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Research Article

Compressibility and strength enhancement of clayey soil using magnesium chloride solution

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Abstract

One of the most important problems of clayey soils are their susceptibility to compression when loads are applied due to weak bonds that allow water to enter and exit between soil particles. In this research, clay soil with a clay content of (72%) from Salah Al-Din governorate, Iraq was used. This soil was treated with magnesium chloride solutions at different concentration ratios (5, 10, and 15%). Compressibility and strength tests were performed on natural and treated soil, results showed that the compression decreased significantly with increasing magnesium chloride concentrations, the final strain after unloading was (1.8, 1.72, 1.0, and 0.95) % at concentrations of (0, 5, 10, and 15) % respectively. It is also noted a significant increase in the unconfined compression strength with enhancing ratio of (21, 27, 38) % at enhancing ratios of (5, 10, 15) % respectively. For direct shear test, cohesion of soil increased by (66, 94, 97) %, while the increase in value of soil's friction angle was (13, 5, 7) % at a solution content of (5, 10, 15) %. The results shows that the enhancement in soil strength is small and almost constant when the magnesium chloride content increases by more than 10% due to soil saturation.

1. Introduction

Soil stabilization is the process employed to improve soil characteristics such as compressibility and shear strength. When the soil has a variety of engineering characteristics that are usually unfavorable makes it unsuitable for carrying structural loads, soil improvement is needed [1]. Most of the design practices in geotechnical engineering are based on settlement and strength criteria when the allowable bearing capacity is based on the minimum value of settlement or soil strength [2]. The total settlement distribution is based on characteristics of soil, clayey soil mostly exhibited greater settlement than sandy soil [3]. Therefore, it requires more attention in its improvement than granular soils.

Chemical stabilization which entails adding chemical materials such as lime, cement and chemical solution to improve clayey soils is widely used for many researchers. Physical and mechanical properties of clayey soil improved significantly by adding chemical stabilizers, which devolve the ability of using the chemical technique in soil stabilization to solve many geotechnical problems [4]. Deep soil mixing (DSM) is also one of the practical and effective methods for soil improvement that increases strength of soil and decreases its compressibility [5]. Depending on the amounts of chemical additives and the time interval of the test, physical and mechanical properties of the treated clayey soil could be considerably improved [6]. Major conclusions from experimental investigations on the effects of adding lime and cement on properties of expansive clay including Atterberg limits, swell, and linear shrinkage were presented by [7]. Hasan et al. also concluded that lime- silica fume additives improve both shear strength and unconfined compressive strength of soft clay soil [8]. Sodium silicate and Portland cement mostly act as active stabilizers because of their ability to alter

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soil properties, such as strength [9]. Class F fly ash can effectively stabilize the clay soil characteristics throughout improving plasticity and compaction behavior, unconfined compressive strength as well as shear strength [10]. Zhang et al. investigated the effect of presence of calcium chloride on the intermittent current efficiency for the dewatering and consolidation of silty clay. Solution of calcium chloride at 15% were used during electric treatment process with 0, 1, 2, 4, 8 h intervals time. Comparison between conventional electro osmosis and intermittent current were made. The results showed that calcium chloride enhance soil properties, it increased shear strength of soil as well as reduced the corrosion of anode. Power consumption caused by $CaCl_2$ injection gave more economically process throughout practical projects [11]. Effect of chloride salts on properties of expansive soil also investigated by El Kady et al., it is concluded that index properties and swelling behavior of soil was improved with increasing chloride salt [12].

Currently, magnesium chloride ($MgCl_2$) is mainly used in soil improvement; however, it has been effectively used for improving clayey soils. Previous studies in literature indicated that $MgCl_2$ is effectively used in improvement of soil as an antifreeze agent more than used in stabilization. $MgCl_2$ is also used in controlling humidity and dust as well as reducing the distraction that take place in coarse particles from surfaces of roads. Manikantha et al. stated the effectiveness of chemical stabilization using sodium hydroxide (NaOH) and magnesium chloride ($MgCl_2$) as soil stabilizers for improving soils characteristics. Unconfined compression was performed on black cotton soil treated with different concentrations of these chemical agents. 1.5% of NaOH and $MgCl_2$ with different molarities (2, 4, 6, 8, and 10) M was used to evaluate the improvement in mechanical strength and overall geotechnical behavior of the soil. Results indicate that increasing the salt concentration enhances the unconfined compressive strength (UCS) with significant improvement in soil stability. This shows the possibility of using chemical stabilization as a useful technique for improving expansive soils for engineering applications [13]. Habibbeyg and Nikraz investigate the effect of green stabilizer by the magnesium chloride ($MgCl_2$) on the geotechnical behavior of the treated clay soil by conducting several laboratory tests including the consistency limits, free swell strain as well as swell pressure of the treated samples. The results state that even a small percentage of $MgCl_2$ was used, it can stabilize expansive clay by improving the soil properties considerably and mitigate their swell potential effectively [14]. The results obtained by Teker et al. showed that the undrained shear strength of the kaolin clay increased as the percentages of $MgCl_2$ and MgO rose [15]. As well as Latifi et al. indicated that the strength of $MgCl_2$-stabilized peat improved significantly when the degree of improvement reaches approximately six times than that for untreated peat [16]. Also, Sharma et al. concluded that most geotechnical properties of black cotton soil are enhanced at 8% $MgCl_2$ [17]. Sadiq et al. concluded that the compressibility and strength properties of clay soil improved greatly by using nano-magnesium oxides due to the ability of nano-magnesium to reduce pore size [18].

Rikhtehgar and Teymur using ($MgCl_2$) to improve the freeze-thaw properties of clay soils. The results showed that $MgCl_2$ reduces the consistency limits of soil as well as enhance durability and compressive strength. Using 14% of $MgCl_2$ solution keep volume of soil its strength under a temperature of $-20\,^{\circ}$C, similar enhancing behavior was found for soil at $-10\,^{\circ}$C temperature treated by 14% and 9% $MgCl_2$ solutions. Soil stability by $MgCl_2$ during initial stabilization was improved under the effect of freeze-thaw cycles, giving an effective solution for improving construction under cold conditions [19]. Tang et al. studied the effect of solution of $MgCl_2$ on the process of electrokinetic stabilization. Soil of marine clay from Zhuhai, China is subjected to six electrokinetic experiments. Results showed using 0.8% $MgCl_2$ solution with 20% concentration represent the effective percentage for the electrokinetic stabilization, greater concentration of $MgCl_2$ solution reduced the anode corrosion amount [20].

The effect of ($MgCl_2$) solution on the different engineering properties of clay soils was investigated by Turkoz et al. Swell pressure, percentage of swell, pinhole and crumb as well as shear strength by triaxial tests was studied at different curing intervals. Analysis by scanning electron microscopy (SEM) also used to observe the difference in sample microstructures. The results show that using solution of $MgCl_2$ effectively improved dispersive and expansive clay soils [21]. Hassan et al. stabilize organic soil with magnesium chloride ($MgCl_2$) to study its effect on strength properties and micro structural behavior of soil. Field-emission scanning electron microscopy (FESEM) as well as energy-dispersive X-ray spectrometry (EDAX) methods was used to observe changes in micro structural whereas unconfined compression tests were performed to evaluate properties of shear strength. Results pointed that the unconfined compressive strength of organic soil improved by using $MgCl_2$ when the strength of soil is enhanced by about (3–5) times compared with that of unimproved soil at the first 7 days of curing. FESEM results gave a clear improvement of organic soil properties throughout enhance the soil porosity which filled by a cementation component material defined as magnesium silicate hydrate (M-S-H) [22].

Jahidin et al. studied the geotechnical properties of marine clay treated with $MgCl_2$. Results indicated that the unconfined compressive strength increased with an addition of 6% $MgCl_2$ until the curing time of seven day and after that the value of strength begin to decrease. The increase in strength was attributed to the cementation products formation that led to enhance bonding between soil particles and also filling the spaces between particles of soils together with $MgCl_2$. Increase applied surcharge cause soil particles to begin repel and consequently causing of soil strength reducing [23]. Kumar and Ganesh concluded that the chemical additives such as cement, $MgCl_2$ and fly ash based geopolymer showed a clear influence on the compaction, penetration and strength characteristics of expansive soil [24]. It is shown by Türköz et al. that the problematic clay soils can be sufficiently stabilized by using magnesium chloride solution, the effective percent of admixtures is 7 percent [25]. Mahdavian et al. examined the magnesium chloride solution effects of on clay soil properties. Different percentages of ($MgCl_2$) were used which are 3%, 5%, 7% and 10%. The experimental program included consistency limits, compaction characteristics, swelling behavior, unconfined compression test and scanning electron microscopy (SEM) tests. Results indicated that there is a clear reduction in swelling percentage compared to untreated soil with a percentage ratio of 4.95%, 3.98%, 2.8%, and 3.9% for samples treated with 3%, 5%, 7%, and 10% $MgCl_2$ respectively. Additionally, the improvement in the soil properties as conducted by SEM results was attributed to chemical reactions between the soil particles and $MgCl_2$ solution [26].

Although previous studies generally agree that magnesium chloride ($MgCl_2$) can improve the engineering behavior of clay soils, the reported optimum dosage and the dominant improvement mechanisms vary considerably. Some researchers reported maximum strength enhancement at relatively low $MgCl_2$ contents (about 6–8%), whereas others suggested that higher concentrations may be required depending on soil mineralogy and testing conditions. Likewise, while several studies attributed the improvement primarily to cementation and pore-filling mechanisms, others emphasized modifications in particle arrangement and reduction of diffuse double-layer thickness as the governing factors. These variations indicate that the effectiveness of $MgCl_2$ treatment is strongly dependent on soil type and environmental conditions. Furthermore, most previous investigations focused on consistency limits, swelling characteristics, or unconfined compressive strength, whereas comparatively less attention has been given to the combined evaluation of compressibility behavior and shear strength parameters of naturally occurring clay soils from Iraq. Therefore, additional studies are required to better understand the influence of $MgCl_2$ stabilization on both deformation and strength characteristics under different loading conditions. Therefore, this study aims to address this gap by providing a comprehensive assessment of the influence of different $MgCl_2$ concentrations on the geotechnical behavior of the investigated low plasticity clay soil (CL) obtained from Salah Al-Din Governorate, Iraq and determining the optimum treatment level for engineering applications.

2. Materials

2.1. Soil Properties

Soil samples were obtained from a site in Salah Al-Din governorate, Iraq from a depth of 1.0 m. The natural soil used in this study is characterized by a light brown color, a smooth texture, and a naturally aggregated (cloddy) structure, Fig.1 shows the location of the studied site. Standard Proctor tests were conducted to determine the compaction characteristics as shown in Fig. 2.

Physical properties of soil are found according to [27-30] and shown in Table 1. The relatively high maximum dry unit weight (18.68 kN/m^3) observed for the tested CL soil may be attributed to its mineralogical and chemical composition. In particular, the presence of iron oxide (Fe_2O_3) at a concentration of 4.81% contributes to an increase in the specific gravity of the soil solids. chemical composition is shown in Table 2, this composition was conducted in chemical laboratory at university of Technology in Baghdad by XRD method. The soil samples were prepared and compacted at the maximum dry unit weight and the optimum moisture content containing 0%, 5%, 10%, and 15% by weight of magnesium chloride solution in a special mold (same specifications as the standard Proctor mold) and then saturated with same water containing the specified concentrations.

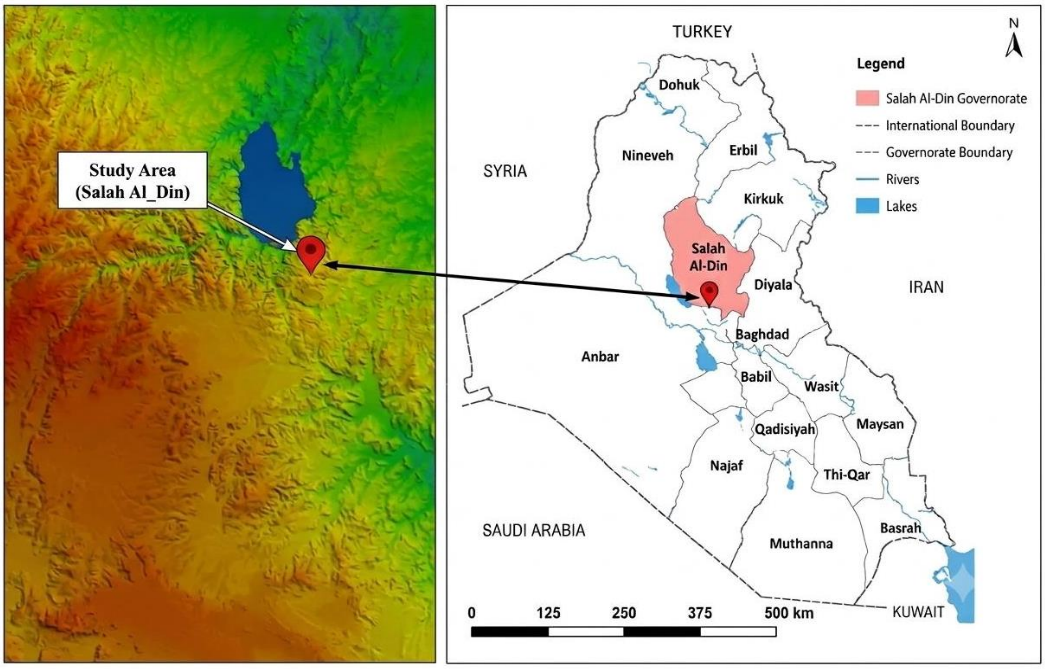


Fig. 1. Location of the study area in Salah Al- Din governorate, Iraq

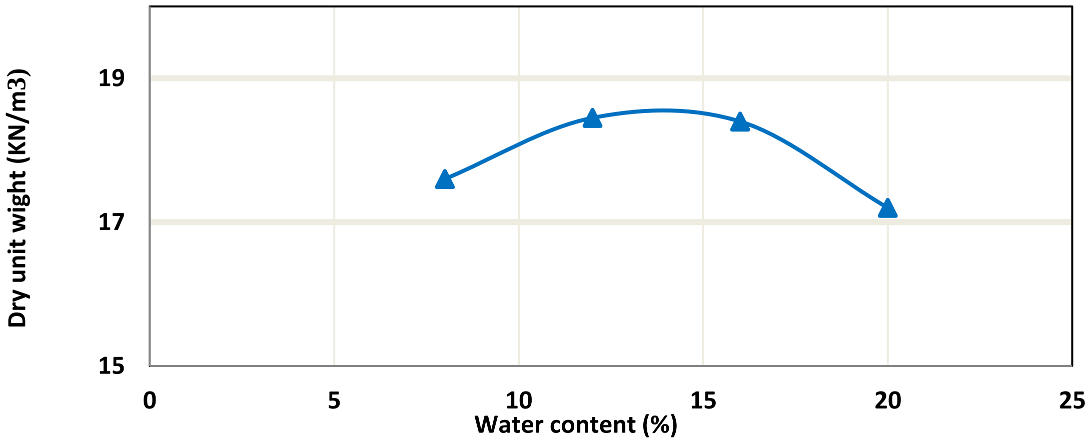


Fig. 2. Relation between dry unit weight and water content in compaction test for the used soil

The saturation process was carried out by gradually introducing the magnesium chloride solution at the top of the compacted specimen in mold while maintaining free drainage at the bottom. Saturation was considered complete when the solution began to emerge from the bottom of the specimen, indicating that the solution had permeated the entire soil sample. Due to the low permeability of the clay soil (containing 72% clay), the saturation process required approximately twenty days to ensure full penetration of the solution throughout the specimen. After the completion of saturation, the specimens were carefully extracted from the molds using a sample extraction jack and cut to prepare according to the requirements of the designated laboratory tests, including the consolidation test (ASTM D2435/D2435M-20), unconfined compression test (ASTM D2166/D2166M-16(2021)), and direct shear test (ASTM D3080/D3080M-23).

Sample preparation stages are shown in Fig. 3. During the specimen saturation period, no significant volume change or swelling was observed because the specimen is confined from top and bottom as shown in Fig 3 (c). Therefore, volumetric changes were not considered to affect the testing program or the interpretation of the results.

Table 1. Physical properties of clay soil

Properties of soil	Values	Specification
Specific Gravity (Gs)	2.885	ASTM D854-23
Liquid Limit (LL) %	48.52	ASTM D4318-17
Plastic Limit (PL) %	23.61	
Plasticity Index (PI)	24.91	
Soil classification according to USCS	CL	
Maximum dry unit weight (KN/m^3)	18.68	ASTM D698-12 (2021)
Optimum moisture content (%)	14.37	
Sand (%)	7	
Silt (%)	21	ASTM D7928-21
Clay (%)	72	

Table 2. Chemical composition of clay soil

Chemical composition	Values
SiO_2	49.32
Al_2O_3	25.67
Fe_2O_3	4.81
K_2O	5.73
MgO	1.98
TiO_2	2.06
SO_3	2.64
CaO	3.41
Na_2O	4.12
losses	0.26

(a) (b) (c)

Fig. 3. Samples preparation stages (a) Compaction stage, (b) Saturation stage, and (c) Extraction stage

2.2. Magnesium Chloride ($MgCl_2$)

Magnesium chloride in the form of pure white powder that manufactured in Chemical Reagent Co., Ltd. in China with a purity of 99% was used in this study as a solution form after dissolved in distilled water. The magnesium chloride hexahydrate ($MgCl_2.6H_2O$) solution was prepared by dissolving a specified weight of magnesium chloride in distilled water according to the concentrations specified in the research.

3. Results and Discussion

After preparing the magnesium chloride solution and preparing the test specimens with maximum density and optimal moisture, the specimen was saturated with magnesium chloride solution at concentrations of (5, 10, 15) %. After removing the specimen from the mold, the specimen was cut to perform strength tests on the specimens before and after adding the magnesium chloride solution. The results were as follows:

3.1. Compressibility Test

By conducting a compressibility test on the samples before and after adding the concentrations of magnesium chloride solution, the results indicate a clear decrease in compressibility with increasing magnesium chloride concentration. Using magnesium chloride ($MgCl_2$) solutions can reduce the compressibility of clay soil by increasing its strength and density through chemical and physical changes. The stabilization mechanisms are based on ion exchange and flocculation, where magnesium (Mg^{+2}) bonds replace other cations (ion exchange) on the clay surface, altering the soil structure. This leads to flocculation, where clay particles clump together, forming a more stable and less compressible structure. The addition of $MgCl_2$ introduced Mg^{2+} ions into the pore fluid, which significantly reduced the thickness of the diffuse double layer surrounding clay particles. Due to their divalent charge, Mg^{2+} ions were more effective than monovalent cations in neutralizing the negative surface charges of clay minerals and compressing the diffuse ion cloud. This compression decreased the repulsive forces between adjacent clay particles and promoted particle flocculation and aggregation.

The percent of decrease in final strain compared to final strain of untreated soil (1.8%) was (4, 44, 47) % at $MgCl_2$ concentrations of (5, 10, 15) %. At concentrations of 10% and 15%, the results are approximately similar which indicate that a concentration of 10% is optimal in improving the compressibility properties of the clay soil and that increasing the concentration gave small different in results (Fig. 4). During the unloading phase, it is noted a clear decrease in the value of the change in final height after treatment (Fig. 5).

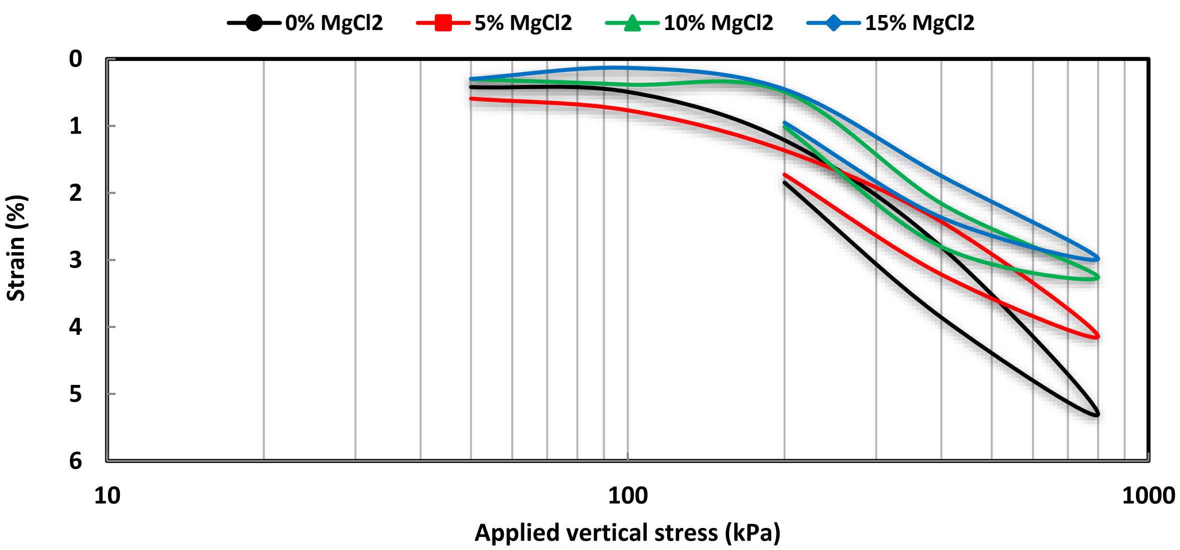


Fig. 4. Results of consolidation test for untreated an treated soil with different different of $MgCl_2$ concentrations

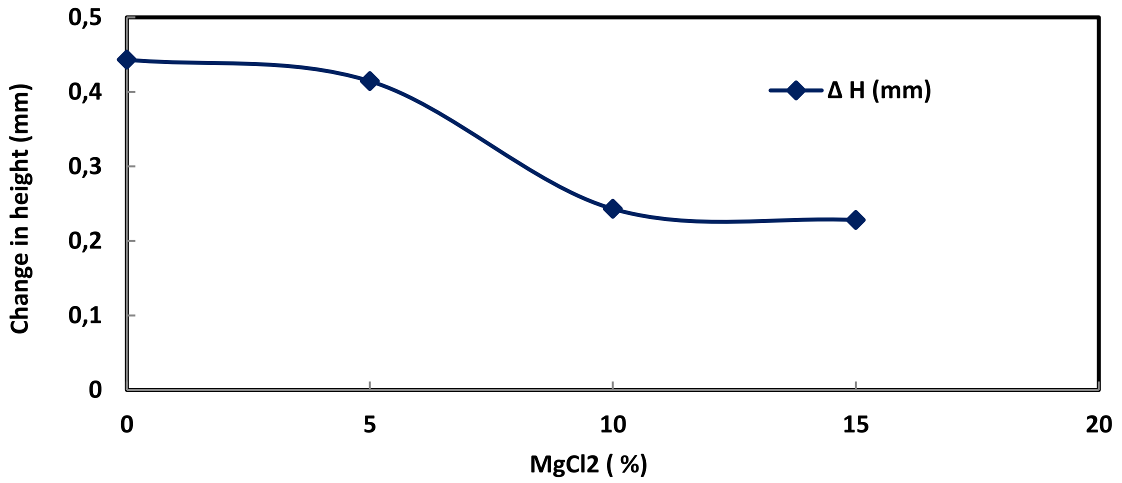


Fig. 5. The relationship between magnesium chloride concentration and final change of sample height

3.2. Unconfined Compression Test

Results of the unconfined compression test indicate an increase in the strength of the samples with increasing magnesium chloride concentration as shown in Fig. 6. The variation of unconfined compressive strength values with $MgCl_2$ concentration is shown in Fig. 7 The increase in UCS was (21, 27, 38) % at concentrations of (5, 10, 15) % respectively. Magnesium chloride ($MgCl_2$) can react with other soil components to form new crystalline cementations compounds such as magnesium silicate hydroxide (M-S-H), filling pores and binding particles which lead to increase soil strength and enhanced its properties.

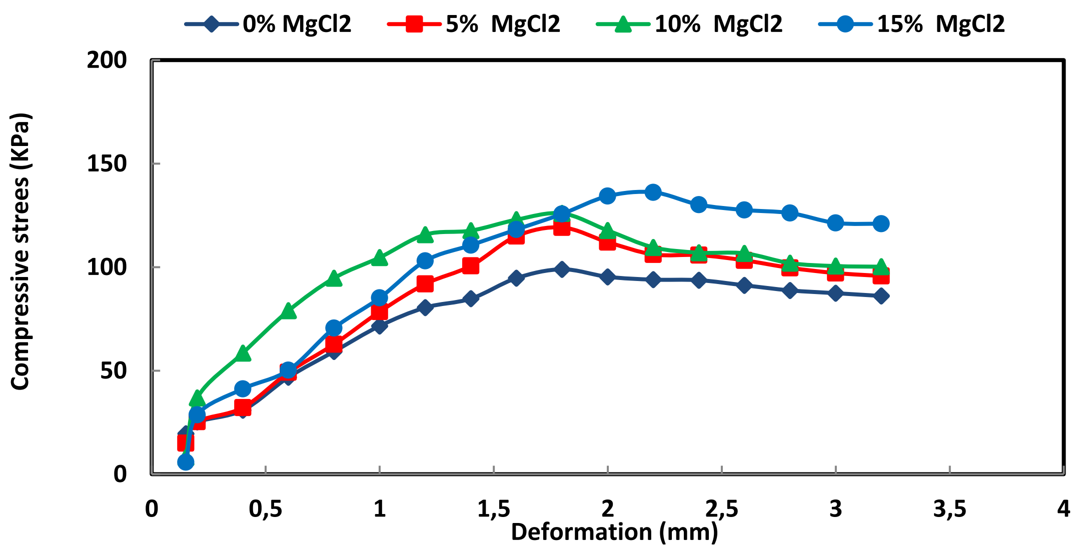


Fig. 6. The relationship between compression stress and deformation at different magnesium chloride concentration

Figure 8 noting the change in the shape of the failure, the sample failure shape before the addition of magnesium chloride solution was in the form of cracks at an angle of approximately 45 degrees at the edge of the sample (Fig. 8a), while the shape of the failure after the addition of magnesium chloride concentrations was in the form of cracks along the length of the sample (Fig. 8b- 8d). The failure mechanism of the untreated soil differed significantly from that of the $MgCl_2$-treated specimens. The untreated clay exhibited an inclined shear failure surface at approximately 45°, which is characteristic of ductile behavior in cohesive soils. In this condition, the soil particles are primarily held together by weak physico-chemical forces and interparticle friction, allowing considerable plastic deformation before failure. Consequently, the applied compressive stress is dissipated through the development of shear planes within the soil mass.

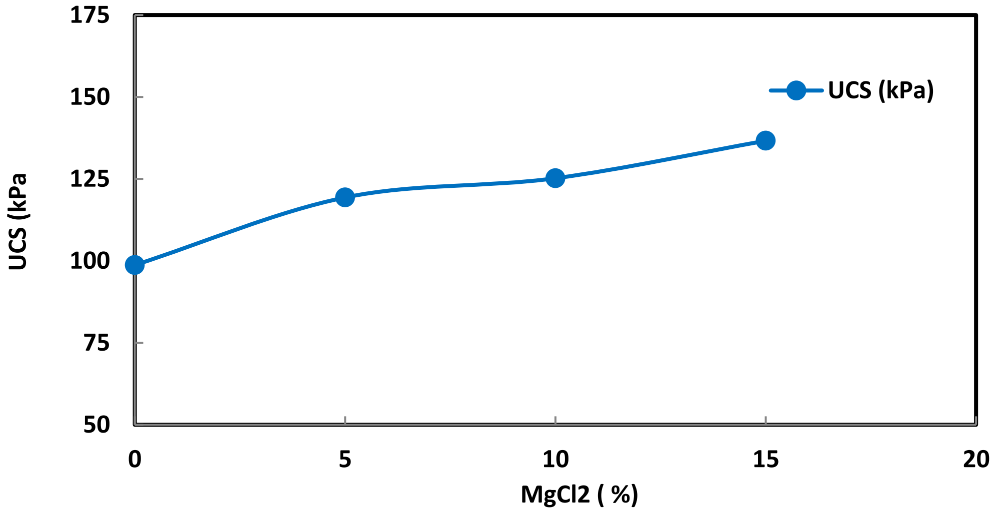
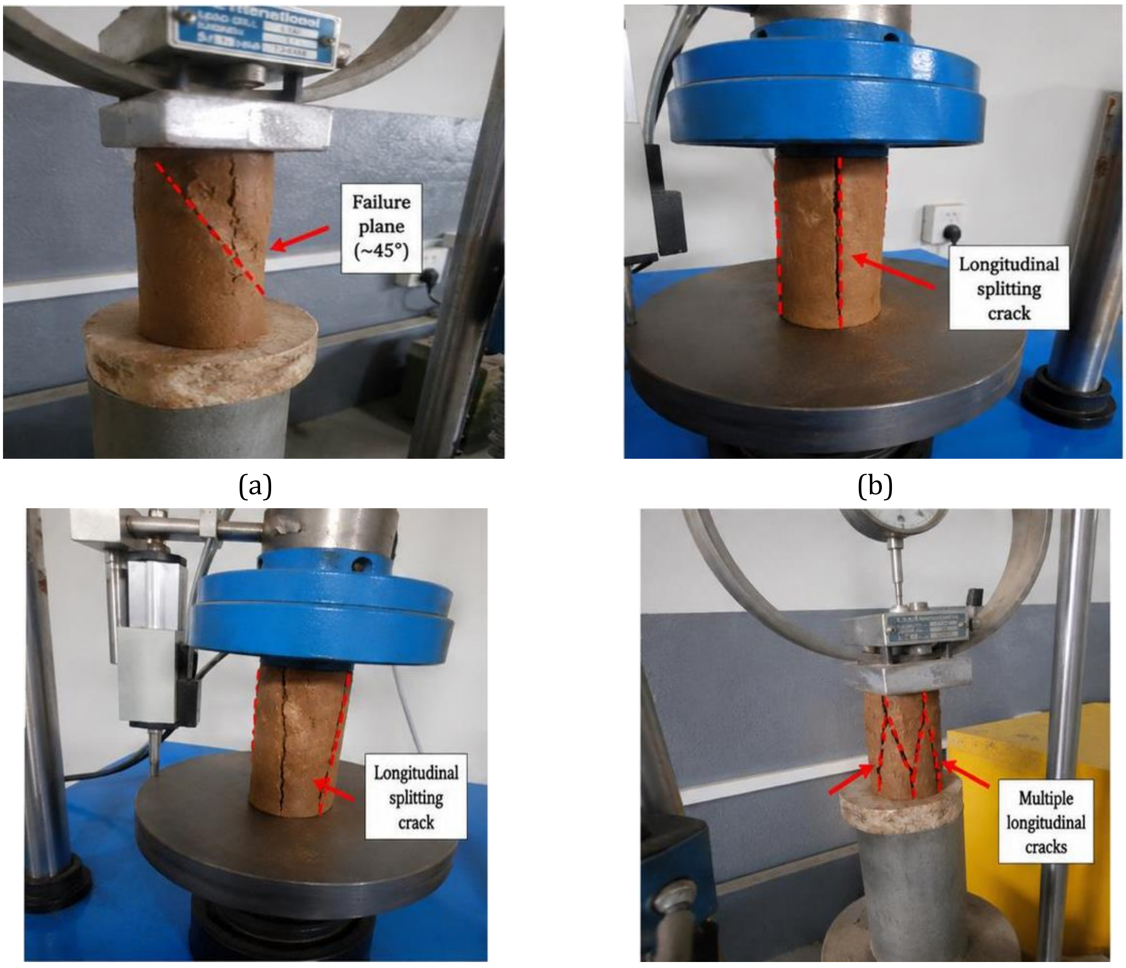


Fig. 7. The relationship between magnesium chloride concentration and unconfined compressive strength values



(a) (b) (c) (d)

Fig. 8. The form of failure in unconfined compressive test (a) Before treatment, (b) Soil treatment with 5% $MgCl_2$, (c) Soil treatment with 10% $MgCl_2$, and (d) Soil treatment with 15% $MgCl_2$

In contrast, the $MgCl_2$-treated specimens exhibited predominantly longitudinal splitting failure, indicating a transition from ductile to brittle behavior. This mechanical transformation can be attributed to the interaction of Mg^{2+} ions with the clay mineral surfaces, which reduced the thickness of the diffuse double layer and promoted stronger interparticle bonding. The resulting denser and more cemented soil structure increased stiffness and compressive strength while reducing the capacity for plastic deformation. Under axial loading, the strong cementations bonds restricted shear deformation; therefore, when the applied stress exceeded the tensile resistance of the bonded structure, cracks propagated rapidly along the specimen axis, leading to longitudinal splitting failure.

3.3. Shear Strength Parameters

The results of the direct shear test show a clear increase in the value of the shear strength in the soil. An increase of 66%, 94%, and 98% in cohesion was observed at magnesium chloride concentrations of 5%, 10%, and 15%, respectively, noting that at a concentration of 15% the increase was very small compared with that at 10%. The angle of internal friction of the soil was approximately not affected and its value was decreased at 10% and 15% $MgCL_2$ concentration (Figs. 9 and 10), this can be attributed to the lubricating effect due to the excess salt content which reduce the friction characteristics between soil particles.

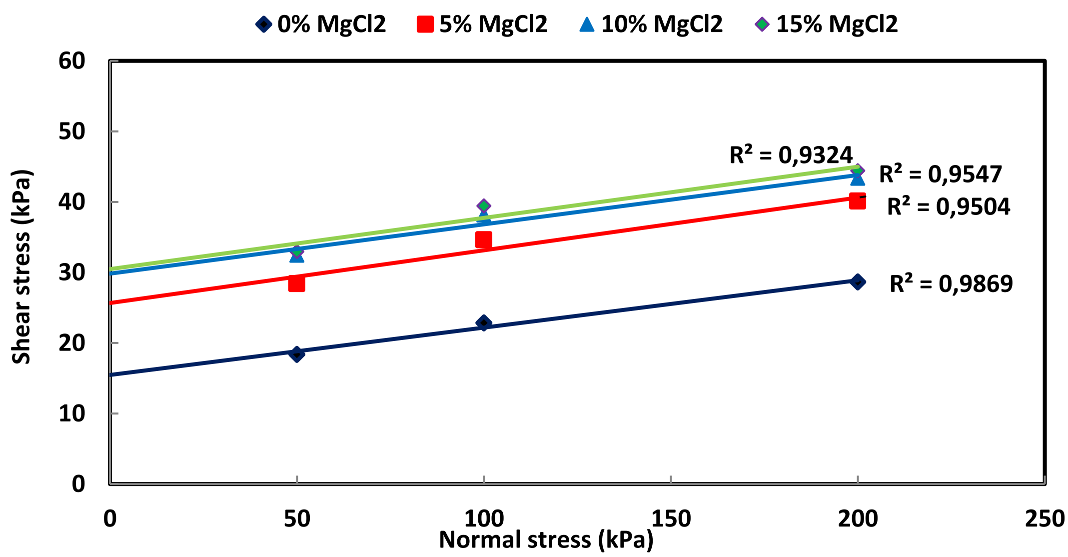


Fig. 9. Direct shear test results for untreated and treated soil with different percentages of magnesium chloride solution

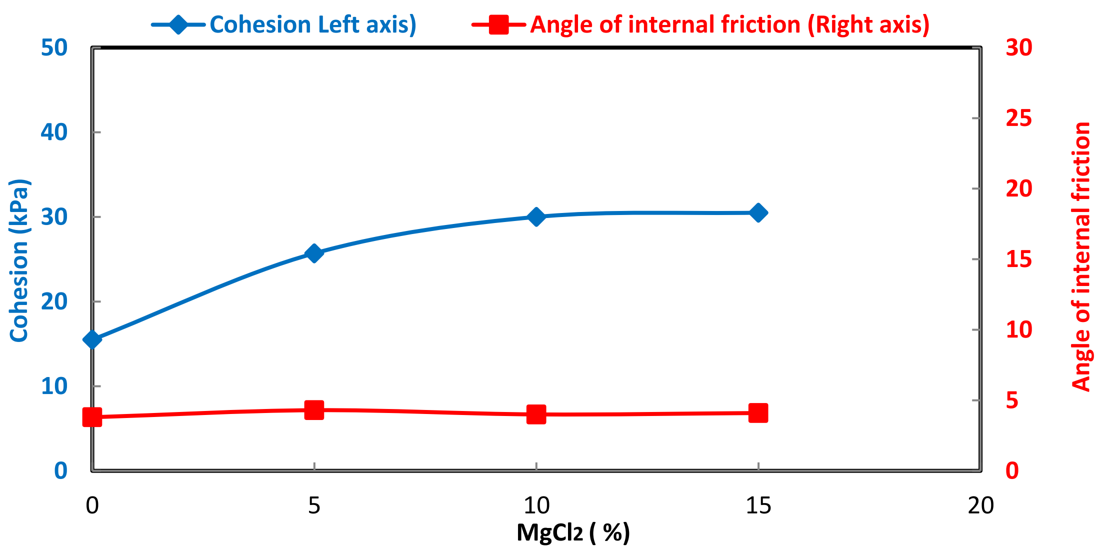


Fig. 10. Variation of cohesion and angle of internal friction under different condition of treatment with magnesium chloride solution

Table 3 shows the summary of the enhancement ratios for soil properties included compression, unconfined compression strength, and shear strength parameters with different magnesium chloride concentration.

Table 3. Variation of soil properties with magnesium chloride concentration

$MgCl_2$ (%)	Final strain (%)	Enhancing (%)	UCS (kPa)	Enhancing (%)	c (kPa)	Enhancing (%)	Ø (o)	Enhancing (%)
0	1.8	0	98.73	0	15.5		3.8	0
5	1.72	4	119.35	21	25.7	66	4.3	13
10	1.0	44	125.21	27	30.0	94	4.0	5
15	0.95	47	136.65	38	30.5	97	4.1	8

4. Conclusions

- Magnesium chloride treatment proved to be an effective stabilization technique for the tested low plasticity clay soil, resulting in noticeable improvements in both strength and compressibility characteristics. The observed improvements are attributed to ion exchange, flocculation, and the formation of cementations compounds that enhanced particle bonding and reduced pore spaces within the soil structure.
- The findings indicate that the effectiveness of magnesium chloride treatment is strongly dependent on the interaction of Mg^{2+} ions with the major mineral constituents identified in the soil, particularly silica (SiO_2) and alumina (Al_2O_3). The interaction between magnesium chloride and the soil constituents plays a key role in determining the extent of improvement achieved.
- The compressibility of the soil decreased significantly with increasing $MgCl_2$ content. The improvement was particularly pronounced up to a concentration of 10%, indicating a substantial reduction in settlement potential and an increase in soil stiffness. Increasing the concentration beyond 10% provided only marginal additional benefits.
- The unconfined compressive strength increased with $MgCl_2$ addition, reflecting the enhanced interparticle bonding within the stabilized soil matrix. Furthermore, the mode of failure changed from an inclined shear-type failure in untreated specimens to predominantly longitudinal splitting in treated specimens, indicating a modification in soil behavior after stabilization.
- Magnesium chloride treatment contributed to a considerable increase in soil cohesion, while the internal friction angle exhibited only minor changes. This suggests that the improvement in shear strength was mainly associated with enhanced cohesion rather than frictional resistance.
- Among the investigated concentrations, 10% $MgCl_2$ provided the most balanced and efficient improvement in soil performance. Although a concentration of 15% produced slightly higher strength values, the additional improvement was relatively small compared with the increase in chemical content, making 10% the optimum treatment level for the tested soil.
- The findings indicate that $MgCl_2$ stabilization may be considered a practical alternative for improving clayey soils encountered in Salah Al-Din Governorate and similar regions with comparable mineralogical compositions $MgCl_2$ treatment is benefit for soils used in road subgrades, embankments, and shallow foundation applications where excessive settlement and insufficient strength are major concerns.
- Result of this study are based on laboratory testing of a single clay soil type. Field performance may be affected by environmental conditions, groundwater chemistry. Therefore, further field-scale investigations are recommended to evaluate the long-term effectiveness, environmental impact, and cost-benefit performance of $MgCl_2$ stabilization under actual service conditions
- Future research should focus on evaluating the long-term durability and performance of $MgCl_2$-stabilized clay soils under various environmental conditions, including repeated

wetting–drying and freeze–thaw cycles. In addition, further investigations are recommended to assess the microstructural and mineralogical changes induced by $MgCl_2$ treatment using advanced techniques such as SEM, XRD, EDAX, and EDS analyses. Also, the effect of $MgCl_2$ on other soil properties such as cation exchange capacity, hydraulic conductivity, long term leaching is recommended.

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