.7	1	
	28	23.8	21.0	20.9	0.5	23.0	21.2	20.9	1	
	98	23.8	21.1	20.9	0.9	20.9	21.1	20.8	1	

Binder content, %	Curing time, Days	Atmospheric Pressure Specimens				Overburden Pressure Specimens				Effect of Binder content
		Water content, %								
		Mean value				Mean value				
		Natural soil, ω_n	Before curing	After curing	Percent reduction in Water content	Natural soil, ω_n	Before curing	After curing	Percent reduction in Water content	Initial reduction in Soil Water content, %
2	7	25.9	22.8	22.7	0.4	25.9	23.0	22.9	1	3.3
	14	25.9	22.6	22.5	0.4	25.3	23.2	22.9	1	
	28	24.7	21.3	21.0	1.5	24.7	21.4	21.0	2	
	60	24.9	21.2	21.1	0.7	26.8	23.6	23.3	1	
	98	24.9	21.4	21.2	0.9	24.7	21.3	21.0	1	
4	7	26.3	22.1	21.9	1.0	26.3	22.3	22.0	1	4.5
	14	27.6	23.7	23.5	0.6	27.6				
	28	26.6	22.9	22.7	0.7	26.5	22.6	22.3	1	
	60	27.7	23.8	23.5	1.1	27.6	23.3	22.9	2	
	90	27.8	24.0	23.7	1.1	27.6	23.3	22.6	3	
7	7	26.7	21.7	21.4	1.4	26.5	21.1	21.1	0	6
	14	29.5	23.7	23.5	0.9	29.5				
	28	27.6	22.5	22.5	0.3	27.6	22.6	22.6	0	
	60	29.5	23.5	23.4	0.8	29.5	23.4	23.4	0	
	90	29.5	23.7	23.6	0.4	29.5	23.6	23.6	0	

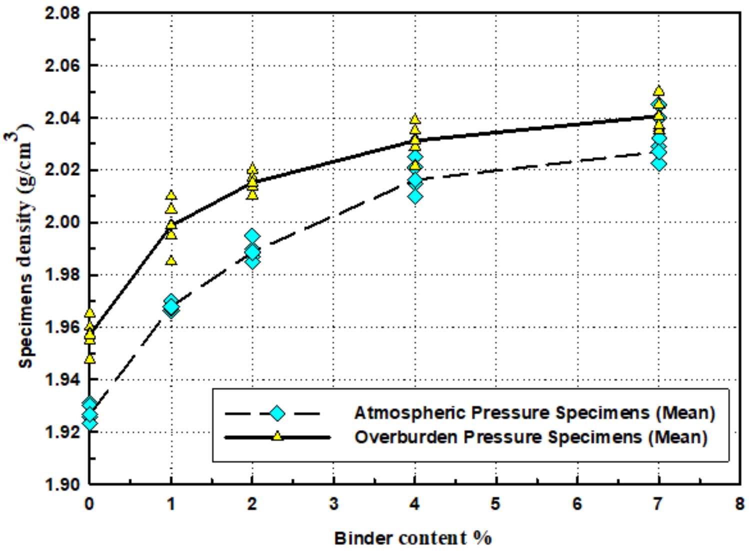


Fig. 11. Specimen density versus binder content for tow curing conditions.

3.3 Specimens Cured Under Overburden Pressure

3.3.1 Effect of Overburden Pressure on the UCS

The development of UCS over time for specimens cured under stress (10.5 kPa) shows a similar trend to that of specimens cured under atmospheric pressure (see Figs. 3, 4 and 5). The percentage increase in soil strength due to the effect of overburden stress was calculated as the ratio of the strength difference between specimens cured under overburden stress and those cured under atmospheric pressure to the strength of specimens cured under atmospheric pressure.

For natural soil, the quantitative analysis shows that the overburden stress results in gradual increases in soil strength over time, from 12% to 33% after 7 and 90 days, respectively. This improvement is attributed to the applied stress compressing the soil particles and allowing pore water to drain from the upper side of the specimen. A similar observation of increased soil strength due to the application of overburden stress was reported by [22].

For stabilized soil, a similar trend of enhanced soil strength during the first 28 days of curing was observed for specimens cured under stress. The UCS ratio of overburden-cured specimens is slightly higher compared to that of specimens cured under atmospheric pressure, as illustrated in Table 6. The increase in soil strength due to the application of overburden stress gradually increased with time. For instance, the addition of 1% binder content improved soil strength from 1% to 7% after 7 and 98 days of curing, respectively. The same observation was noted when the binder content increased to 2%, where the improvement in soil strength increased from 4% to 5% after 7 and 98 days of curing, respectively. In contrast, the improvement in soil strength ranged between 6% and 7% after 7 and 90 days when the binder amount increased to 4% and 7%. Similar observations were noted for stabilized soil specimens treated with different binder contents, where soil strength increased due to the application of overburden stress and longer curing times [1, 23–25].

Regarding the effect of overburden stress applied during the curing period, further increases in soil strength are mainly related to the applied stress. The applied stress causes compression within the stabilized soil matrix by reducing the spacing between binder grains and soil particles. This densification facilitates the buildup of bonds generated from binder hydration reactions [20]. The general trend for soil improvement under overburden stress is consistent with previous studies that used cement kiln dust and cement to stabilize different soil types [1, 19–25, 31].

3.3.2 Strain at Failure

The reduction in failure strain for specimens cured under an overburden stress of 10.5 kPa follows a trend similar to that observed for specimens cured under atmospheric pressure. However, the quantitative analysis shows that the failure strain ratio is consistently lower compared to the specimens cured under atmospheric pressure as illustrated in Table 7. To illustrate the effect of overburden stress on failure strain, the reduction in failure strain (in percentage) was calculated as the ratio of the difference in failure strain between specimens cured under overburden stress and those cured under atmospheric pressure to the failure strain of specimens cured under atmospheric pressure.

For natural soil, the failure strain decreased further over time due to the effect of overburden stress, with a reduction ranging from 11.8% to 20% after 7 and 90 days of curing, respectively. For stabilized soil with 1% binder content, the failure strain decreased over time from 5.9% to 10.9% after 7 and 98 days, respectively. When the binder content increased to 2%, the reduction ranged from 1.2% to 5.2% over the same curing times. Similar trends were observed for stabilized soils treated with 4% and 7% binder content, with a more pronounced effect compared to 1% and 2% binder content. However, the percent reduction in failure strain is more pronounced in natural soil specimens compared to stabilized soil specimens with various binder contents.

Generally, the overburden stress has an effect on further decreasing the failure strain compared to the specimens cured under atmospheric pressure. A similar observation has been found in previous studies that used cement kiln dust and cement to stabilize different soil types [1, 19–25].

3.3.3 Water content and Density

For the natural soil specimens, the quantitative analysis shows that the applied stress caused a gradual reduction in soil water content from 4% to 9% after 7 and 90 days of curing, respectively, as shown in Table 8. This reduction in soil water content was attributed to the effect of overburden stress applied over the curing time, which facilitates drainage during curing (Fig. 6B).

The applied stress caused a slight reduction in water content of stabilized soil treated with 1%, 2% and 4% binder content. In contrast, the applied stress had a negligible effect on water content when the binder content increased to 7% (Table 7). The results further demonstrate that the applied stress has a more significant influence on the water content of natural soil compared to stabilized soil specimens.

Hydration reactions of the binder caused an initial reduction in soil water content, while the further reduction over time was mainly attributed to the pozzolanic reactions occurring between the binder and the soil for specimens cured under atmospheric pressure. In contrast, for specimens cured under stress, the further reduction over time was attributed to both the pozzolanic reactions between the binder and the soil and the overburden stress which caused drainage during curing. This finding is consistent with other studies [12, 19, 24].

The density of stabilized soil cured under an overburden pressure of 10.5 kPa shows a similar increasing trend with binder content; however, the measured densities are higher than those of specimens cured without applied pressure, as illustrated in Fig. 11. The applied stress contributes to an increase in the density of both natural and stabilized soil specimens by reducing the pore spaces between soil particles. Hydration and pozzolanic reactions of the binder consume pore water and generate cementitious products that fill the pore spaces within the soil matrix, resulting in increased density after treatment. This general trend of increased soil density is consistent with previous studies [12, 13].

3.4 Relations Between UCS - Water Content/Plastic Limit Ratio and Stiffness (E_{50})

3.4.1 Relation Between UCS And Water Content/ Plastic Limit Ratio

The ratio of water content (ω) to the plastic limit (Pl) of soil was used to explain correlation between water content and the unconfined compression strength after treatment for specimens subjected to two curing conditions (Fig. 12). The general trends show an increase in UCS accompanied with decreasing water-to-plastic limit ratio for various binder contents. A scattered trend is evident, particularly when the water-to-plastic limit ratio ranges between 1.1 and 1.2 for specimens cured under atmospheric pressure. In contrast, a similar scattered trend is noted when the water-to-plastic limit ratio is between 1 and 1.1 for specimens cured under stress (water contents become more closer to soil plastic limit). Previous studies have demonstrated that natural soils gain strength as their water content decreases from the liquid limit toward the plastic limit. Treated soils are considered to be within the plastic range when their shear strength is around 100 kPa [12].

Reference [33] reported that the remolded clay exhibits a shear strength around 200 kPa when the soil water content becomes near the plastic limit of the soil, and decreases to 2 kPa when the soil water content becomes closer to the liquid limit. Moreover, previous studies mentioned that soil strength varies from 110 to 170 kPa at the soil plastic limit. Therefore, stabilized soil is regarded as being within the plastic range (ω/PL more than 1) when its shear strength is around 100 kPa. A similar trend is consistent with previous studies for soil treated with various binder types [12, 34].

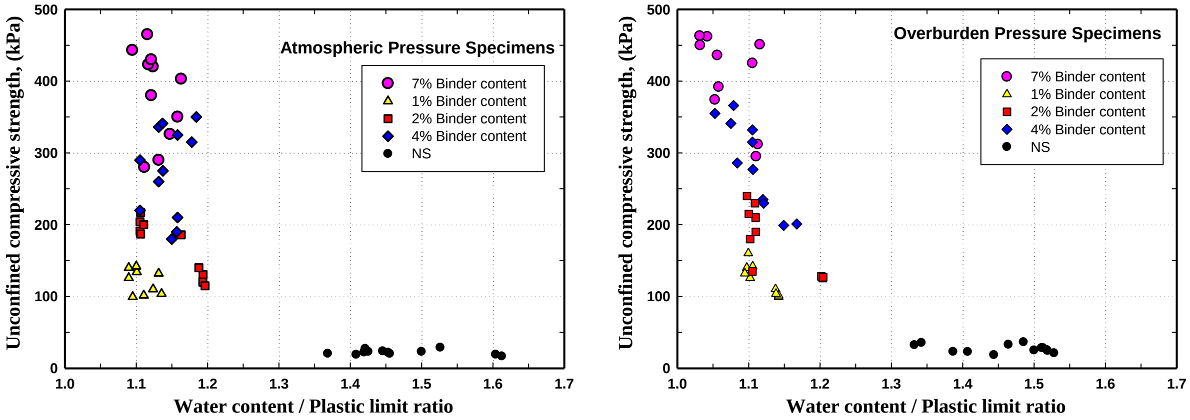


Fig. 12. Unconfined compressive strength versus water content/ plastic limit ratio for natural and stabized soil specimens for two diffrent curing times

3.3.2 Relations Between UCS And Strain at Failure

Fig. 13 shows the correlation between unconfined compressive strength (UCS) and failure strain for specimens cured under two different curing conditions. For specimens cured under atmospheric pressure, the natural soil shows low shear strength of about 23 kPa, with a high failure strain of about 28%. The addition of different binder contents (1%, 2%, 4%, and 7%) results in a reduction in failure strain to 13.3%, 8.5%, 4.2%, and 3.9%, respectively, accompanied by corresponding increases in soil strength of up to 120, 170, 265, and 400 kPa, respectively. Moreover, it was observed that further increases in unconfined compressive strength due to the addition of 7% binder content have less impact on reducing failure strain.

The correlation between unconfined compressive strength and failure strain has been reported in previous studies. Reference [12] found a significant reduction in failure strain occurs when soil strength is around 200 kPa or lower, whereas the reduction becomes less pronounced at higher strength levels for stabilized Swedish clay treated with various binders. For marine sediments treated with cement, lime, and fly ash, [35] proposed a correlation between unconfined compressive strength and failure strain as q_u = (20–130) times the failure strain. Reference [37] showed that failure strain decreases with increasing unconfined compressive strength, and the relationship can be expressed as a power function between UCS and failure strain (failure strain = $1.06\ q_u^{-0.62}$) for cement-treated zinc-contaminated clay. This observation is also consistent with previous studies on stabilized soil treated with various binder types [34, 36].

In contrast, the application of overburden stress reduces the failure strain to 23%, 12%, 8.1%, 4%, and 3.7% due to addition of 0%, 1%, 2%, 4% and 7% binder content respectively. This reduction is accompanied by increases in UCS of up to 33, 130, 180, 300, and 410 kPa, respectively. As discussed earlier, the application of overburden stress during curing further reduces failure strain, this reduction is accompanied by an increase in unconfined compressive strength. Generally, similar trends have been reported in previous studies for specimens cured under overburden stress compared to unstressed specimens [1, 19, 21–24].

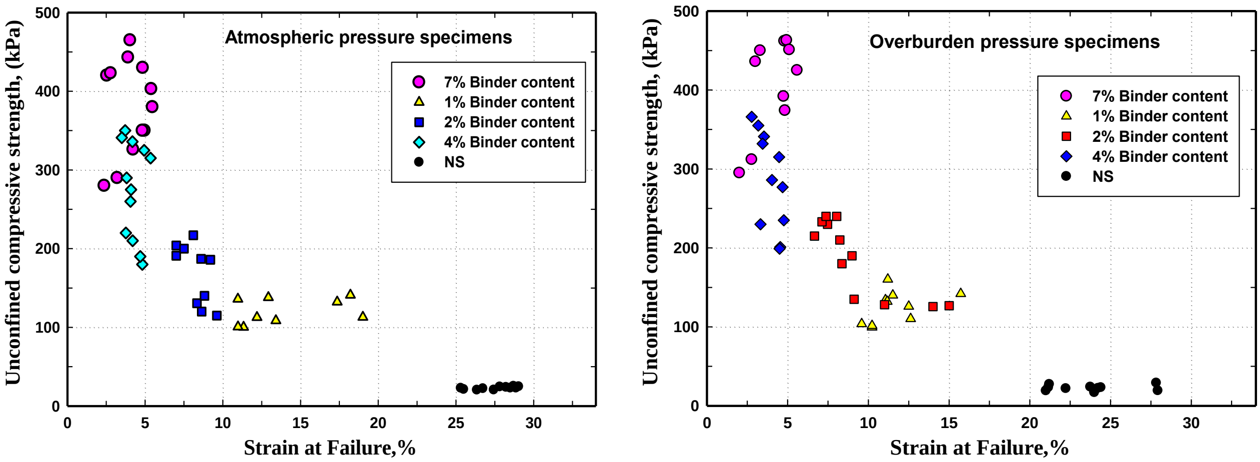


Fig. 13. Unconfined compressive strength versus failure strain for natural and stabilized soil specimens cured under diffrent conditions

3.3.3 Relations Between UCS And the Stiffness

The stiffness of natural and stabilized soil was defined as the secant modulus of elasticity (E_{50}), which is determined from the stress-strain curve at half of the peak UCS value. Fig. 14 shows the correlation between the modulus of elasticity and the unconfined compressive strength for natural soil specimens cured under two curing conditions. Fig. 15 and 16 show the correlation between the modulus of elasticity and the unconfined compressive strength for stabilized soil cured under atmospheric and overburden stress, respectively. The relation between the secant modulus of elasticity and the UCS can be expressed by using the Eq (1):

$$E_{50} = k\ q_u \quad (1)$$

Where E_{50}: Secant modulus of elasticity, k: Strength coefficient, q_u: Unconfined compressive strength.

From Figs. 14, 15, and 16, it can be seen that there is a linear correlation between E_{50} and UCS. The upper and lower limits for the strength coefficient of natural and stabilized soil cured under different curing conditions are presented in Table 9. For specimens cured under atmospheric pressure (Fig. 15), the results show that soil stiffness increases with soil strength and is further enhanced by increasing binder content and curing time. This can be attributed to the formation of cementitious compounds, including C–S–H and C–A–H, generated through hydration and pozzolanic reactions. Higher binder contents lead to the production of more cementitious compounds. The increased formation and deposition of cementitious compounds fill the pore spaces, resulting in a denser soil and, consequently, increased stiffness. This trend is consistent with previous studies [9–14].

In contrast, the applied stress leads to a further enhancement in soil stiffness for both natural and stabilized soil specimens (Figs. 14 and 16). The enhancement in soil strength and stiffness has been reported for specimens cured under overburden stress compared to those cured under atmospheric pressure [19, 29, 47]. These effects are commonly attributed to compression during the formation of cementitious products. As discussed earlier, the applied stress decreases the pore space between soil particles, leading to a denser soil structure. The reduction in pore space improves contact points and enhances cementitious bonding. In addition, the applied stress can influence the distribution and orientation of hydration products, resulting in a more uniform and interconnected bonding system. Therefore, overburden stress during curing is a non-negligible factor in predicting the mechanical properties of stabilized soils. The general trend of soil improvement under overburden stress is consistent with previous studies that used cement-based stabilizers to improve different soil types [1, 19–25].

Table 9. Upper and lower value for the strength coefficient (k) for different curing condition

	Atmospheric Pressure Specimens		Overburden Pressure Specimens	
	k values			
	Upper limit	Lower limit	Upper limit	Lower limit
Natural soil	6	9	7	13
Stabilized soil	13	64	13	74

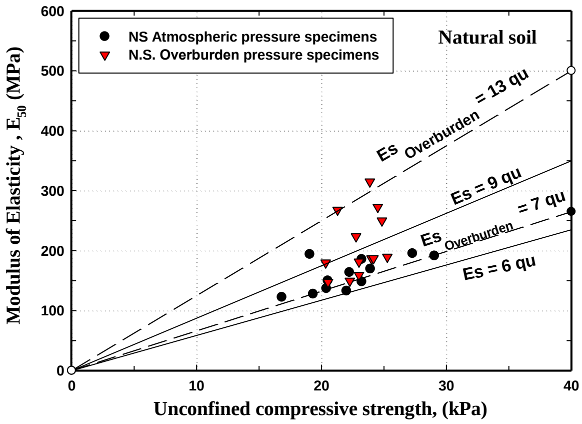


Fig. 14. Soil stiffness versus unconfined compressive strength for natural soil specimens cured under two conditions.

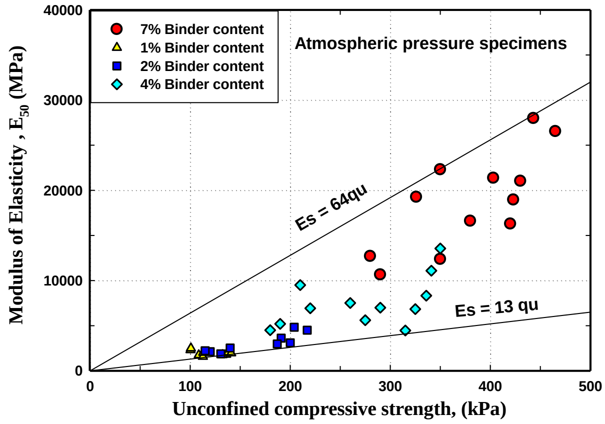


Fig. 15. Soil stiffness versus unconfined compressive strength for stabilized soil specimens cured under atmospheric pressure for all curing times.

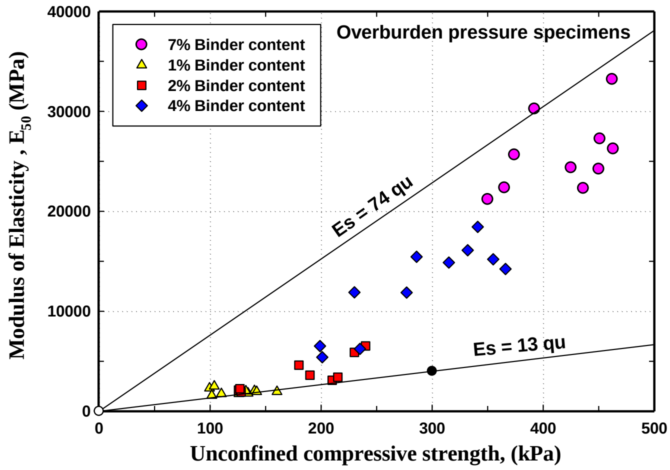


Fig. 16. Soil stiffness versus unconfined compressive strength for stablized soil specimens cured under overbredin pressure for all curing times

Many previous studies have reported varying conclusions regarding the correlation between the secant modulus of elasticity (E_{50}) and the unconfined compressive strength [34, 38-47]. A summary of previous studies is presented in Table 10. Overall, the findings of this study are generally consistent with those reported in previous research on cement-treated soils, and are particularly close to the findings reported by [44, 47].

Table 10. Upper and lower value for the strength coefficient (k) from pervious study

Author(s)	Type of Soil	Binder type	Binder content, %	Curing condition	k values	
					Upper limit	Lower limit
[34]	Silt, silty clay, and laterite soils	Cement	7% - 13%	Atmospheric Pressure	100	226
[38]	Marine clay	Cement	10% - 30%	Atmospheric Pressure	60	140
[39]	Soft clay	Cement	5% - 20%	Atmospheric Pressure	115	150
[40]	Very soft clay	Cement	5% - 35%	Atmospheric Pressure	96	129
[41]	Clay in Finland	Cement	3% - 37%	Atmospheric Pressure	100	200
[42]	Marine clay	Cement	10% - 20%	Atmospheric Pressure	150	275
[43]	Soft clay	Cement and cement kiln dust	10%- 13%,	Atmospheric Pressure	99	159
[44]	Clayey silt	Cement	1%-7%	Atmospheric Pressure	16	85
[45]	Marine clay	Cement	10%- 30%	Atmospheric Pressure	30	169
[46]	Organic Low Plasticity Silts/Clays.	Cement	Water-cement ratio of 0.55	Atmospheric Pressure	39.9	57.7
[47]	Hight plasticity clay	Cement	50-200 kg/m3	Atmospheric Pressure	19	75
				Cured under pressure of 200-400 kPa	18	86

5. Conclusions

The effects of overburden stress over time on the strength and deformation characteristics of natural and stabilized fine-grained soils are presented and discussed in this study. The results are limited to an overburden stress of 10.5 kPa applied during different curing periods, and to stabilized lean clay soil with binder contents ranging from 1% to 7%. In addition, the vertical strain during curing and suction effect were not measured in this study. Based on the results, the following conclusions can be made:

- The findings confirm that the general trend of the unconfined compressive strength and stiffness of soil is enhanced by increasing binder dosage and longer curing time. For specimens cured under overburden pressure, the unconfined compressive strength exhibits a pronounced gain in soil strength within the first 28 days of curing, followed by more gradual increases thereafter. In contrast, the specimens cured under atmospheric pressure (without stress) show a rapid increase during the first 28 days of curing with negligible improvement in soil strength beyond this period.
- Soil density increased after treatment with increasing binder dosages. A further increase in soil density was observed when curing stress was applied to both natural and stabilized soils.
- The results show that the failure strain decreases with increasing binder content and curing time, which gradually changes the failure behavior of the soil from plastic to brittle behavior. These improvements are mainly attributed to the production of cementitious compounds formed from hydration and pozzolanic reactions. Further reduction in failure strain was observed due to the application of overburden stress.
- Applying stress during curing led to further increases in soil strength and stiffness over time for both natural and stabilized soils. Significant improvement was noticed in natural soil at longer curing time, where the strength increased from12% to 33% after 7 and 90 days, respectively compared with natural soil specimens cured under atmospheric pressure. For stabilized soils, additional improvements in soil strength were observed over time due to applied stress. Compared with stabilized soil specimens cured under atmospheric pressure, the additional increases in strength were approximately 6%, 5%, 6%, and 7% due to the addition of 1%, 2%, 4%, and 7% binder contents, respectively.
- The enhancement in unconfined compressive strength and stiffens due to the application of overburden stress is mainly attributed to physical densification. The reduction in pore space allows pore water to drain and increases particle contact points, resulting in higher density and lower water content. The increase in particle contact points leads to an improvement in the effectiveness of cementitious products such as C–S–H and C–A–H generated from cement hydration and pozzolanic reaction, which bind soil particles together and further enhance soil strength and stiffness.
- These findings confirm that the application of overburden stress during curing is a non-negligible factor controlling the strength and deformation behavior of fine-grained soils and should be considered essential for laboratory testing to achieve maximum strength development in practical geotechnical engineering applications.
- Further research is needed to investigate the effect of increasing overburden stress beyond 10.5 kPa, as well as to incorporate microstructural and mineralogical analyses (e.g., SEM and XRD) to better understand the mechanisms governing strength development and cementitious bonding in stabilized soils. Additionally, future studies should evaluate field applicability and long-term performance under realistic conditions, including non-uniform and time-dependent stress states, as well as durability aspects such as cyclic loading, wetting–drying cycles, and creep behavior.

References

[1] Pigeot L, Dufour N, Soive A, Calissano H, Batilliot L, Dermenonville F, Loukili A. Influence of curing under stress on the geotechnical behavior of a treated silty soil. In Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society. 2024 Sep 17 (pp:2538-2542). CRC Press.

[2] Lorenzo GA, Bergado DT. Fundamental parameters of cement-admixed clay—New approach. Journal of geotechnical and geoenvironmental engineering. 2004;130(10):1042-50. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(10.

[3] Chompoorat T, Maikhun T, Likitlersuang S. Cement-improved lake bed sedimentary soil for road construction. Proceedings of the Institution of Civil Engineers-Ground Improvement. 2019;172(3):192-201. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(1042).

[4] Eskisar T. Influence of cement treatment on unconfined compressive strength and compressibility of lean clay with medium plasticity. Arabian Journal for Science and Engineering. 2015; 40(3):763-72. https://doi.org/10.1007/s13369-015-1579-z.

[5] Liu L, Zhou A, Deng Y, Cui Y, Yu Z, Yu C. Strength performance of cement/slag-based stabilized soft clays. Construction and Building Materials. 2019; 211 :909-18. https://doi.org/10.1016/j.conbuildmat.2019.03.256.

[6] Sanijya G, Bala M R, Samatha C P. Sustainable stabilization of native subgrade soil for low-volume roads using copper slag and cementitious materials. Research on Engineering Structures & Materials. 2025; 11(4): 1683-1702.

[7] Miller GA, Azad S. Influence of soil type on stabilization with cement kiln dust. Construction and building materials. 2000;14(2):89-97. https://doi.org/10.1016/S0950-0618(00)00007-6.

[8] Miller GA, Zaman M. Field and laboratory evaluation of cement kiln dust as a soil stabilizer. Transportation Research Record: Journal of the Transportation Research Board. 2000; 1714 (1): 25-32. https://doi.org/10.3141/1714-04.

[9] Ebrahimi A, Edil TB, Son YH. Effectiveness of cement kiln dust in stabilizing recycled base materials. Journal of materials in civil engineering. 2012; 24 (8): 1059-66. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000472.

[10] Ismail AI, Belal ZL. Use of cement kiln dust on the engineering modification of soil materials, Nile Delta, Egypt. Geotechnical and Geological Engineering. 2016; 34(2):463-469. https://doi.org/10.1007/s10706-015-9957-6.

[11] Yoon IH, Moon DH, Kim KW, Lee KY, Lee JH, Kim MG. Mechanism for the stabilization/solidification of arsenic-contaminated soils with Portland cement and cement kiln dust. Journal of Environmental management. 2010; 91(11):2322-8. https://doi.org/10.1016/j.jenvman.2010.06.018.

[12] Åhnberg H, Johansson SE, Pihl H, Carlsson T. Stabilising effects of different binders in some Swedish soils. Proceedings of the Institution of Civil Engineers-Ground Improvement. 2003 Jan;7(1):9-23. https://doi.org/10.1680/grim.2003.7.1.9.

[13] Chew SH, Kamruzzaman AH, Lee FH. Physicochemical and engineering behavior of cement treated clays. Journal of geotechnical and geoenvironmental engineering. 2004; 130(7):696-706. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:7(696).

[14] Ranaivomanana H, Razakamanantsoa A, Amiri O. Effects of cement treatment on microstructural, hydraulic, and mechanical properties of compacted soils: Characterization and modeling. International Journal of Geomechanics. 2018; 18 (9) :04018106. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001248.

[15] Pakbaz MS, Alipour R. Influence of cement addition on the geotechnical properties of an Iranian clay. Applied Clay Science. 2012; 67:1-4. https://doi.org/10.1016/j.clay.2012.07.006.

[16] Rouhanifar S, Afrazi M, Fakhimi A, Yazdani M. Strength and deformation behaviour of sand-rubber mixture. International Journal of Geotechnical Engineering. 2021;15(9):1078-1092. https://doi.org/10.1080/19386362.2020.1812193.

[17] Afrazi M, Yazdani M. Determination of the effect of soil particle size distribution on the shear behavior of sand. Journal of Advanced Engineering and Computation. 2021;5(2):125-134. DOI: http://dx.doi.org/10.25073/jaec.202152.331.

[18] Al-Jabban W, Laue J, Knutsson S, Al-Ansari N. Briefing: Common laboratory procedures to prepare and cure stabilised soil specimens: a short review. Geotechnical Research. 2020; 7 (1): 3–10, doi: https://doi.org/10.1680/jgere.19.00035.

[19] Åhnberg H, Bengtsson PE, Holm G. Effect of initial loading on the strength of stabilised peat. Proceedings of the Institution of Civil Engineers-Ground Improvement. 2001; 5(1):35-40. https://doi.org/10.1680/grim.2001.5.1.35

[20] Åhnberg H. Strength of stabilised soil-a laboratory study on clays and organic soils stabilised with different types of binder. Ph.D. thesis, Lund University, Lund, Sweden, 2006.

[21] Zhao Y, Taheri A, Karakus M, Deng A, Guo L. The Effect of Curing under Applied Stress on the Mechanical Performance of Cement Paste Backfill. Minerals. 2021; 11(10):1107. https://doi.org/10.3390/min11101107.

[22] He X, Chen Y, Wan Y, Liu L, Xue Q. Effect of curing stress on compression behavior of cement-treated dredged sediment. International Journal of Geomechanics. 2020; 20(11):04020204. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001857.

[23] Åhnberg H. On yield stresses and the influence of curing stresses on stress paths and strength measured in triaxial testing of stabilized soils. Canadian Geotechnical Journal. 2007; 44(1):54-66. https://doi.org/10.1139/t06-096.

[24] Shibi T, Ohtsuka Y. Influence of applying overburden stress during curing on the unconfined compressive strength of cement-stabilized clay. Soils and Foundations. 2021; 61(4):1123-1131. https://doi.org/10.1016/j.sandf.2021.03.007.
[25] Haritwal DK, Agarwal BK, Reddy AV, Kumar S. Influence of Curing Stress and Curing Time on Unconfined Compressive Strength Behaviour of Cemented Clay. Proceedings of the Indian Geotechnical Conference 2019: IGC-2019 Volume III (pp. 87-97), Springer, Singapore, 25 April, 2021. https://doi.org/10.1007/978-981-33-6444-8_8.
[26] ASTM D2487-11. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM International, West Conshohocken, PA, USA. 2018.
[27] Al-Jabban W, Laue J, Knutsson S, Al-Ansari N. Effect of Disintegration Times of the Homogeneity of Soil prior to Treatment. Applied Sciences. 2019; 9(22):4791. https://doi.org/10.3390/app9224791.
[28] ASTM D2166/D2166M-16. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International: West Conshohocken, PA, USA. 2016.
[29] Rothhämel M, Al-Jabban W, Laue J. Influence of low temperature curing and freeze-thaw-cycles on the stiffness of silt stabilised with hydraulic binder. Proceedings of the Deutsche Gesellschaft für Geotechnik (DGGT) (pp. 432-437), Fachsektionstage Geotechnik, Würzburg, Germany, October 29-30, 2019.
[30] Ziagharib A, Maurice C, Macsik J, Jia Q, Laue J. Performance of Excavated Sulfur-Rich Soil Stabilized with Binder: A Field Study of Mixing Efficiency. Advances in Civil Engineering. 2023;2023(1):5446332. https://doi.org/10.1155/2023/5446332.
[31] Consoli NC, Rotta GV, Prietto PDM. Yielding–compressibility–strength relationship for an artificially cemented soil cured under stress. Geotechnique. 2006; 56 (1):69–72. doi: https://doi.org/10.1680/geot.2006.56.1.69.
[32] Sariosseiri F, Muhunthan B. Effect of cement treatment on geotechnical properties of some Washington State soils. Engineering geology. 2009;104(1-2):119-25.
[33] Wood DM. Soil behaviour and critical state soil mechanics. Cambridge university press; 1990.
[34] Rashid AS, Kalatehjari R, Noor NM, Yaacob H, Moayedi H, Sing LK. Relationship between liquidity index and stabilized strength of local subgrade materials in a tropical area. Measurement. 2014; 55:231-237. https://doi.org/10.1016/j.measurement.2014.05.018.
[35] Wang D, Abriak NE, Zentar R. Strength and deformation properties of Dunkirk marine sediments solidified with cement, lime and fly ash. Engineering Geology. 2013; 166:90-99. https://doi.org/10.1016/j.enggeo.2013.09.007.
[36] Ignat R. Field and laboratory tests of laterally loaded rows of lime-cement columns. PhD thesis, Royal Institute of Technology (KTH), Stockholm, Sweden, 2015.
[37] Du YJ, Wei ML, Jin F, Liu ZB. Stress–strain relation and strength characteristics of cement treated zinc-contaminated clay. Engineering Geology. 2013; 167:20-26. https://doi.org/10.1016/j.enggeo.2013.10.005.
[38] Lee FH, Lee Y, Chew SH, Yong KY. Strength and modulus of marine clay-cement mixes. Journal of geotechnical and geoenvironmental engineering. 2005;131(2):178-86. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(178).
[39] Lorenzo GA, Bergado DT. Fundamental characteristics of cement-admixed clay in deep mixing. Journal of materials in civil engineering. 2006;18(2):161-74. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(16.
[40] Jongpradist P, Jumlongrach N, Youwai S, Chucheepsakul S. Influence of fly ash on unconfined compressive strength of cement-admixed clay at high water content. Journal of Materials in Civil Engineering. 2010;22(1):49-58. https://doi.org/10.1061/(ASCE)0899-1561(2010)22:1(49.
[41] Hassan M. Engineering characteristics of cement stabilized soft Finnish clay–A laboratory study. Licentiate's thesis, Helsinki University of Technology, Helsinki, Finland. 2009.
[42] Dingwen Z, Libin F, Songyu L, Yongfeng D. Experimental investigation of unconfined compression strength and stiffness of cement treated salt-rich clay. Marine Georesources & Geotechnology. 2013;31(4):360-74. https://doi.org/10.1080/1064119X.2012.690826.
[43] Yoobanpot N, Jamsawang P, Horpibulsuk S. Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. Applied Clay Science. 2017; 141:146-156. https://doi.org/10.1016/j.clay.2017.02.028.
[44] Al-Jabban W, Laue J, Knutsson S, Al-Ansari N. A comparative evaluation of cement and by-product petrit T in soil stabilization. Applied Sciences. 2019;9(23):5238. https://doi.org/10.3390/app9235238.
[45] Kang GO, Tsuchida T, Kim YS. Strength and stiffness of cement-treated marine dredged clay at various curing stages. Construction and Building Materials. 2017; 132:71-84. https://doi.org/10.1016/j.conbuildmat.2016.11.124.
[46] Cai H, Chen C, Wei S, Zhu S. Strength development of cemented soil cured in water-air conditions at varied temperatures: Experimental investigation and model characterization. Journal of Materials in Civil Engineering. 2023; 35(3):04022466. https://doi.org/10.1061/(ASCE)MT.1943-5533.00046.

[47] Qiu C, Li Y, Li X, Xu G, Zhang D. Effects of High Curing Pressure on the Unconfined Compressive Strength of Cement-Stabilized Bottom Sediments with High Water Content. Buildings. 2025; 15(16):2869. https://doi.org/10.3390/buildings15162869.

[48] Ziagharib A, Macsik J, Jia Q, Maurice C. Factors influencing the effectiveness of acid sulfate soil stabilization with cement-based binders. Bulletin of Engineering Geology and the Environment. 2026; 85(3):155. https://doi.org/10.1007/s10064-026-04784-8.