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INVESTIGATION OF THE COLLAPSE POTENTIAL OF GYPSUM SAND SOIL IN UNSATURATION CONDITIONS USING A MODIFIED OEDOMETER

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Research Paper

Abstract: *This study examines the impact of varying soaking durations on collapse potential (CP) within gypsum sand soil containing 29% gypsum content. It explores the enhancement of CP through the addition of CKD (Cement Kiln Dust) in concentrations ranging from 1% to 5%, employing a modified oedometer apparatus. The oedometer provides accurate measurements of soil compressibility, consolidation properties, and settlement behaviour under realistic load conditions, which are crucial for foundation design and long-term stability predictions. It also aids in assessing soil-structure interaction and validating soil behaviour models, enhancing the accuracy of geotechnical analyses. The oedometer is preferable over other available devices because it is specifically designed for consolidation and collapse studies, making it ideal for testing how additives like CKD affect the soil's collapse potential under controlled soaking conditions. This study categorized specimens into seven groups based on saturation and unsaturation conditions, varying soaking durations of one, two, and three weeks to investigate CP. The findings revealed that the CP under saturation conditions without matric suction for a one-week soaking period exceeded CP under the same conditions with zero matric suction ($\psi = 0$) by 16%. Additionally, CP increased by 16%, 41%, and 136% when specimens were tested under $\psi = 0$ after one, two, and three weeks of soaking, respectively, compared to the one-week soaking period. Furthermore, under matric suction of 40 kPa (indicating reduced moisture content), CP results increased by 55% and*

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228% for two and three-week soaking periods, respectively, compared to the unsaturation state at 40 kPa matric suction with a one-week soaking period. The optimal CKD addition percentage for improving CP ranged from 2% to 3%, contingent upon the specific case study.

Keywords: *Collapse Potential, Gypsum Sand Soil, Unsaturation Conditions, Modified Oedometer Device, CKD, Soaking Period.*

1. Introduction

Soil saturation risk reduction calls for precise planning and engineering especially while constructing on collapsible soils which have high gypsum content (Khodabandeh & Nagy, 2022). Such challenging soils require careful mitigation measures implementation and deep understanding of the causes of soil saturation to ensure reliable structures and safety (Nokande et al., 2022). The engineering properties of loess soils can be improved by stabilizing them with chemicals (Khodabandeh, Nagy, et al., 2023). Loess soils' durability, strength and stability can be enhanced by engineers that use applicable cement, lime fibres, nanomaterials as stabilizing agents (Haeri et al., 2019). This leads to increased construction activities in loess deposits regions hence minimizing the dangers associated with collapsible soil.

Some benefits of gypsum soil in building include enhancing soil stability and structure, being economical since it is readily available at a low cost, improving water infiltration as well as reducing surface crusting, and mitigating swelling behaviour of expansive soils. However, gypsum soil offers some significant disadvantages such as dissolution and erosion problems due to high solubility in water , settlement issues caused by high collapse potential when saturated, durability concerns due to potential for sulphate attack on construction materials and concrete and lower load- bearing capacities requiring additional ground improvement techniques (Abdolvand & Sadeghiamirshahidi, 2024). About 32% of Iraq's landscape consists of soils that are rich in gypsum (Al-Gharrawi et al., 2023).The presence of gypsiferous soils in Al-Najaf provides an exceptional case study that highlights the difficulties presented by these geological circumstances (Abdalhusein et al., 2019).This region, which has gypsum-rich soils, emphasises the significance of thorough design and engineering to guarantee the durability and stability of structures. The construction projects in Al-Najaf have provided important insights into the common challenges and necessary techniques when building on difficult soils. To ensure the longevity and safety of structures built on gypsum-rich soils, it is important to have a thorough understanding of the properties of these soils and to apply appropriate technical solutions (Husain et al., 2019).

Comprehensive approach is necessary to predict settlement and understand the geotechnical soil characteristics which consider the inherent complexities, and variations in soil behaviour. In order to have more accurate evaluations as well as effective strategies for dealing with challenging soils that may be encountered during construction, engineers are required to perform detailed site investigations; advanced laboratory and field testing; as well as, sophisticated modelling techniques (Mahmood et al., 2020). Soil infiltration is essential for maintaining soil nutrition content, improving agricultural productivity, and promoting efficient water use. By considering factors that affect infiltration such as slope of the land surface, compaction level, vegetation cover of the area under consideration among others we will be able to improve water utilization efficiency leading to better conservation practices and promoting sustainable environment management (Al-Saoudi et al., 2014). The magnitude and rate at which settlement occurs are vital aspects in geotechnical engineering which have a major impact on the safety, resilience and operational efficiency of infrastructure. Settlement must be carefully assessed, estimated, and controlled to protect an engineering project's structure and lifespan. Understanding elements like early soil moisture content and rock use can prevent settlement (Abdalhusein et al., 2019). High-gypsum soils have been studied extensively to better understand their features and natural issues in infrastructure design and construction. By characterising soils with high gypsum concentrations, inventing technical solutions, and using predictive modelling, scientists and engineers can reduce construction risks. Continuous research is needed to maintain building security, longevity, and operational reliability in gypsum-rich environments (Akhtarpour et al., 2018). Understanding soil instability processes including porosity and gypsum dissolution-induced cementation bond weakening helps improve structure safety and lifetime. By studying gypsum degradation dynamics, water content changes, and stabilising methods, engineers can optimally build on gypsiferous soils (Husain et al., 2018).

Paul and Chakrabortty (2021) studied alluvial sand deposit inclination for soil settlement in the Ganga basin. They conducted many double consolidation experiments to compare collapse behaviour of different sand and collapse lump combinations. The soil mixture's collapsed potential and lump collapse percentage correlated linearly. In particular, alluvial soil with 90%, 70%, and 30% collapses had collapse potentials of 19.58%, 17.01%, and 12.22%. The collapse potential nearly doubled when the soil combination contained 50% sand and 50% collapsing lumps. These findings improve foundation construction standards for similar quaternary alluvial formations like the Ganga basin, where lumped soil deposits collapse. Using ASTM D5333 standards, Khodabandeh, Kopecskó, et al. (2023) studied the probability of soil collapse at many immersion pressures. Under immersion loads between 100 and 500 kPa, the study examined stress-strain behaviours both before and after saturation. Their findings imply that the probability of soil collapse declined as perlite and metakaolin percentages rose—a shift of up to 8%. Regarding this potential, perlite outperformed metakaolin. Conversely, metakaolin reduced soil collapse by means of pozzolanic and chemical reactions, therefore improving particle bonding. Additionally, examined in this work was the effect of metakaolin and perlite on soil ultrasonic pulse velocity. They observed that the pulse velocity dropped as the perlite content rose, which they connected to the heterogeneous distribution of the perlite possibly leading to wave entrapment. Conversely, metakaolin acted as a filler and raised ultrasonic pulse velocity by promoting a more consistent soil structure.

2. Work Methodology

2.1 Soil Properties

Al-Shakerchy's gypsum content map of Al-Najaf City's distribution and concentration was absolutely vital in choosing material samples for testing. This map showed areas with varying gypsum levels following thorough geological studies and sampling, so enabling focused sample collecting. The acquired materials were examined for building usage since gypsum content influences cement and plaster properties (Al-Shakerchy, 2007). Soil gypsum concentration found by ASTM C-2599 at 29% specimen, which were obtained from 0.75 metres to prevent top soil organic compounds from contaminating anything. As organic elements in the first 0.5 metres could alter gypsum content data, this deeper sampling depth ensures accuracy and dependability (Abdalhusein et al., 2022).

The specific gravity (Gs) of the soil sample was determined to be 2.36, as per the ASTM D854-14 standard (Astm, 2012). The soil's gypsum content was evaluated using a Proctor test, following the guidelines of ASTM D698-00a (Astm, 2012). Figure 1 depicts that the Proctor test yielded a maximum dry density of 18.01 kN/m^3, accompanied by an optimal water content of 8%. The Sand Cone Test method, as outlined in ASTM D1556-00, was used to determine the field density. The result obtained was 17.88 kN/m^3 (Astm, 2024). The water content at the location was measured to be 3.85%, and the soil was categorised as Sand Well-Graded (SW) (Astm, 2010). According to the particle size distribution analysis conducted following ASTM C136 and shown in Figure 2, the soil was classified as well-graded sand (SW) according to the Unified Soil Classification System (USCS) (Aashto, 2014).

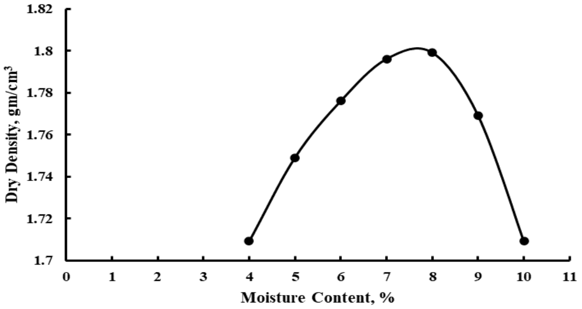


Figure 1: Proctor Test Results of the Tested Sample.

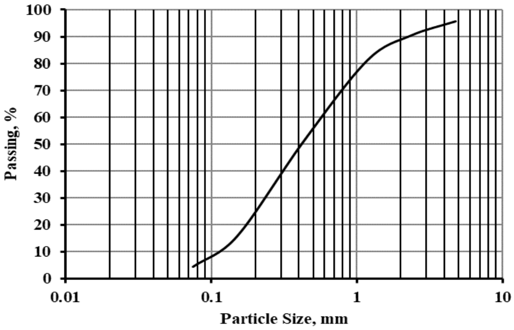
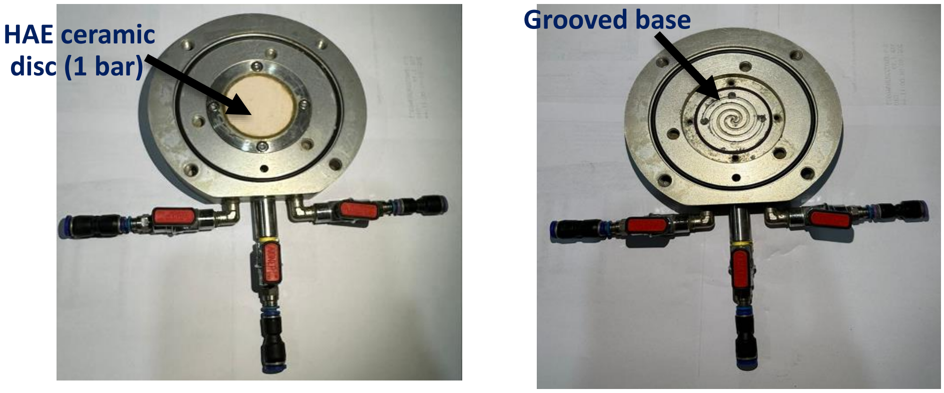


Figure 2: Particle Size Distribution of the Tested Sample.

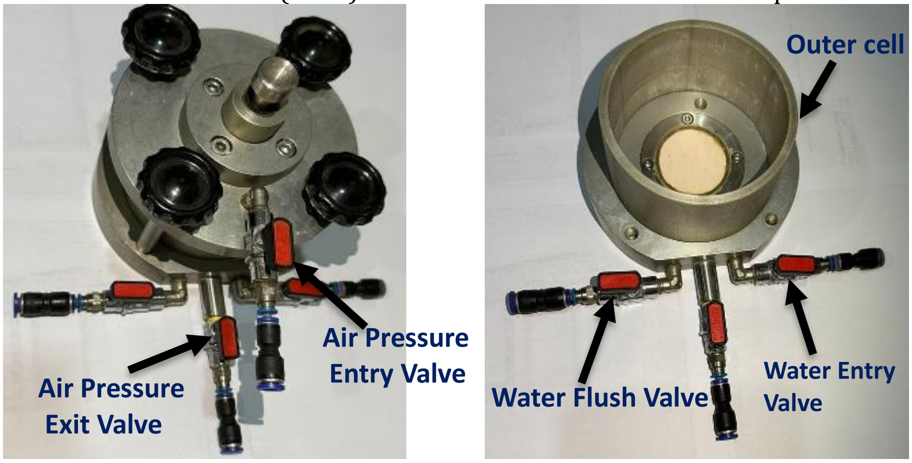
2.2 Modified Oedometer Device

The oedometer is a geotechnical tool that evaluates soil at rest compression and consolidation characteristics under well-defined loading and soaking conditions. These include; a rigid ring, soil sample, and vertical stress application loading system. This is performed by carefully monitoring the vertical deformations that helps in understanding how soils respond to each stage of applied loading or soaking. In addition, it's counterpart includes the consolidation testing machine which measures these properties as well but might not have equivalent control over soaking conditions with reference to precision and tri-axial testing machine which determines behaviour of soils under different stress paths but is more complicated in terms of rigidity and less concerned with vertical deformation (Aversa & Nicotera, 2002). An Oedometer works by applying vertical stress on a confined soil sample within a stiff ring while measuring the resultant deformations vertically. The process involves incrementally loading the soil sample and noting down the corresponding deformations so as to evaluate compressibility characteristic and consolidation properties of soil. Oedometer calibration involves using known property reference materials to ensure accurate measurements. Load calibration also forms part of this procedure (Karimpour-Fard et al., 2020). Suction control has been integrated into certain apparatus to adapt traditional Oedometer test equipment for unsaturated conditions. In this experiment, an unsaturated Oedometer was utilized, meticulously calibrated and adjusted for its purpose. The equipment, as detailed by Fredlund and Rahardjo (1993) and depicted in Figure 3, includes essential components such as an air pressure controller, top cap, and a High Air Entry (HAE) ceramic disc.

The 5 cm HAE disc, illustrated in Figure 3(a), rests on a grooved base plate (Figure 3(b), facilitating the release of trapped air bubbles through a flush valve (Figure 3(d) prior to commencing the test. To ensure water tightness under elevated pressures, the HAE disc is securely affixed to the grooved base using screws and an O-ring, as shown in Figure 3(b). The top cap, depicted in Figure 3(c), regulates the air pressure. For this experiment, a 1 Bar HAE ceramic disc with a 100 kPa air entry value was chosen, aligning with the natural moisture content of the sample under test. This corresponds to a matric suction of 50 kPa, as determined from the Soil Water Retention Curves (SWCCs) presented in Figure 5.The Oedometer test samples measure 2 cm in height and 5 cm in diameter. During testing, the specimen is enclosed by an external cell (Figure 3(d), which is filled with air. A highly precise LVDT, offering an accuracy of 0.01 mm, is positioned outside the cell to measure the axial displacement of the specimen. The LVDT is capable of detecting displacements up to approximately 2.5 cm. A water volume device, often used in conjunction with an oedometer, measures the volume of water absorbed or expelled by a soil sample during testing. The device operates on the principle of measuring changes in water volume through precise monitoring. As the soil sample in the oedometer consolidates under applied load, water either seeps into the sample (if it's absorbing water) or is expelled (if it's releasing water). The device accurately tracks these changes in water volume. By measuring the water volume changes, the device helps determine the soil's response to soaking periods. In gypsum sand soil, which has a high potential for collapse when saturated, tracking water volume changes allows for precise measurement of how much water the soil absorbs before collapsing. Figure 4 illustrates the use of a Water Volume Change (WVC) device equipped with a 7.5 cm LVDT to measure the total volume change of the soil under examination. The water capacity of this WVC device is 125 cc, facilitating accurate monitoring of volume variations in the soil sample throughout testing. This capability provides crucial data for analysing the soil's response under varying condition



a: HAE ceramic disc (1 bar) b: Grooved base plate



c: Inner cell d: Outer cell

Figure 3: Details of the Unsaturated Oedometer Cell.

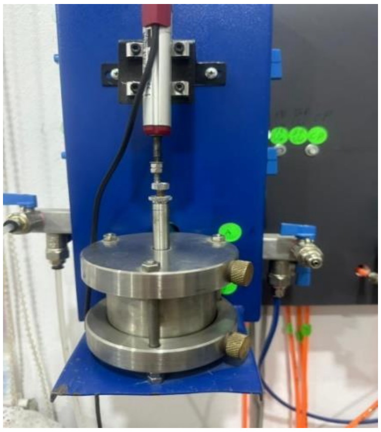


Figure 4: Water Volume Change (WVC).

2.3 Soil-Water Characteristic Curve (SWCC)

The adapted Oedometer is used to test the SWCC carefully, and the results are good. This gadget can change both the matric suction and the net normal stress. This lets it accurately model different stress states and overburden conditions. Keeping the temperature stable in these tests is very important because changes in temperature have a big effect on the readings and the attributes of the soil. For accurate results, it is important to keep the temperature steady and under control during the whole testing process. It's also important to think about how air moves through clay discs that let a lot of air in. The matric suction measure can also be off if air gets in. This is especially important in soils with a high air permeability rate. This problem can be lessened by making sure the equipment is properly sealed and calibrated. For any reliable result, it is necessary that sources of inaccuracy in water content calculation for this SWCC be checked. Inaccuracies may result from such factors as heterogeneity of soil, techniques employed during sample preparation or errors in measurement among others. These problems can be identified and eliminated by doing thorough validation tests and calibrations respectively. By considering factors such as temperature regulation, air diffusion, and sources of inaccuracy, significant steps have been taken toward ensuring the reliability and accuracy of experimental results (Abdalhusein et al., 2024). Figure 5 illustrates the SWCC results of the tested sample.

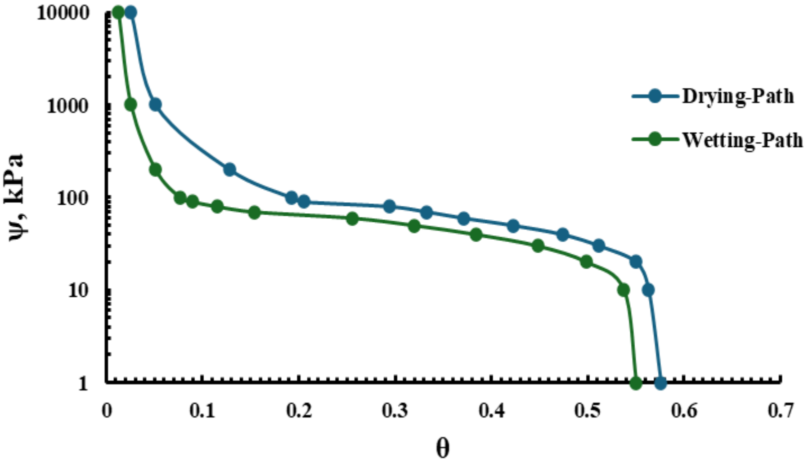


Figure 5: SWCC of the Tested Sample.

2.4 Test Methodology

In this study, forty-two consolidation tests were conducted using the Unsaturated Oedometer Device. These tests were divided into seven groups, with each group comprising six tests based on varying percentages of Cement Kiln Dust (CKD) additions: 0%, 1%, 2%, 3%, 4%, and 5%. The first group consisted of conventional tests with a soaking period of one week. The second group included eighteen tests under unsaturated conditions with zero matric suction and soaking periods of one week, two weeks, and three weeks. The remaining groups were tested under unsaturated conditions with both zero and 40 kPa matric suction and the same three soaking periods, as detailed in Table 1.

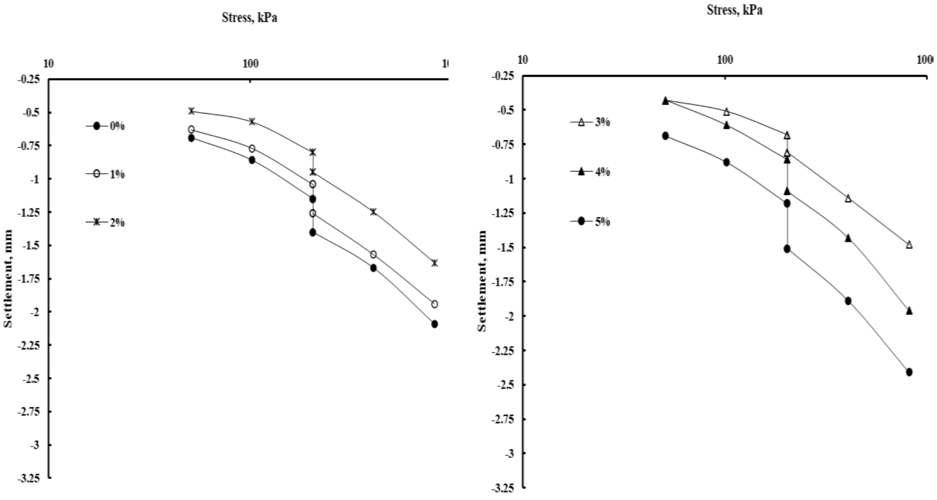
Table 1: Test Procedure of CP.

Test No.	Group No.	Description	Matric Suction (ψ), kPa	Soaking Period	CKD, %
1	1	Saturation	N/A	1-Week	0
2					1
3					2
4					3
5					4
6					5
7	2	Saturation with HAE Ceramic Disc	0	1-Week	0
8					1
9					2
10					3
11					4
12					5
13	3	Saturation with HAE Ceramic Disc	0	2-Week	0
14					1
15					2
16					3
17					4
18					5
19	4	Saturation with HAE Ceramic Disc	0	3-Week	0
20					1
21					2
22					3
23					4
24					5
25	5	Saturation with HAE Ceramic Disc	40	1-Week	0
26					1
27					2
28					3
29					4
30					5
31	6	Saturation with HAE Ceramic Disc	40	2-Week	0
32					1
33					2
34					3
35					4
36					5
37	7	Saturation with HAE Ceramic Disc	40	3-Week	0
38					1
39					2
40					3
41					4
42					5

3. Result and Discussion

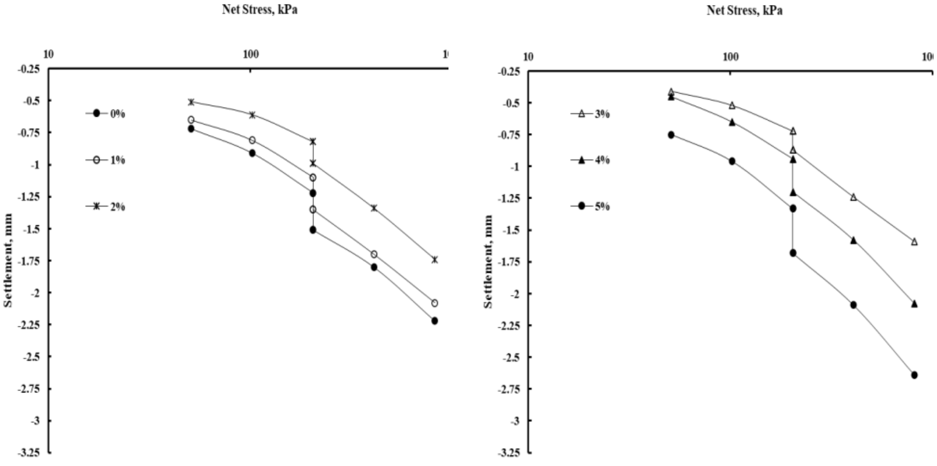
3.1 Saturation and Unsaturation with ψ = 0 kPa

The first group was tested using the conventional Oedometer method with a one-week soaking period and six different percentages of CKD, as illustrated in Table 1. The conventional oedometer method provides precise measurements of soil compressibility and settlement behaviour under controlled loading conditions, essential for accurate prediction of foundation settlements and long-term stability assessments in geotechnical engineering. This group was conducted, as depicted in Figure 6, to delineate the distinction between the conventional method and the unsaturated method under matric suction (ψ = 0), as shown in Figure 7. The presence of high air entry (HAE) ceramic discs notably increased the coefficient of primary consolidation (CP). Groups 3 and 4, illustrated in Figures 8 and 9, were tested under identical conditions to Group 2, but with soaking periods extended to two weeks and three weeks, respectively.



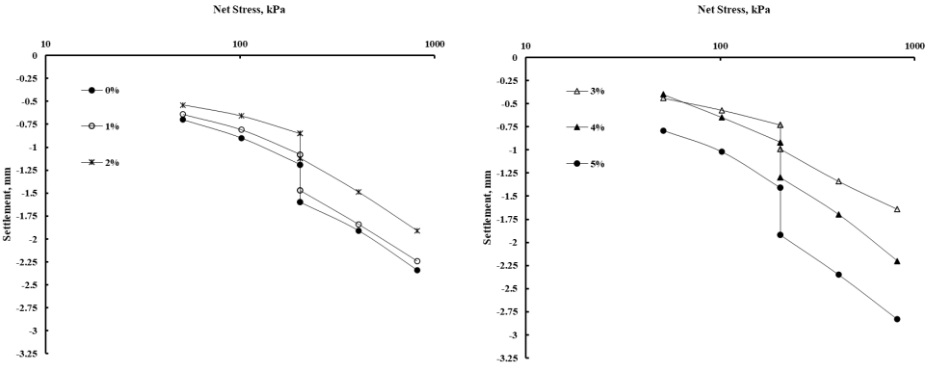
a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 6: Stress – Settlement Curve of the Tested Specimens (Conventional Test with 1-Week Soaking).



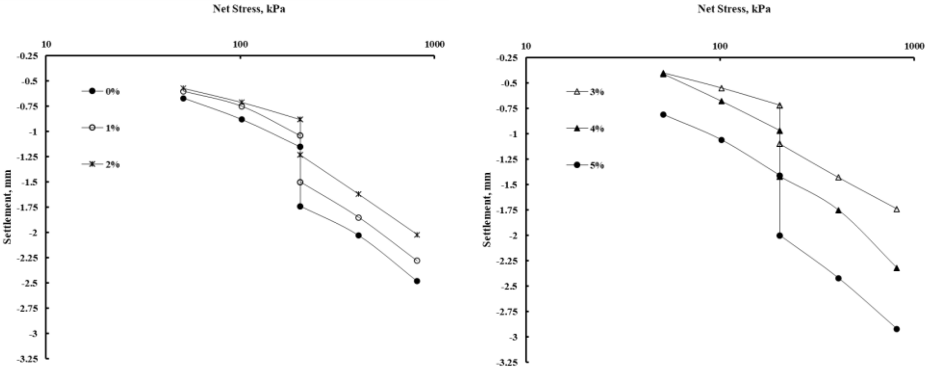
a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 7: Stress – Settlement Curve with ψ = 0 kPa (Unsaturated State with 1-Week Soaking).



a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 8: Stress – Settlement Curve with ψ = 0 kPa (Unsaturated State with 2-Week Soaking).



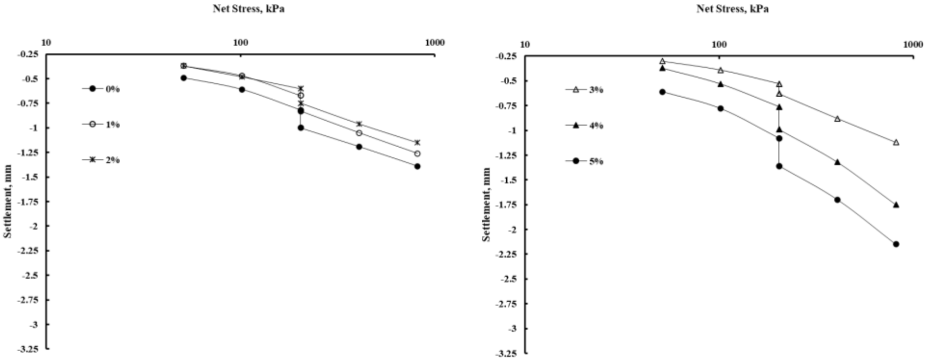
a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 9: Stress – Settlement Curve with ψ = 0 kPa (Unsaturated State with 3-Week Soaking).

3.2 Unsaturation with ψ = 40 kPa

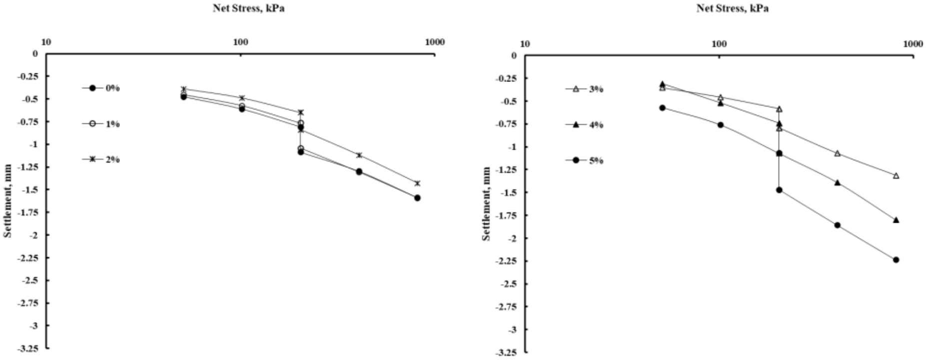
In this procedure, the matric suction was elevated to 40 kPa, indicating the specimen was subjected to drying conditions, reducing water pressure from 150 kPa to 110 kPa to simulate scenarios such as evaporation or a decline in the water table. Groups 5 to 7 underwent testing under these conditions, and Figures 10 to 12 elucidate the relationship between net stress and settlement of the tested specimens across the six CKD material percentages outlined in Table 1. Figure 10-a illustrates the impact of adding 1% and 2% CKD. Adding 1% resulted in decreased collapse potential and settlement in each load increment, attributed to CKD's role as both filling material, occupying voids between soil particles, and cementing material due to its inherent properties. Increasing CKD to 2% showed a similar behaviour, although there was no reduction in settlement during the first two load increments (50 kPa and 100 kPa); subsequent load increments (200 kPa, Soaking-200 kPa, 400 kPa, and 800 kPa) exhibited significant decreases in settlement and collapse potential. Figure 10-b depicts that the lowest settlement across all load increments and the least collapse potential occurred with 3% CKD. Increasing CKD to 4% led to increased settlement and collapse potential, with behaviour similar to that observed with 5% CKD. Figures

11 and 12 present settlement results for groups 6 and 7 with CKD additions, showing trends consistent with groups 4 and 5.



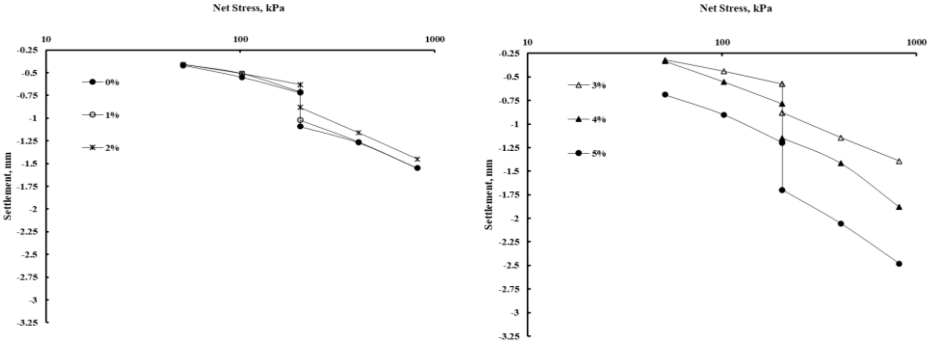
a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 10: Stress – Settlement Curve with ψ = 40 kPa (Unsaturated State with 1-Week Soaking).



a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 11: Stress – Settlement Curve with ψ = 40 kPa (Unsaturated State with 2-Week Soaking).



a: 0%, 1%, and 2% of CKD a: 3%, 4%, and 5% of CKD

Figure 12: Stress – Settlement Curve with ψ = 40 kPa (Unsaturated State with 3-Week Soaking).

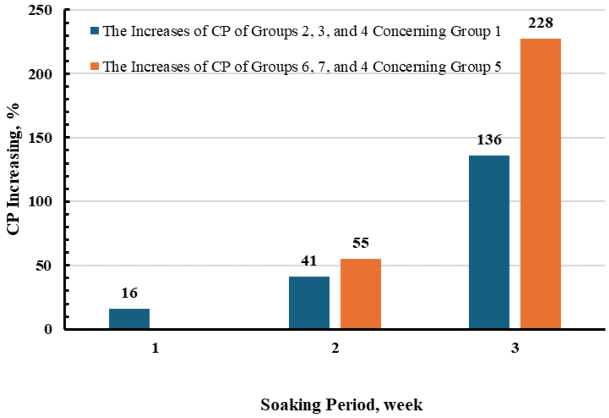


Figure 13: The Increases of CP of the Tested Specimens in the Case of No CKD Additive.

The increase in the coefficient of CP for the tested specimens in groups 2, 3, and 4, compared to the conventional test in group 1, is depicted in Figure 13. The CP increased by 16%, 41%, and 228% for groups 2, 3, and 4, respectively. Additionally, the increases in CP for groups 6 and 7, compared to group 5, are also shown in Figure 13, with CP percentages rising by 55% and 228%, respectively. The increase in coefficient of CP during the one-week soaking period under unsaturated conditions (with HAE ceramic discs and zero matric suction) is attributed to the saturation process, where water fills the voids between soil particles due to the physical representation of air pressure (Ua) and water pressure (Uw) within the specimen voids. The collapse potential also increased with a two-week soaking period, as gypsum materials became more pliable with prolonged dissolution, leading to increased settlement at the 200 kPa level. Extending the soaking period to three weeks continued the dissolution of gypsum, creating voids between soil particles that facilitated settlement phenomena. Figure 14 illustrates the enhanced CP for groups 1, 2, 3, and 4 without CKD additives, while Figure 15 clarifies the improved CP for groups 5, 6, and 7 also without CKD material. Table 2 summarizes the optimal percentage of CKD identified in this study to enhance CP.

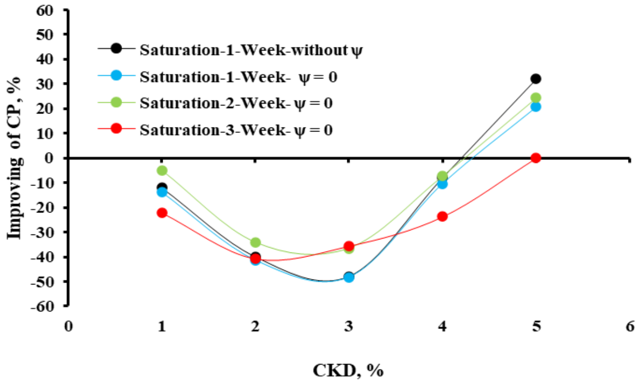


Figure 14: The Increases of CP of Groups 1, 2, 3, and 4 Concerning Case of No CKD Additive.

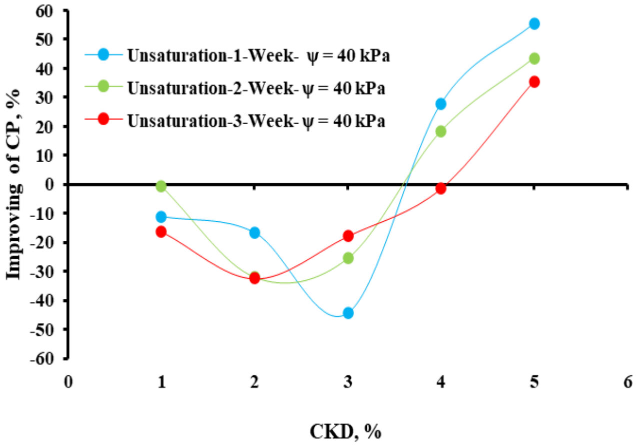


Figure 15: The Increases of CP of Groups 5, 6, and 7 Concerning Case of No CKD Additive.

Table 2: The Optimum CKD Percent for this Study to Improve the CP

Group No.	Group Specifications Test Type	Matric Suction, ψ	Soaking Period	Optimum CKD, %
1	Saturation without HAE Ceramic Disc	N/A	1-week	2.75
2	Unsaturation with HAE Ceramic Disc	0	1-week	2.75
3		0	2-week	2.5
4		0	3-week	2
5		40 kPa	1-week	3
6		40 kPa	2-week	2.4
7		40 kPa	3-week	2

4. Conclusion

In conclusion, this study comprehensively investigated the CP of gypsum sand soil with 29% gypsum content under varying soaking periods and unsaturation conditions, using a modified oedometer device. The results clearly demonstrated significant increases in CP percentages across different saturation states and soaking durations, particularly notable when compared to conventional tests. The addition of CKD showed promising results in improving soil stability, with optimal percentages identified between 2% and 3%. This research underscores the critical role of the oedometer in accurately assessing soil compressibility, consolidation properties, and settlement behaviour, thereby enhancing our understanding of foundation design and long-term stability predictions in geotechnical engineering.

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