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***Corresponding author:**

Email address:

m.m.almoadhen@mtu.edu.iq

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Effectiveness of calcium chloride (CaCl_2) solution in enhancing the hydro-mechanical properties of gypsum-bearing soils

Muataz M. Al-Moadhen¹, Hadeel M. Hussein², Noor S. Atia³¹Civil Techniques Department, Technical Institute – Anbar, Middle Technical University, Baghdad, Iraq²Civil Engineering Department, Ashur University, Baghdad, Iraq³Civil Engineering Department, Alshaab University, Baghdad, Iraq

Abstract: Gypsum soil often undergoes strength loss, high compressibility, and collapse upon wetting, exhibiting serious damage to civil infrastructure. This study was performed to investigate the effectiveness of calcium chloride (CaCl_2) solution as a chemical additive for enhancing the hydro-mechanical properties of natural silty sand soil bearing a 26% gypsum content. The soil was treated with three CaCl_2 dosages (10, 20, and 30%) and tested under wetted and unwetted conditions after a 14-day curing period. The results indicate that CaCl_2 treatment is an effective approach for stabilization of gypsum-bearing soils, and the use of a 20% CaCl_2 solution offers the highest overall performance index ($\text{PI} = 0.94$), with an increase in dry unit weight and cohesion, and a decrease in gypsum dissolution, permeability, angle of friction, compressibility, and collapsibility. The findings were further substantiated by SEM analysis, which demonstrates a denser and more compact microstructure for soil treated with 20% CaCl_2 , which was associated with enhanced particle bonding and structural integrity.

Keywords: Chemical stabilization, calcium chloride (CaCl_2), gypsum-bearing soils, common-ion approach.

1. Introduction

Many buildings in arid and semi-arid regions are constructed on soils bearing considerable amounts of gypsum mineral ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), a soluble salt that has an unpredictable effect on the engineering behavior of soil. Gypsum, when dry, is stable and can offer provisional cementation and bonding between soil particles. It, however, rapidly dissolves in water, losing interparticle bonds, leading to an increase in porosity and cavities, and a sudden reduction in volume, stiffness, and strength [1, 2]. Hence, gypsum-bearing soils are constantly subjected to excessive collapsibility and

uneven settlement, posing risks to long-term stability and serious issues for geo-engineering applications [3]. The collapsible potential of gypsum soils significantly increases as gypsum content and overburden pressures increase. Coarse soils containing gypsum, despite the high permeability properties, can undergo substantial collapsibility if exposed to loading under wetting conditions. Different stabilization methods have been considered to mitigate the adverse impact of gypsum in soils, including mechanical stabilization through soil densification by dynamic compaction [e.g., 4, 5] and chemical stabilization through the

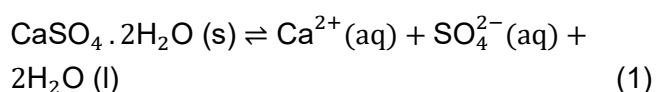
use of binding admixtures such as lime, slag, fly ash, and cement [e.g., 6, 7, 8]. These traditional additives, despite their wide use, have some drawbacks in terms of cost and environmental demand, and are considered less effective in soluble salt-rich soils [9]. In recent years, calcium chloride (CaCl_2) has gained attention among chemical stabilizers owing to availability, low cost, effectiveness, and simplicity in use. Nevertheless, the available publications on the use of CaCl_2 in gypsum soils are relatively few and concentrate mainly on selected engineering properties. For example, Ramanjaneyulu and Kumar [10] assessed the effect of using CaCl_2 on compaction and California bearing capacity (CBR) of high-plasticity clays stabilized with gypsum. They showed that adding 2% of CaCl_2 leads to an improvement in compaction and CBR parameters. Muhauwiss and Hassoun [11] studied the durability of pestiferous soils treated with CaCl_2 under drying-wetting cycles and observed that the collapsible potential increases with the cycles by 30-50%, and there is a fluctuation effect on soil cohesion. Sharo et al. [12] used $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ as a stabilizer for curing expansive non-gypsum soils, concluding that density, CBR, and soil strength were improved with a reduction in swelling potential. Choi [13] highlighted the importance of adding CaCl_2 with fly ash in improving the geotechnical properties of dark brown clays. The enhancement mechanism of CaCl_2 is mainly dependent on the concept of the common-ion effect based on Le Chatelier's principle, where the weak electrolyte intensity is increased by adding a common ion, shifting the equilibrium to the left. This lowers ionization and dissociation and minimizes gypsum dissolution, which in turn works on improving soil inter-particle cementation, reducing collapsibility and volume-change behavior, and enhancing soil stability. It, therefore, could enhance the entire chemical and hydro-mechanical behavior of the soil. Nevertheless, excessive CaCl_2 contents may produce chemical reactions resulting in

progressive corrosion of metals that are embedded in structures such as foundations [14]. Also, while CaCl_2 can provide an improved stable structure, it may be temporary and suffer long-term issues [15].

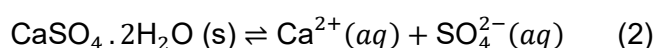
The aim of this study is to evaluate the effectiveness of using calcium chloride (CaCl_2) as an alternative chemical stabilizer in the treatment of natural gypsum-bearing silty sand soil. An experimental testing program was set to investigate the influence of CaCl_2 on the hydro-mechanical properties of the soil, including compaction, compressibility, collapsibility, permeability, dissolution, and shear strength. The optimum CaCl_2 dosage at which the soil demonstrates higher performance was also determined. The observed behavior was supported microscopically using SEM scanning.

2. Common-ion Concept in Gypsum Bearing Soils

The common-ion concept is a term that is used regularly in chemistry to describe the solubility reduction of a dissolving salt that appears when the dissolved salt is added to a solution containing a common source of one of its constituent ions [16]. It can also be expressed as the reduction in the ionization of a weak electrolyte as a result of the addition of a strong electrolyte (the common ion) in the solution [17]. The common-ion concept generally depends on Le Chatelier's Principle. While common-ion application is of wide occurrence in the chemical industry, it can be applied in soil mechanics for saline and soluble soils in spite of its complexities in terms of heterogeneity, ion exchange activity, and spatial variability. For gypsum-bearing soils, the gypsum (calcium sulfate dihydrate) dissolves in pure water as follows:



The resulting liquid water is often neglected for simplicity:



The dissociation of calcium chloride (CaCl_2) results in two ions:



Because CaCl_2 increases the concentration of Ca^{2+} ions in pore water, equilibrium shifts to the left (toward solid gypsum) according to Le

Chatelier's principle, reducing gypsum dissolution. This shift causes a notable reduction in the concentration of SO_4^{2-} ions and a decrease in the overall solubility of the gypsum phase.

3. Experimental Testing Program

3.1. Material used

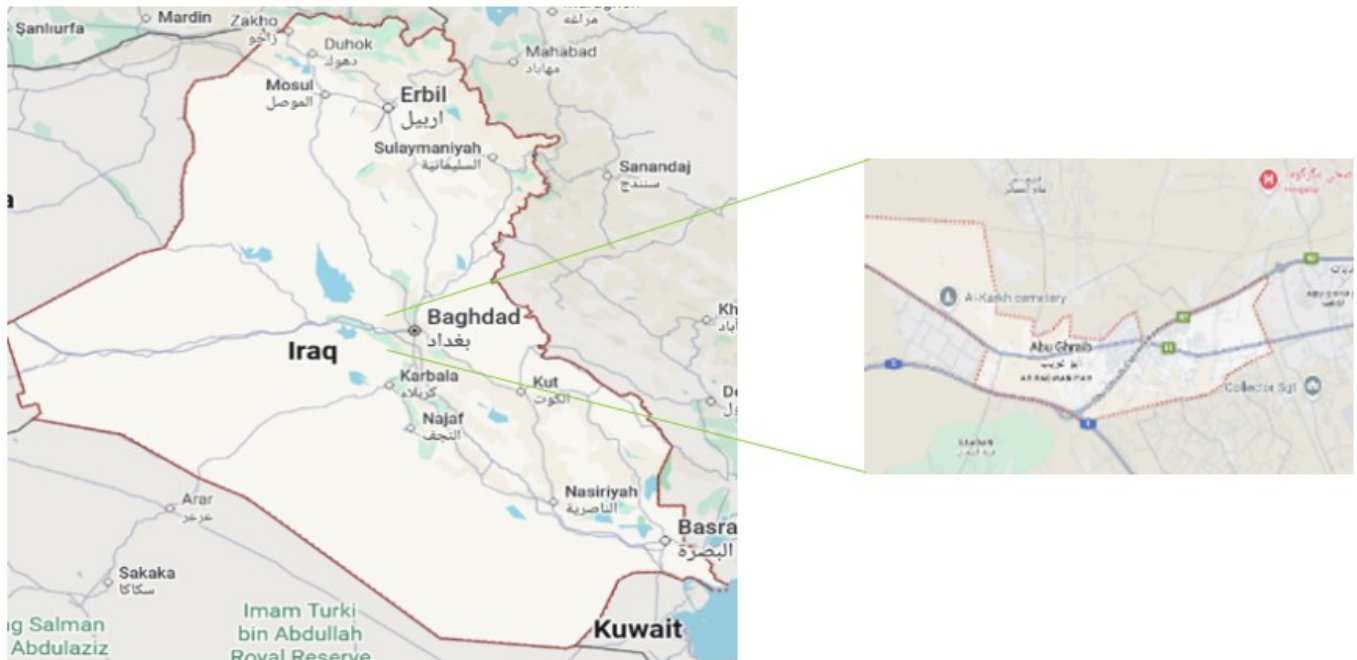


Fig. 1. Construction site at Baghdad city-Iraq



Fig. 2. A photo of the soil and CaCl_2 used

To assess the effectiveness of the CaCl_2 stabilization method, natural gypsum soil was used for a better representation of realistic in-situ conditions. The soil was brought from a construction site in Baghdad city, the capital city of Iraq (Fig. 1 and 2), where gypsum-bearing soils are widely distributed. The gypsum content was

determined to be 26%. The essential index properties of the soil were obtained following the procedures described in the British standard [18–20] and summarized in Table 1, and the particle size distribution was shown in Fig. 3, indicating that the soil was dominated mostly by sand and silts with very low fine content and, according to the

USCS method, it was classified as silty sand soil.

Commercial calcium chloride (CaCl_2) was purchased as a dry powder (shown in Fig. 2) and stored under controlled moisture and temperature conditions. CaCl_2 was prepared as a solution with 10, 20, and 30% concentrations for the experiments and was mixed by gradually dissolving the pre-weighed amount of the CaCl_2 powder into clean water under continuous slow agitation until a homogeneous and consistent solution was formed. The CaCl_2 concentrations

were calculated based on the total mass of the solution (water + CaCl_2), referring to the mass percentages. 10% CaCl_2 concentration, for example, was prepared by mixing 10 g of CaCl_2 powder with 90 g of water to form 100 g total solution, and for 20% and 30%, similar procedures were followed but with different percentages. The chosen CaCl_2 dosages provide a broad range of treatment levels for investigating the effect of increasing calcium-ion availability on the treatment of gypsum-bearing soil.

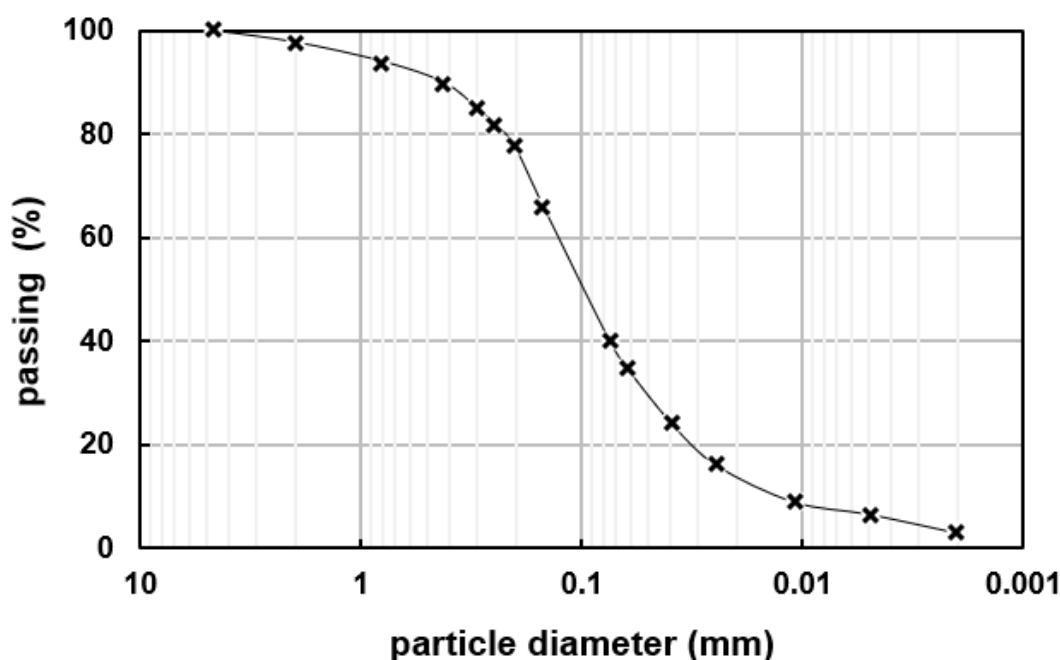


Fig. 3. PSD of the silty sand soil

Table 1. The properties of silty sand soil

Property	Value
Gypsum content (%)	26
pH	7.7
Gs (specific gravity)	2.58
Liquid Limit LL (%)	26.1
Plasticity index	3.4

3.2. Laboratory experiments

A series of hydro-mechanical experiments were conducted to evaluate the effectiveness of the CaCl_2 stabilization method. These experiments include compaction, compression, collapsibility, permeability, dissolution, and shear strength. Scanning electron microscopy (SEM) was also performed to support the observed behavior. The

experiments were carried out following testing procedures described in the British Standards [20–24] using standard laboratory equipment. All soil samples were prepared using similar compaction energy to achieve approximately similar density conditions.

The compacted samples were wrapped for 14 days inside airtight bags at room temperature

prior to the tests. This duration was to allow for better interaction between CaCl_2 solution and soil particles, enhancing the performance of stabilization effects before testing. This curing period has been widely used in soil stabilization studies [25, 26] and represents an intermediate stage at which changes in strength, compressibility, and microstructure can be observed.

For each property test, for each condition, three samples were identically prepared and measured under the same laboratory conditions, and the reported values in the results represent the average measured values. The variation between the repeated values was in the range of approximately 3%, which indicates acceptable reproducibility and consistency.

4. Result and Discussion

4.1. Compaction

The compaction curves of gypsum-bearing silty sand soil stabilized with CaCl_2 solution are presented in Fig. 4. Compaction behavior of the

soil was considerably influenced by the addition of CaCl_2 . As the concentration of CaCl_2 increased, the maximum dry unit weight ($\gamma_{d-\max}$) increased progressively, accompanied by a minor reduction in the optimum moisture content. The rate of increase in the maximum dry unit weight was 5.7, 7.5, and 8.6% for the soil treated with 10, 20, and 30% CaCl_2 , respectively. This is normal, as gypsum acts as a temporary bonding agent between sand particles, and when compacted with pure water only, part of the gypsum is dissolved, deteriorating the bonding and reducing the skeleton's dense packing of the sand. Adding CaCl_2 limits gypsum dissolution, preserving the gypsum bonding under compaction, and allowing sand particles to rearrange themselves more efficiently, resulting in a more stable structure with a higher density. On the other hand, CaCl_2 helps in improving the lubricity characteristic of water, which reduces the amount of moisture required in the process of particle re-arrangement.

4.2. Compressibility and collapsibility

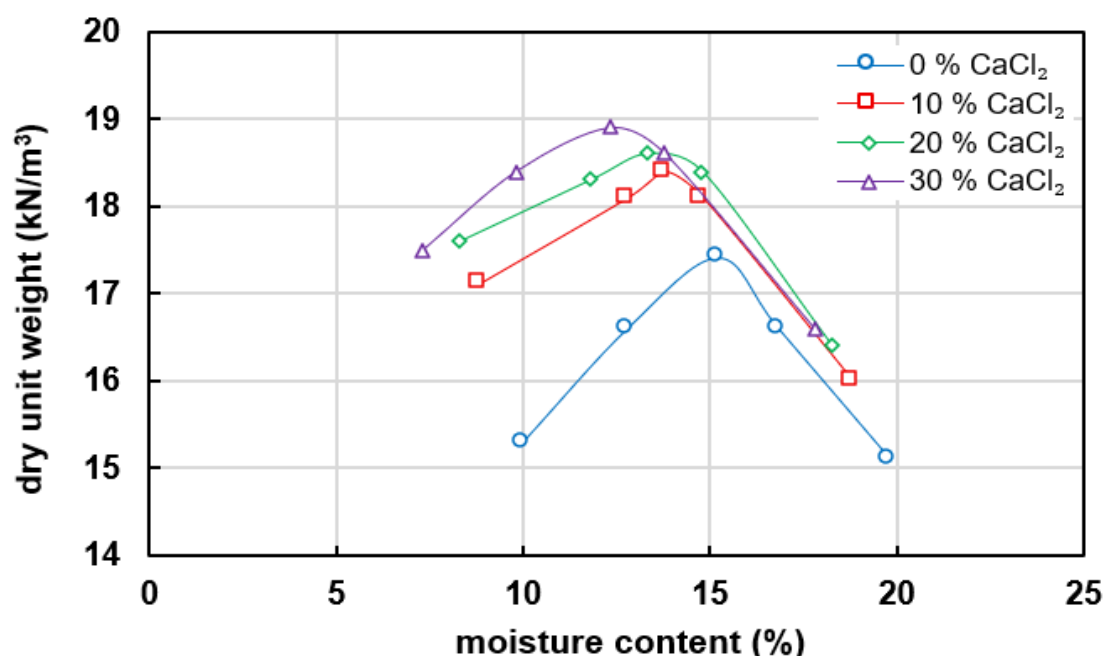


Fig. 4. Compaction characteristics of gypsum-bearing silty-sand soil treated with CaCl_2

The one-dimensional compression characteristics of the silty sand soil containing gypsum stabilized with three different CaCl_2 amounts are presented in Fig. 5a. For all soil

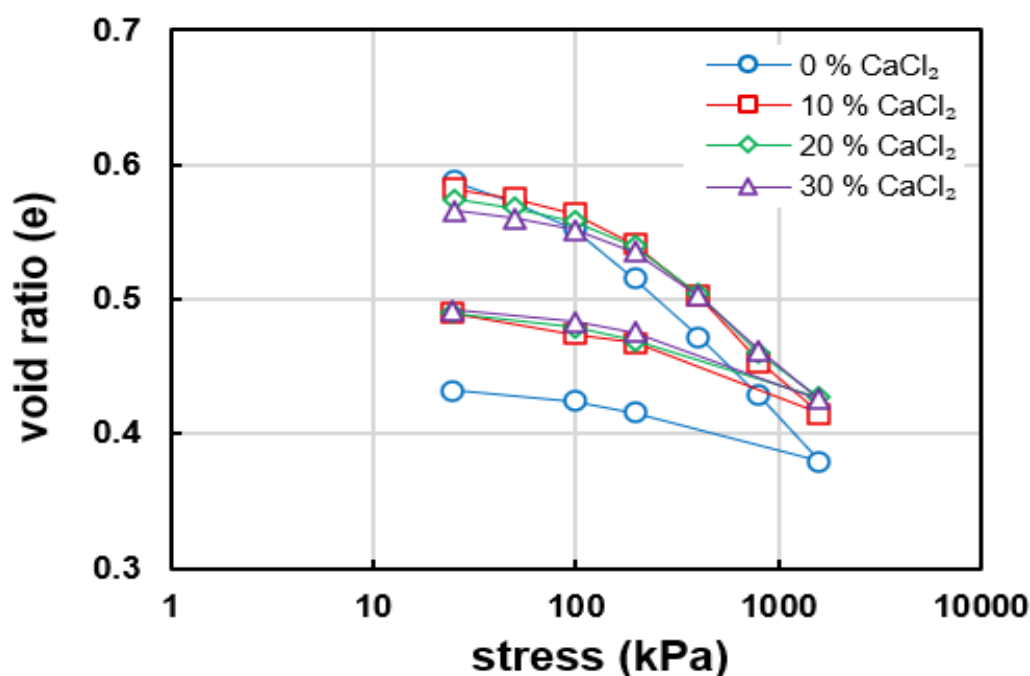
samples, the void ratio decreased consistently with increasing vertical stress, a standard compression behavior of coarse soils. The untreated sample that contains 0% CaCl_2 showed the greatest

compressibility, indicating weak bonds. Adding CaCl_2 solution progressively decreased compression and made the curves flatter. At 20% CaCl_2 , the compression index (C_c) was reduced by about 24%. While void ratios showed a moderate reduction at initial stresses, the soil samples showed a pronounced decrease in compressibility with higher stiffness and enhanced structure, indicating stronger interparticle cementation. Adding further CaCl_2 content led to only secondary additional development, specifically at higher stresses, meaning that a stable soil structure has already been accomplished. This suggests that CaCl_2 treatment is a practical approach for enhancing the compressibility behavior of gypsum-bearing sand, with an ideal result occurring at 20% CaCl_2 solution.

Fig. 5b shows the collapsibility results of the silty sand soil treated with various CaCl_2 amount. For all samples, the collapsible strain increased as vertical stress increased, and the relationship was non-linear, with a small strain increase at low stress. For the untreated sample, the curve

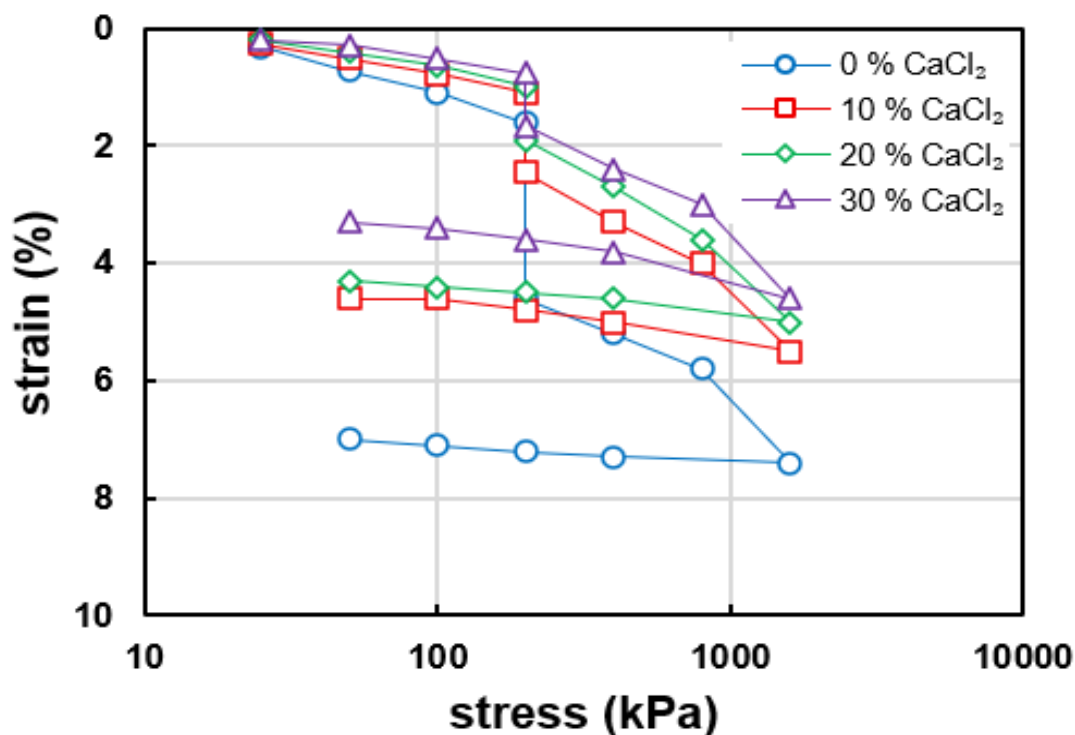
displayed a noticeable jump in collapsible strain at the wetting stress. This was caused by the loss of interparticle cementation and fabric destruction when wetting under the applied loading. For CaCl_2 -treated samples, the collapsible strain showed a reduction at all stress levels. Adding 10% CaCl_2 solution resulted in partial reduction, but it was not enough to stop soil collapse completely. At 20% CaCl_2 , a significant enhancement was observed where the collapse potential (CP) was reduced from 3 to only 0.92%, and the soil showed sustained stiffness and stabilized collapse, suggesting that treatment of gypsum-bearing sands with 20% CaCl_2 can be effective in terms of minimizing soil collapse. As CaCl_2 dosage increased further, above 20%, a reduction occurred, but it was only marginal compared to 20%. This could be due to soil reaching the ion-saturation limit, where no additional improvements can occur. The excessive dosages of CaCl_2 affect adversely by increasing salt solubility and leaching, leading to long-term structure instability.

4.3. Permeability



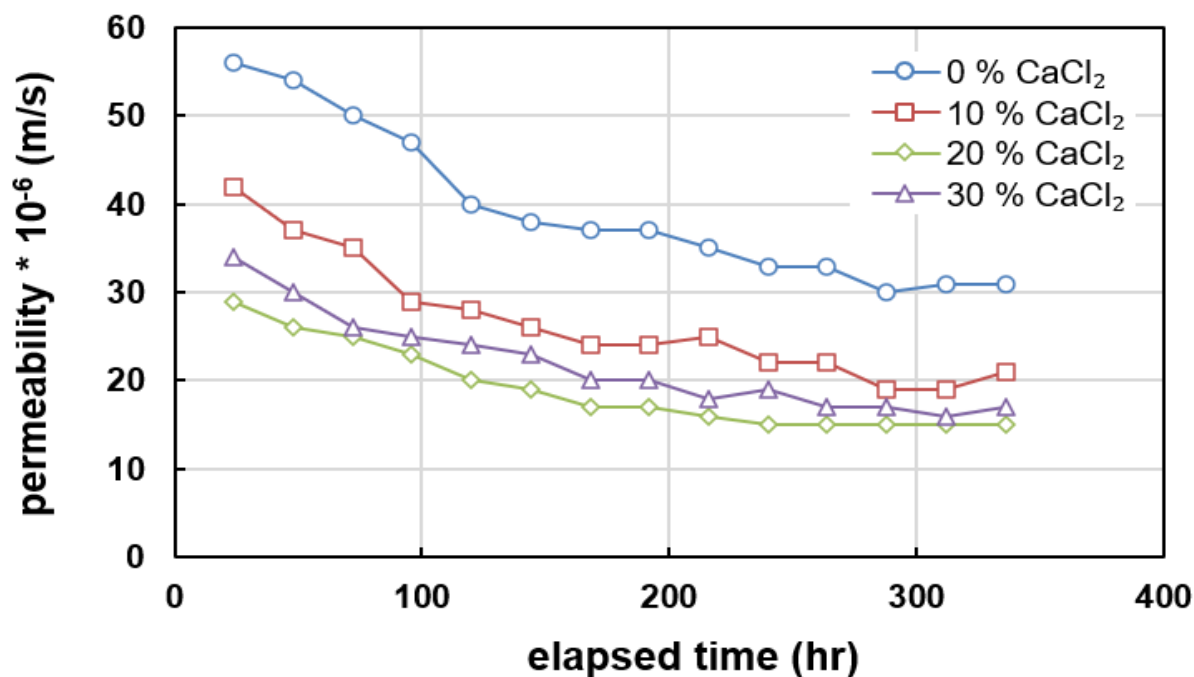
(a)

Fig. 5. (a) Compressibility and (b) Collapsibility of silty sand soil mixed with different CaCl_2 solutions



(b)

Fig. 5. (continued)

Fig. 6. Variation of permeability (k_h) with elapsed time (t)

The variation of permeability coefficient (k_h) with time (t) after curing period is illustrated in Fig. 6. It is normal to see that the permeability of the soil decreases with time. This can be attributed to recrystallization of the dissolved gypsum at particle edges, which partially closes pores and develops

inter-connections, making flow paths smaller. Also, gypsum cementation between particles gets stronger as time progresses, making soil denser and lowering its permeability. Once CaCl_2 was introduced, it caused flocculation of the silt grains associated with gypsum participation, and this

blocks the pores further and accelerates k_h reduction. This behavior was evident when the soil was stabilized with CaCl_2 up to 20%. At 20%, permeability showed minimum values overall and stabilized after 144 hours. The value of k_h decreased by about 45% after two weeks. Here, the dissolution-precipitation of gypsum reaches equilibrium, providing a relatively high-density and

stable structure. However, excessive concentration of CaCl_2 makes permeability rise again, which is because of extra dissolution and leaching out of the excessive salts, creating interconnected micro-pores in the fabric and re-opening the flow paths. Therefore, 20% CaCl_2 can be considered the optimum concentration for permeability improvement.

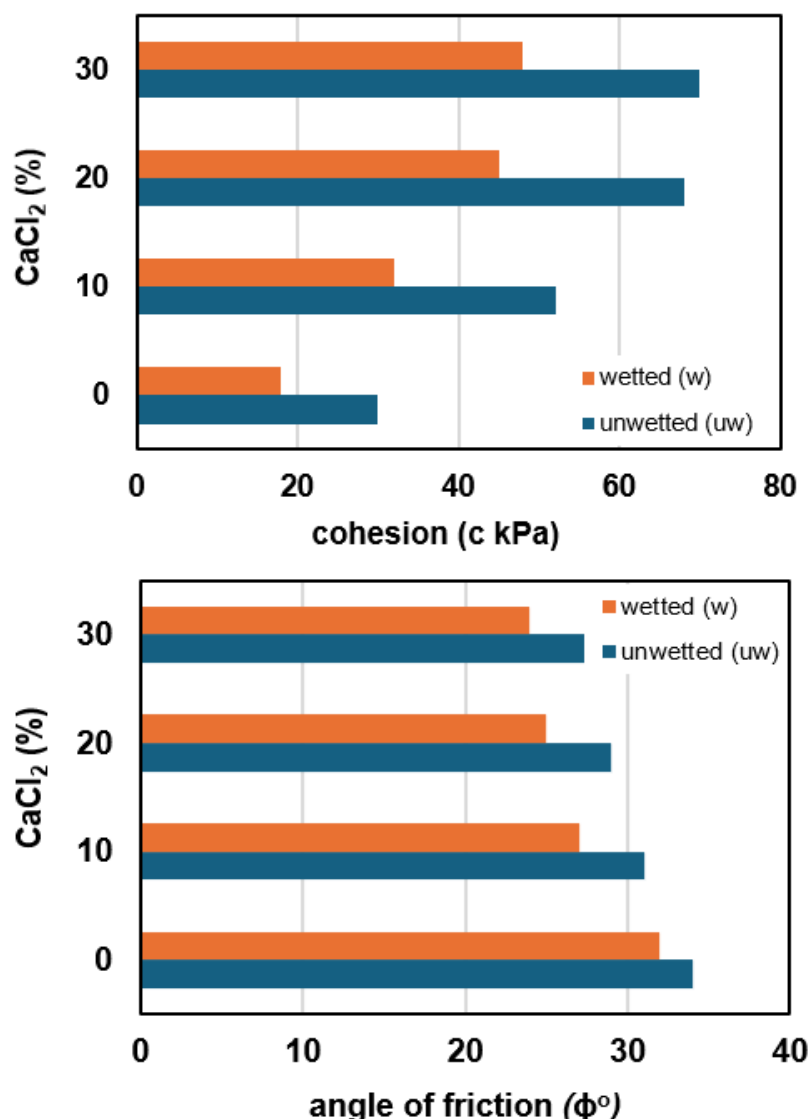


Fig. 7. Effect of CaCl_2 on shear strength parameters of gypsum-bearing silty sand soil

4.4. Shear strength

Fig. 7 presents the effect of CaCl_2 addition on cohesion (c) and angle of friction (ϕ), the shear strength parameters, under wetted (w) and unwetted (uw) conditions. The cohesion increased markedly for both conditions (c_w and c_{uw}) as the concentration of CaCl_2 increased. At 0% CaCl_2 , the

soil showed relatively low cohesion (c), indicating weak cementing bonds, and when CaCl_2 was increased, such cementation improved, increasing c . Moreover, the wetted samples display a lower c than unwetted samples, which is because, under wetting conditions, partial dissolution of gypsum occurs, leading to weakened bonds and loss of

particle contacts. On contrary, the addition of CaCl_2 results in a slight reduction in the angle of friction (ϕ) for both wetted and unwetted conditions (Fig. 7). The salt participation works on smoothing particle surfaces, reducing interlocking. Also, the lubricant effect of CaCl_2 keeps particles apart from each other, and so frictional resistance decreases. For shallow foundations at low-stress levels, there may still be gains in total shear strength, even though the low values of ϕ . The reduction in ϕ has an important implication for deep foundation infrastructures that are subjected to high confining

stresses (e.g., piles and drilled shafts). Their design is predominantly controlled by the frictional term of shear strength, which means that any decrease in ϕ , even if accompanied by an increase in c , can lead to a loss in shaft resistance, end-bearing capacity, and stiffness. Therefore, in the analysis of deep foundations in CaCl_2 -treated gypsum soils, suitable ϕ values should be considered derived from high-stress investigations, rather than depending on low-stress results that could overestimate the ϕ contribution.

4.5. Gypsum dissolution

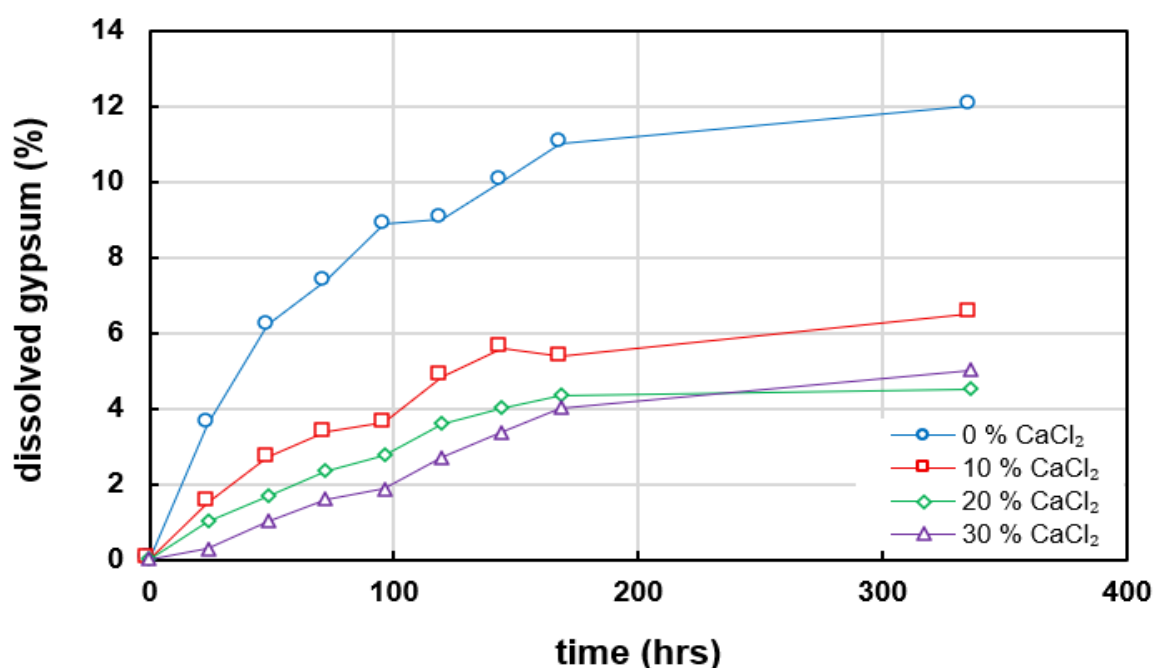


Fig. 8. Gypsum dissolution-time relationship

Fig. 8 demonstrates the gypsum dissolution rate (GD) over 2 weeks for gypsum-bearing silty sand with 0, 10, 20, and 30% CaCl_2 concentration. In all samples, the GD increased with leaching time, showing a nonlinear relationship, and the rate and extent of the increase depend mainly on CaCl_2 content. For the untreated sample, the GD rose rapidly in the initial stages of leaching, as there is no competing ion in solution and only pure water was present. Later, the increase went slowly due to the domination of the diffusion-limited stage. In the initial stages, when the pore water reaches gypsum particles, it results in a large ion gradient between the surrounding water and gypsum surfaces, which

leads to rapid dissolution. As dissolution continues, the dissolved calcium and sulfate ions increase in the gypsum-surrounded pore water, reducing the potential for more dissolution. Also, the transport of the dissolved ions in pores gets slower because of the restricted pore-network tortuosity. The gradual transition from a surface-ion-governed to a diffusion-limited stage leads to a slower dissolution rate over time. Adding CaCl_2 leads to a reduction in gypsum solubility, resulting in a relatively slow increase in the GD in nearly all leaching periods, particularly in the 20% and 30% concentrations. The GD can be estimated based on the maximum possible gypsum that can dissolve (GD_{Max}) and the

dissolution coefficient (k) using the form:

$$GD(t) = GD_{Max} \cdot (1 - e^{-kt}) \quad (4)$$

4.6. SEM Scan

Fig. 9 shows the results of scanning electron microscopy (SEM) of soil samples. The untreated sample microstructure illustrated loose particle arrangement with weak bonding and interconnected large voids induced by gypsum dissolution due to water flow. Adding 10% $CaCl_2$ solution led to partial pore filling and enhanced interparticle bonding as a result of reduced dissolution and salt precipitation. The treated

sample with 20% solution exhibited the densest microstructure with very low pore connectivity and strong particle cementation bridges, corresponding to the lowest permeability. However, when the $CaCl_2$ dosage approached 30%, further excessive gypsum accumulation and precipitation occurred, producing localized microcracks and secondary flow paths within the soil matrix. This behavior confirms the explanation of the increase in the permeability of the soil treated with 30% $CaCl_2$.

4.7. Quantitative analysis of the performance index

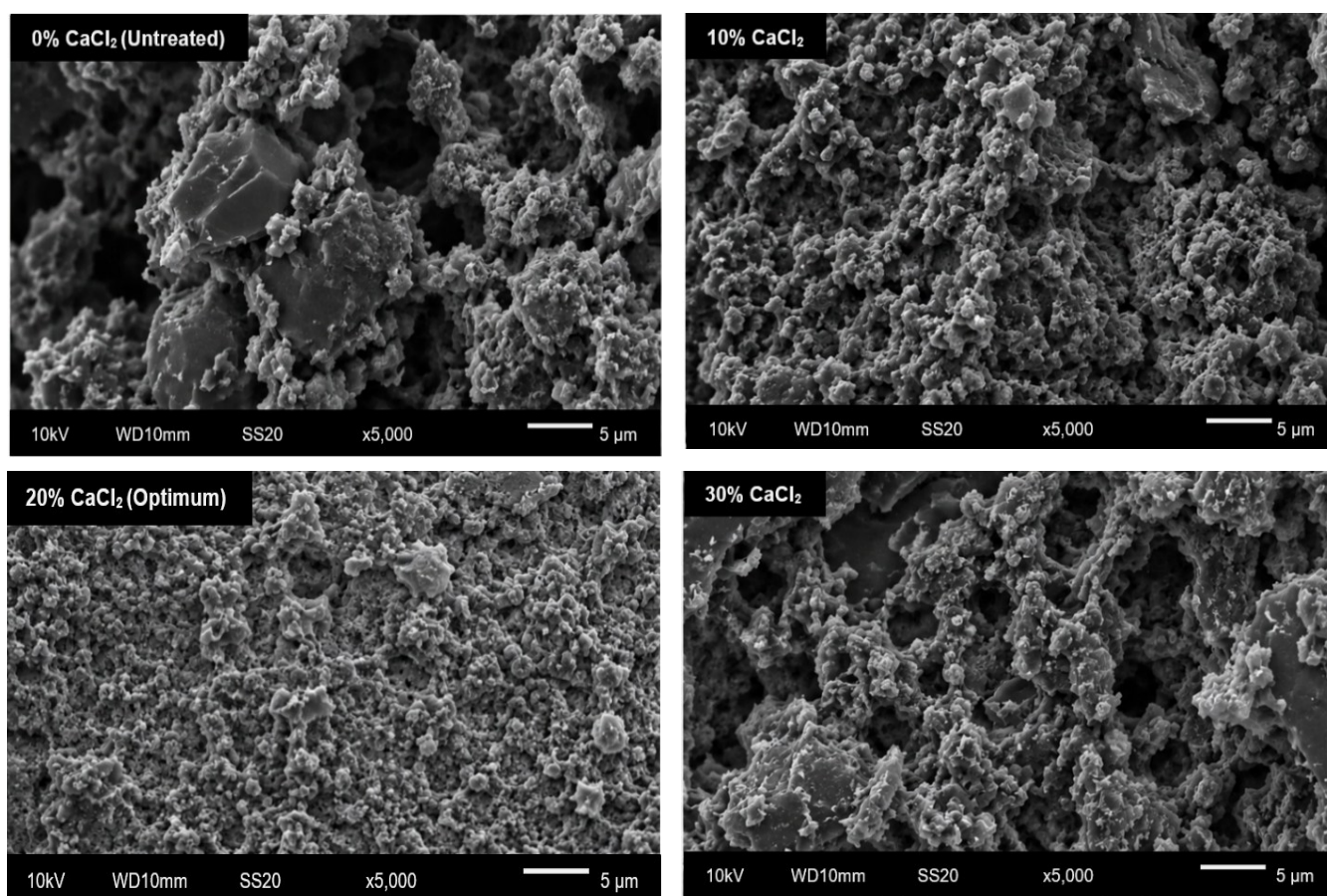


Fig. 9. Microstructure of the soil at different $CaCl_2$ concentrations using SEM test

In this section, a quantitative analysis was performed on the tested hydro-mechanical soil properties to obtain the overall performance index (PI). Table 2 summarizes the measured parameters of soil properties at different $CaCl_2$ concentrations. Each parameter was normalized to provide values between 0 and 1. The overall performance index (PI) was calculated from the

arithmetic mean (average) of the normalized parameters (presented in Table 3).

The results indicate that the use of a 20% $CaCl_2$ solution offers the highest overall performance index ($PI = 0.940$). While the 30% $CaCl_2$ concentration displays comparable performance (0.928), using an excessive amount of $CaCl_2$ raises concerns related to corrosion

susceptibility of metallic infrastructures [14], salt leaching, and long-term durability issues [15]. Therefore, the 20% concentration was considered

the favorable treatment level from both performance and practical implementation perspectives.

Table 2. The measured parameters of the soil samples at different CaCl_2 concentrations

CaCl_2 solution concentration (%)	Maximum dry unit weight ($\gamma_{d-\max}$ kN/m ³)	Compression index (Cc)	Collapse potential (CP %)	Permeability (k_h m/s)	Gypsum dissolution rate (GD %)	Unwetted cohesion (c_{uw} kPa)	Wetted cohesion (c_w kPa)	Unwetted angle of friction (ϕ_{uw} °)	Wetted angle of friction (ϕ_w °)
0	17.4	0.142	3.00	31×10^{-6}	12	30	18	34	32
10	18.4	0.124	1.34	21×10^{-6}	6.5	52	32	31	27
20	18.7	0.107	0.92	15×10^{-6}	4.5	68	45	29	25
30	18.9	0.102	0.90	17×10^{-6}	5.0	70	48	28	24

Table 3. Performance index (PI) based on the normalized parameters of the soil samples

CaCl_2 (%)	$\gamma_{d-\max}$	Cc	CP	k_h	GD	c_{uw}	c_w	ϕ_{uw}	ϕ_w	Performance index (PI)
0	0.921	0.718	0.300	0.484	0.375	0.429	0.375	1.000	1.000	0.622
10	0.974	0.824	0.668	0.714	0.692	0.743	0.667	0.912	0.844	0.782
20	0.989	0.945	0.978	1.000	1.000	0.971	0.938	0.853	0.781	0.940
30	1.000	1.000	1.000	0.882	0.900	1.000	1.000	0.824	0.750	0.928

5. Conclusion

Several stabilization techniques were used to minimize the detrimental effect of gypsum minerals in soils. Chemical stabilization using calcium chloride (CaCl_2) solution with varying concentrations (10, 20, and 30%) was used in this study to enhance the hydro-mechanical properties of gypsum-bearing silty sand soil. It was concluded that CaCl_2 effectively improved soil behavior after a 14-day curing period by increasing unit weight and apparent cohesion, and decreasing compressibility, permeability, and collapse potential. The improvement is essentially due to suppression of gypsum dissolution through physicochemical interactions at the sand particle surfaces by increasing Ca^{2+} ions in solution, which enhances interparticle cementation, turning the soil response from a friction-governed to a cementing-governed behavior. The results confirm that 20% CaCl_2 provided an optimum improvement level with the highest favorable performance index, beyond which further improvement benefits become

minimal. It is, therefore, recommended for the short- to medium-term to use a moderate CaCl_2 dosage for gypsum-bearing coarse soils for better results and effective stabilization. Further investigations on other soil types with different gypsum contents and long-term durability under wet-dry cycles, salt leaching behavior, chloride-corrosion risks, and field-scale performance are required before broad-scale implementations.

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Declaration of Generative AI

The authors declare that they do not use Generative AI and AI-assisted technology tools to generate the content of the manuscript.

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