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CONSOLIDATION BEHAVIOR OF SOIL STABILIZED WITH CEMENT: EXPERIMENTAL ANALYSIS OF ROHRI CANAL'S SOIL (PAKISTAN)

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Abstract
This research aims to study the consolidation characteristics of clayey soil samples taken from the Rohri Canal in Pakistan, using Ordinary Portland Cement (OPC) as a stabilizer. This study, however, deviates from the general trend of literature that, over the years, has shown a significant decrease in compressibility of soils over time, by revealing a peculiar short-term effect of cement addition, which initially results in an increase in vertical strain and compressibility parameters of soils. The results of the incremental loading Oedometer test on soil samples containing 5% and 10% cement content, after short curing periods, revealed that the 10% cement content-24h sample recorded the highest vertical strain of 27.4%, coefficient of volumetric compressibility (m_v = 0.128 m²/MN), and compression index (C_c = 0.239), almost tripling the value of the untreated soil samples, which recorded a value of 0.087 for the compression index. This unusual increase in compressibility is due to the formation of a porous soil-cement skeleton, which collapses under high vertical stress levels, up to 640 kPa.
Comparative analysis of sources (2015-2026) indicates that, although the process of long-term curing for 28 to 90 days results in densification of the microstructure through the formation of Calcium Silicate Hydrate, short-term stabilization can increase settlement risks. These results are critical for the design and construction of hydraulic fillings in Pakistan, as immediate mechanical response is the main concern.

1. INTRODUCTION AND BACKGROUND

The mechanical stability of geotechnical infrastructure ranging from building foundations and road pavements to hydraulic embankments is fundamental to structural integrity. Soils characterized by low bearing capacity or high compressibility often require stabilization to prevent excessive settlement, erosion, or shear failure. Chemical stabilization, particularly using Ordinary Portland Cement (OPC), is a globally recognized technique that improves soil engineering properties through hydration and pozzolanic reactions [1], [2]. The resulting cement-modified soil forms a matrix with enhanced shear strength and reduced permeability, making it suitable for a variety of civil engineering applications [3].

In the Sindh province of Pakistan, the irrigation network, including major conduits like the Rohri Canal, relies on extensive embankment systems. These embankments are frequently constructed from local silty and clayey soils that are highly susceptible to erosion, seepage, and breach failures [4]. Breach events cause catastrophic losses in property, human life, and agricultural productivity, exacerbated by the region's existing water scarcity [5], [6]. Traditional soil materials often fail to meet the performance criteria required for extreme hydraulic conditions. While cement stabilization offers a potential solution for reinforcing these embankments, there is a distinct lack of experimental data regarding the consolidation behavior of Pakistan-specific soils, especially during the critical early stages of construction and curing.

The primary objective of this study is to evaluate the consolidation characteristics of cement-stabilized clayey soil collected from the Rohri Canal. The research focuses on:

- Determining the index properties and compaction characteristics of the natural soil.
- Analyzing the effect of cement content (5% and 10%) on vertical strain and compressibility.
- Investigating the impact of short-term curing (1h, 3h, 24h) on the compression index (C_c) and coefficient of volumetric compressibility (m_v).
- Contrasting local experimental findings with global literature trends to explain unique early-age behaviors.

The scope of this research is limited to a specific clayey soil from the Rohri Canal, Pakistan. Stabilization is investigated using 5% and 10% cement contents by dry weight. Curing durations are restricted to short-term intervals (up to 24 hours) to simulate rapid construction scenarios. Consolidation behavior is assessed using incremental loading Oedometer tests according to ASTM D2435 standards.

2. Literature Review

The consolidation behavior of cement-stabilized soils has been extensively studied in recent years (2020–2026), with a consensus that cement treatment generally improves stiffness and reduces long-term settlement.

2.1 General Trends in Compressibility

Global literature consistently reports that the addition of cement to fine-grained soils leads to a significant reduction in the compression index (C_c) and the coefficient of volumetric compressibility (m_v). Zidan [1] demonstrated that for Egyptian cohesive soils, C_c values could be reduced by 37% to 92% depending on the soil's consistency and cement dosage. This reduction is typically proportional to the cement content and curing time. Kutanaei et al. [2] corroborated these findings in loess and clay samples from Iran, where cement proportions up to 8% markedly enhanced stiffness.

Furthermore, cement stabilization raises the yield or preconsolidation stress, allowing the soil to resist consolidation at higher applied loads. Umar et al. [7] and Bayesteh [8] reported that yield stress could increase fourfold or more with 10% cement addition, often reaching levels that exceed typical service stresses in highway and embankment applications.

2.2 Microstructural Evolution

The mechanical improvements observed at the macro level are rooted in microstructural changes. SEM and XRD analyses have identified the formation of cementitious products, primarily Calcium Silicate Hydrate (C-S-H) and ettringite (AFt), which fill interparticle voids and bond soil grains into a rigid matrix[9], [10], [11], [12]. Pu et al. [7] noted that this hydration process transforms large pores into micro-pores, effectively densifying the soil skeleton. Axel et al. [13] described this as a "thick cement network" that encases soil particles and covers voids, boosting both compressive and shear strength.

However, the development of this microstructure is sensitive to environmental conditions. He and Chen [5] emphasized that "stress curing" curing the soil while under a confining load further refines the pore structure and enhances yield characteristics compared to unconfined curing.

Conversely, factors like compaction delay can have a "destructive effect" on the formation of these cementitious bonds, as noted by Nazari et al.[14].

2.3 The Role of Curing Time

Curing time is perhaps the most critical variable in determining the final consolidation properties. While some immediate strength gain is achieved through cation exchange and flocculation, the primary reduction in compressibility occurs during the long-term pozzolanic phase. Pakir et al. [15] and Shojamoghadam et al. [16] found that C_c and m_v continue to decrease significantly as curing progresses from 7 to 90 days. Short-term curing (less than 24–48 hours) often captures only the initial hydration phase, where the soil-cement matrix may not yet have reached a stable configuration capable of resisting high consolidation pressures [1], [16], [17], [18].

2.4 Research Gaps

Despite the abundance of long-term studies, there is a notable scarcity of data regarding the immediate (first 24 hours) consolidation response of cement-stabilized soils, particularly those derived from active irrigation sites like the Rohri Canal. Most literature focuses on 7-day or 28-day strengths, which may overlook critical settlement risks during the construction phase. This study addresses this gap by focusing on the 1-hour to 24-hour curing window.

3. Materials and Methods

3.1 Soil and Cement

The natural soil used in this investigation was sourced from the toe of the Rohri Canal in Pakistan. Preliminary characterization was performed to establish its baseline properties. The soil was classified using the Unified Soil Classification System (USCS) as a low-plasticity inorganic clay (CL) as shown in table 1. Ordinary Portland Cement (OPC) was used as the stabilizing agent, sourced from a local supplier to represent materials commonly used in regional construction.

Table 1: Index Properties of Rohri Canal Soil

LL(%)	PL(%)	PI(%)	Specific Gravity	Type of soil
21.8	13.87	7.93	2.60	Low plastic inorganic clay

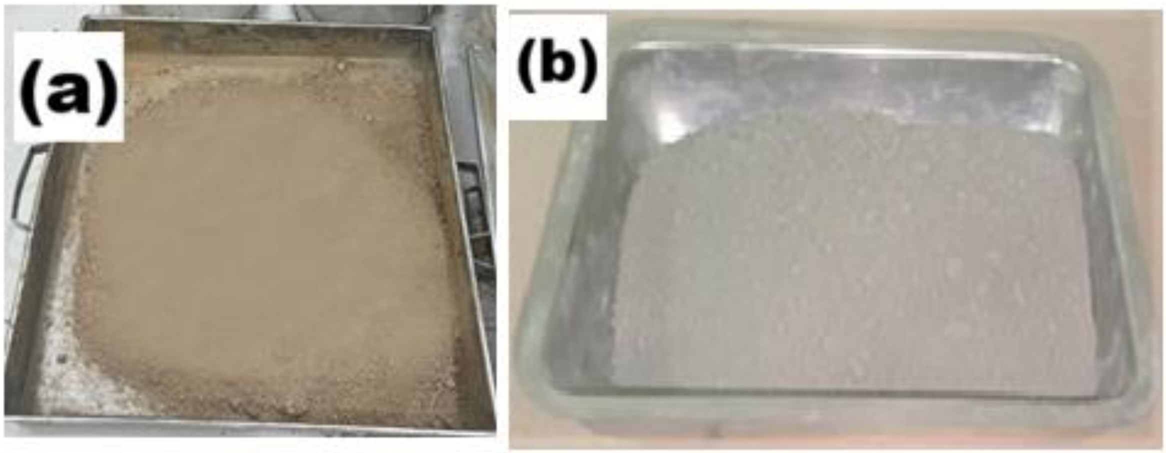

Figure 1 (a) Clayey soil, (b) OPC Cement

Sieve analysis was conducted to determine particle size distribution, and it was observed that the material was clayey-silt having specific gravity 2.60.

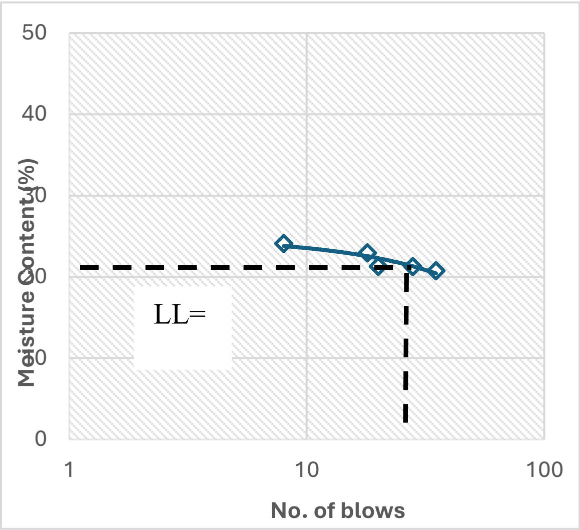

Figure 2 Optimum Moisture Content Value

3.2 Compaction Characteristics

Standard Proctor compaction tests (ASTM D1557) were conducted to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) as shown in table 2 and figure 3.

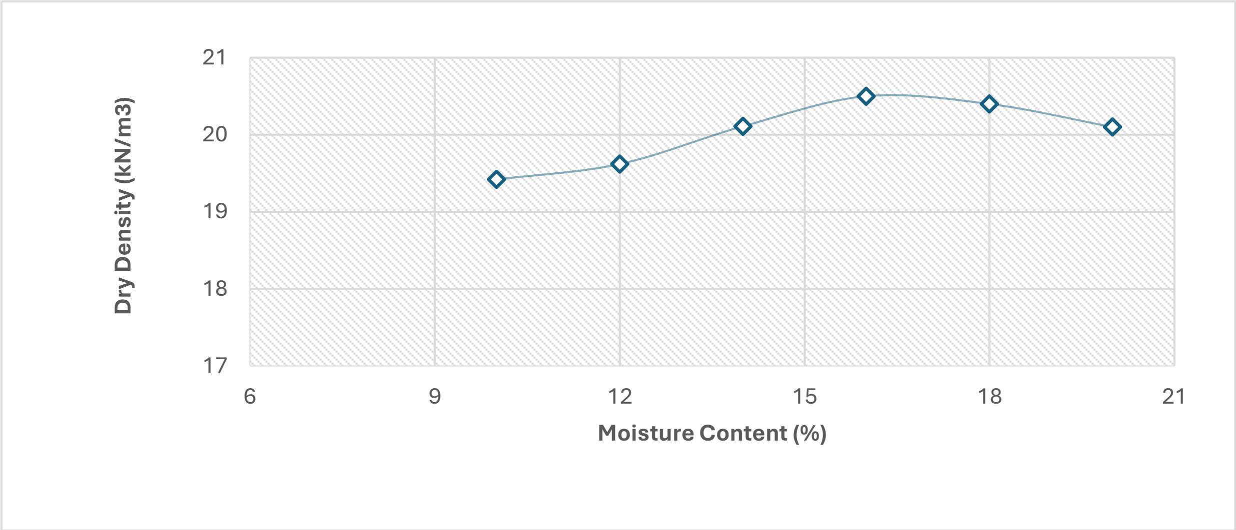

Figure 3 Proctor Compaction Curve

Table 2: Moisture Content vs. Dry Unit Weight

Water Content (%)	10	12	14	16	18	20
Dry Unit Weight (kN/m³)	19.42	19.62	20.11	20.5	20.4	20.1

3.3 Sample Preparation and Curing

Six samples were prepared for the testing having different proportion of cement but constant moisture content, after mixing the soil, cement and water, the samples were left for a particular time period for hardening purpose .the cement percentage is kept as 5% and 10% by dry weight of soil and moisture content in this study is kept as 16% (optimum moisture content) for all the samples. The time duration from the preparation of sample to the testing is kept as 1h, 3h and 24h. Table 3 shows different percentages of the materials and description of moisture content, specific gravity and bulk density.

Table 3: Description of material used in this research

Soil(%)	Cement Content (%)	Duration of curing Time (hours)	Optimum Moisture content (OMC) (%)	Specific Gravity	Bulk Density (Gm/cc)
95	5	1 h	16	2.691	1.735
90	10	1 h	16	2.702	1.790
95	5	3 h	16	2.691	1.884
90	10	3 h	16	2.702	1.705
95	5	24 h	16	2.691	1.477
90	10	24 h	16	2.702	1.429

Sieve analysis was conducted in order to know the different particle sizes of the soil and it was observed that the material was clayey-silt having specific gravity 2.68. Particle size distribution curve is shown in figure 4. From standard proctor test the optimum moisture content of the soil was found to be 16%. Figure 4 shows moisture-densities curve.

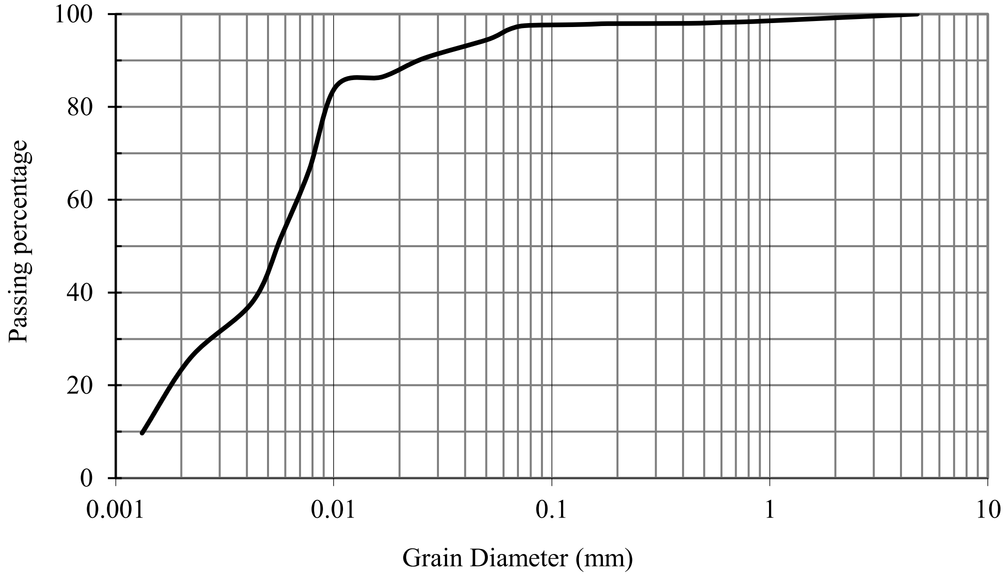

Figure.2 Particle size distribution curve

Direct shear tests and Oedometer tests were performed on the prepared samples. But this study mainly focuses on the consolidation behavior which was determined by oedometer tests. Each sample was allowed to hold a bond between soil particles and cement for a particular time interval in addition of moisture content (MC). A mould of 25mm in diameter and 50 mm in height was used for the preparation of specimens. The specimens were prepared by dropping the material just above the water level till the mould became full. The base and top of mould were enclosed with a porous stone. The preparation of specimen as well as all the tests were performed in fully saturated conditions, Oedometer tests were performed in order to know the consolidation behavior of the prepared samples according to ASTM D2435. Series of loads was applied on the specimen in the incremental steps of 5, 10, 20, 40, 80, 160, 320, 640kpa. Each stage of load v. as applied then the specimen was allowed to consolidate for 24 hours.

3.4 Stress Strain Behavior

Plotted vertical strains are shown in Figure 08 where the results arc plotted in terms of c - log o'v. The vertical strains are plotted for stress interval of 0 - 640 kPa. When comparing the vertical strains under same applied vertical effective stresses, it was observed that the sample containing 10% cement having 24 hours hardening period showed higher strain values. The specimen with no cement showed lower strains, remaining all the specimens showed higher strains than the sample having no cement and lower strains than the sample having 10% cement with 24 hours hardening period. The range of strain values observed in all the tests were between 7 and 27%. The strain percentage corresponding to different percentages of cement and hardening period is shown in Table 04.

Series of loads was applied on the specimen in the incremental steps of 5, 10, 20, 40, 80, 160, 320, 640kpa. Each stage of load v. as applied then the specimen was allowed to consolidate for 24 hours.

Table 4: strain values with different samples

Material	H(mm)	Delta H(mm)	Strain (%)
C=0%, t=o	17.38	0	0
		1.27	7.3
		1.66	9.5
		2.01	11.5
		2.28	13.1
		2.54	14.6
C=5%, t= 1h	22.36	2.3	10.2
		2.89	12.9
		3.39	15.1
		3.84	17.1
		4.21	18.8
C=5%, t= 3h	21.06	1.76	8.3
		2.38	11.3
		2.99	14.1
		3.44	16.3
		3.83	18.1
C=5%, t= 24h	23.87	2.5	10.4
		3.57	14.9
		4.59	19.2
		5.38	22.5
		6.06	25.3
C=10%, t= 1h	20.68	2.08	10.0
		2.66	12.8
		3.27	15.8
		3.82	18.4
		4.18	20.2
C=10%, t= 3h	21.71	2.16	9.9
		2.86	13.1
		3.55	16.3
		4.07	18.7
		4.5	20.7
C=10%, t= 24h	24.06	2.65	11.0
		3.8	15.7
		4.96	20.6
		5.85	24.3
		6.6	27.4

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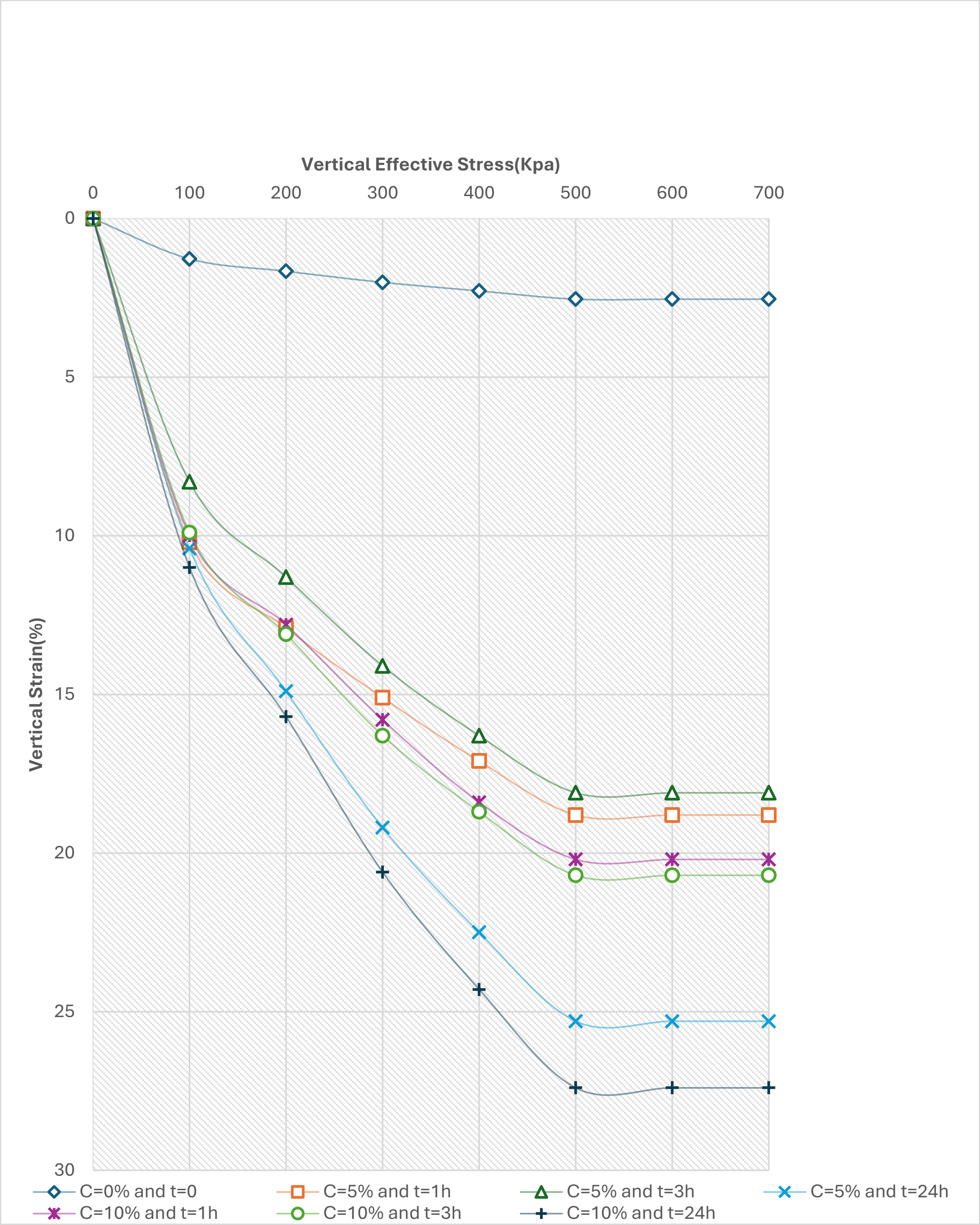

Figure 5 vertical strain verses effective vertical stresses

The strains are calculated as defined in the form or equation 01. At every incremental stage Of vertical stress the change in height of the specimen was calculated. Using this change in height of specimen the strains at every stage are calculated.

$$\in = \frac{\text{Change in height of specimen } (\Delta H)}{\text{Origional height of specimen} (H)} \text{ X } 100$$

3.5 Compressibility and compression index

The compressibility can be defined as coefficient of volumetric compressibility (my) and it is the change in volume per unit volume per unit incremental effective stress [19]. The compression index (Cc) can be defined as the slope of linear portion of consolidation line in the plot e - log δ a (Figure 06) and it is dimensionless quantity. The coefficient of volumetric compressibility mv and compressibility index Cc can be written as equation 03 and 04 respectively [19].

$$mv = \frac{1}{1+e0}\left(\frac{e0-e1}{\sigma'1-\sigma'0}\right) \qquad (m^2/MN)$$

$$Cc = \frac{e0 - e1}{\log(\sigma'1/\ \sigma'0)}$$

Where e represents void ratio, o'y represents effective stresses and subscripts 0 & 1 represents the two points on normal consolidation line. The calculated values of mv and Cc are shown in Table 05. The values of mv and Cc are calculated for stress range of σ' 0 = 320 kPa and σ' 1 = 640 kPa. It is more defined by [19] that for a particular soil the value of mv is not constant but it depends on stress range over which it is calculated.

Table 5.Calculated Values of mv and Cc

Material	Mv(m^2/MN)	C_c
c=0%, t=0	0.058	0.087
c=5%, t=1h	0.062	0.100
c=5%, t=3h	0.069	0.105
c=5%, t=24h	0.114	0.211
c=10%, t=1h	0.066	0.101
c=10%, t=3h	0.076	0.126
c=10%, t=24h	0.128	0.239

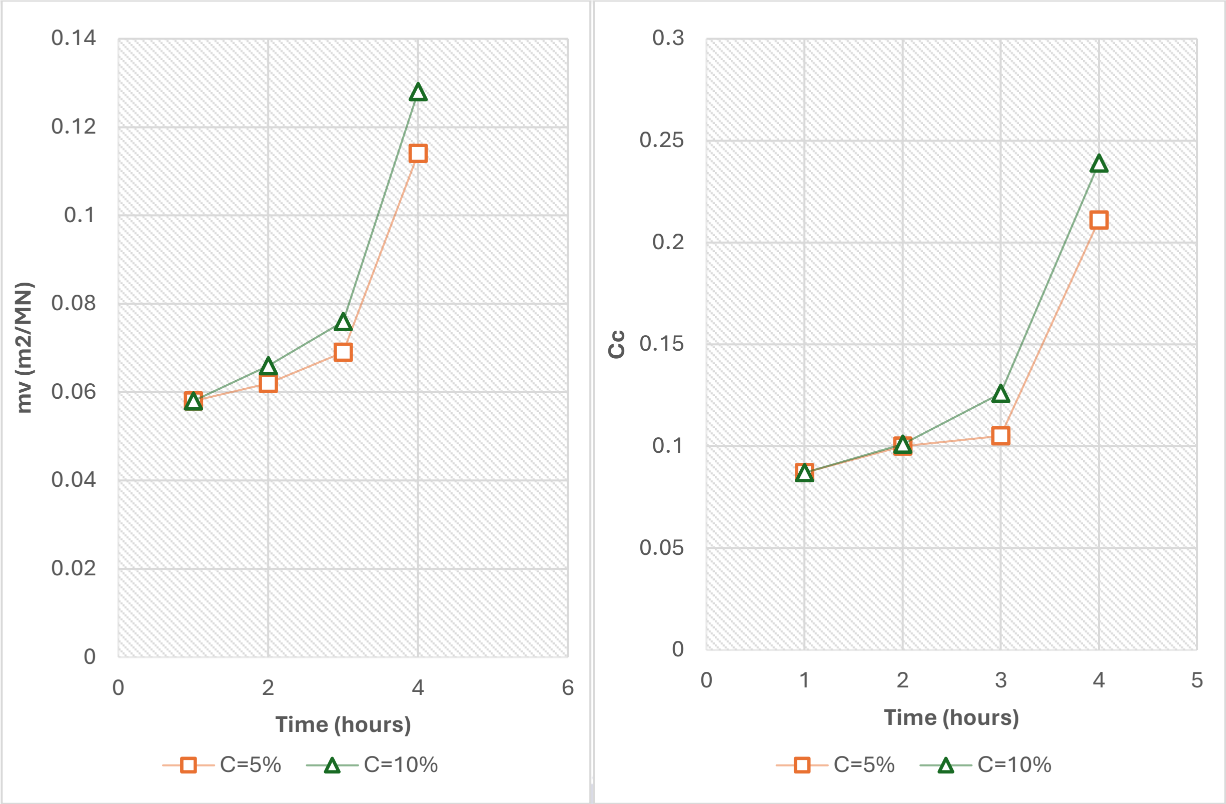

Figure 6 consolidation line of mv and Cc with respect to time

It was observed that m v depends on the amount of cement content and on the hardening period. The specimen having higher cement content and greater hardening period showed higher value of mv and specimen having zero cement possess lower value of mv. Similarly the slope of consolidation line in the plot e -log δv (in figure 06) depends on the cement content in the specimen and hardening period, The results show that line plotted on graph with specimen having higher cement content and greater hardening period have higher slope and vice versa.

4. Results and Discussion

The vertical strain values at different stress levels revealed a significant deviation from expected performance. In all stabilized samples, the vertical strain was higher than that of the natural, untreated soil.

The results indicate that vertical strain increases with both cement content and curing time within the 24-hour window. The 10% cement-24h sample showed the most extreme deformation, with a vertical strain of 27.4%, nearly double that of the natural soil. When comparing the vertical strains under the same applied vertical effective stresses, it was observed that the sample containing 10% cement with 24 hours hardening period showed higher strain values. The specimen with no cement showed lower strains, while all other specimens showed intermediate strain values. The range of strain values observed in all tests was between 7% and 27%.

4.1 Discussion of the Unique Finding

The increase in compressibility in the short term (up to 24 hours) is a unique finding that appears to contradict the established literature. While sources like Zidan [1] report massive reductions in C_c for cemented soils, those studies typically utilize curing periods of 7 to 28 days.

The mechanism behind the observed increase in the Rohri Canal soil can be explained by the state of the soil-cement matrix during early hydration. Upon mixing cement with soil and water, hydration begins immediately, creating a rigid but highly porous skeletal structure. This skeleton initially maintains a higher void ratio than the natural soil because the early-age bonds resist the initial compaction and particle rearrangement. However, these bonds are still fragile. As the vertical stress increases to high levels (640 kPa), this porous skeleton reaches its yield point and undergoes a sudden and catastrophic structural collapse.

In contrast, untreated soil particles are softer and more lubricated, allowing them to rearrange and come closer together gradually even at lower stresses, resulting in a lower initial void ratio but also lower total strain during the high-stress increment. As cement content and curing time increase within the first 24 hours, the "rigidity" of the porous skeleton increases, which paradoxically leads to a larger potential for volume reduction when that skeleton eventually fails under heavy loads.

The strain hardening behavior was observed in the preliminary investigation. With the increase of cement percentage in soil and the higher hardening period, there was a tendency toward increased compressive strength, but this was accompanied by higher compressibility in the short term.

When examining the effect of time, soil samples with 5% and 10% cement showed almost similar strain values for 1-hour and 3-hour time periods, but significantly higher strain for the 24-hour time period. This indicates that cement requires sufficient time to develop bonds with soil particles, and by 24 hours, a more developed but still porous skeleton has formed that is susceptible to collapse under high stresses.

At all three time periods (1h, 3h, and 24h), specimens with 10% cement showed higher strain values compared to specimens with 5% cement. This confirms that higher cement content creates a more rigid but potentially more collapsible early-age structure.

4.2 Comparative Analysis with Literature

A comparison with global trends provides further context. Literature focusing on long-term curing (28+ days) emphasizes the maturation of the C-S-H network, which fills the pores and provides the matrix with enough strength to resist collapse even at stresses exceeding 1000 kPa [20], [21], [22]. The study on early-age consolidation noted that the interaction between bonding and densification is highly kinematic, supporting the idea that the consolidation stress regime during curing is vital[23].

The findings from the Rohri Canal soil highlight a "critical window" of vulnerability. For rapid construction projects in Pakistan, where cement-stabilized soil might be loaded shortly after placement (e.g., during emergency canal repairs), the risk of significant settlement is unexpectedly high. The stabilization process does not immediately provide the consolidation resistance that is typically associated with "cemented soil" in the long-term literature.

It is important to note that the coefficient of volumetric compressibility m_v is not constant for a particular soil but depends on the stress range over which it is calculated [19]. This study calculated m_v and C_c for the stress range of 320–640 kPa, representing high vertical stress conditions relevant to embankment loading.

5. Conclusions

Based on the results obtained from this study it is concluded that:

1. When amount of cement is increased into soil, the shear strength of soil increases.
2. Effect of time (i.e. from sample preparation to testing) has greater effect on the strength of cemented soil, as this period increases the soil shows high shear strength.
3. Larger vertical strain was observed as much as 27% in the specimen with 10% cement and having 24 hour hardening period.
4. Void ratio increases with the increase in the amount of cement.
5. Lower void ratio was seen in natural soil after consolidation at 640 kPa as compared to cemented soil.
6. Vertical strain and void ratio are proportion to the amount of cement in the soil, as the amount of cement is increased into soil sample, it shows high vertical strain value and void ratio.
7. The coefficient of compressibility m_v for natural soil and 10% cement having 24h hardening

period were 0.058 and 0.128 m^2/MN respectively, whereas the compression index Cc values for same samples were 0.087 and 0.239 respectively.

8. Up to this study, the cemented soil may not be appropriate for the use in embankments of canals to reduce the seepage loses in the canals. However, more detailed studies be conducted to achieve better conclusion

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