Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Critical Gypsum Content in Leaching of Gypseous Soil

Qutayba Al-Saffar
University of Mosul
Mohammed Jaro
University of Mosul
Muwafaq Awad
mfqawad2015@uomosul.edu.iq
University of Mosul
Zeena AlKazzaz
University of Mosul
Abdulnasser Ali
University of Mosul

Research Article

Keywords: gypseous soils, leaching, critical gypsum content, shear strength, compressibility, permeability

Posted Date: September 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10812140/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Critical Gypsum Content in Leaching of Gypseous Soil

Qutayba Al-Saffar[1], Mohammed Jaro[2], Muwafaq Awad[3*], Zeena AlKazzaz[4], Abdulnasser Ali[5]

[1]PhD; Assistant Professor, Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq: dr.qutayba@uomosul.edu.iq, ORCID: 0000-0003-1584-0101

[2]PhD; Assistant Professor; Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq: m.jaro@uomosul.edu.iq

[3]PhD; Assistant Professor; Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq: mfqawad2015@uomosul.edu.iq

[4]Lecturer; Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq:zeena.kazzaz@uomosul.edu.iq; ORCID: 0000-0001-9359-4722

[5] Assistant Lecturer; Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq: abdulnasser.alshuwaykhi@uomosul.edu.iq

[*]Corresponding Author

Corresponding Author:
Email: mfqawad2015@uomosul.edu.iq

Abstract

Gypseous soils cover portions of the arid and semi-arid regions known with their satisfactory engineering behavior at dry-state; however, they are susceptible to progressive deterioration upon water exposure, due to the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$). While the consequences of gypsum dissolution - strength loss, increased compressibility, and elevated permeability are well documented in the literature, no prior study have quantified the minimum residual gypsum that persists indefinitely regardless of leaching duration. This investigation introduces the concept of the Critical Gypsum Content (CGC), a residual threshold beyond which no further gypsum dissolution occurs during leaching. Laboratory leaching tests were conducted on four natural gypseous soils designated as (S1- S4) with initial gypsum contents of 14–31% collected as undisturbed soil samples from different regions located at south and south-west of Mosul city-Nineveh-Iraq. Total Soluble Salts (T.S.S.) were monitored at three-day intervals until stabilization, after which direct shear, consolidation, and permeability tests were performed on pre- and post-leaching soil samples. Results demonstrate that gypsum dissolution was rapid during the first 15–18 days and decreased as the CGC was approached, with CGC values ranging from 5.2% to 11.1% and attainment times between 27 and 66 days. Reaching the CGC caused substantial reductions in cohesion (54.8–68.8%), confirming that gypsum cementation is the primary source of soil cohesion, while the internal friction angle decreased only slightly (12.1–14.8%). Leaching significantly increased soil compressibility, with the compression index rising by 2.4–3.5 times, and increased permeability by 5.6–35 times, depending on gypsum content. Higher-plasticity soils exhibited greater resistance to dissolution and permeability growth, indicating a protective role of clay minerals. The results further revealed a positive feedback mechanism between gypsum dissolution and permeability, which accelerates soil deterioration and contributes to the progressive failure of gypseous soil subgrades.

Keywords: *gypseous soils; leaching; critical gypsum content; shear strength; compressibility; permeability*.

1. Introduction

Gypseous soils defined as soils containing sufficient gypsum (CaSO4.2H2O) to materially alter their engineering behavior. They cover approximately 27-36% of the surficial deposits in Iraq (Karkush et. al, 2008; Al-Kaabi, 2007) and extend to cover approximately 100 million hectares worldwide and are mainly distributed in arid and semi-arid regions of the Middle East, Central Asia, North Africa, Australia, and the southwestern United States (FAO, 2006). Gypsum is widely available in different sizes, from the size of a rock to the size of a few micrometers as a mineral, in different types of soils (Faris 2020). These soils are predominantly found in regions where annual rainfall is low and evaporation rates are high, conditions that promote the accumulation of soluble salts within the soil profile (Al-Layla and Al-Saffar, 2014; Silva et. al., 2025).

In their natural dry state, gypseous soils exhibit deceptively favorable engineering properties: high strength, low compressibility, and adequate bearing capacity for most structural applications. The behavior is to due cementing bonds form between soil particles because of gypsum crystals (Nashat, 1990). As long as the gypseous soils in dry state condition, they exhibit high strength, however, when water from rain falls, rising water table, seepage from surface water from daily use reaches gypseous soils, it initiates gypsum dissolution process. With time, this process causes to degrade the gypsum cementing bonds resulted in changing the soil structure (Fattah et. al., 2008). The process of dissolving gypsum from the soils due to exposing to water for a period of time is named leaching (Aldaood et. al., 2015; Al-Riahi et. al., 2024). It was reported that at 20 C^o the dissolution rate is approximately of 2.4 g/L, a value that causes soil collapse over timescale (Razouki and Al-Omari, 2007). Gypsum dissolution from soils and transport of the dissolved ions causes to form voids in soils resulted in soil collapse (Mahmood et. al., 2020). For instance, the consequences of gypsum dissolution in road subgrades are severe and economically significant. Road pavements constructed on gypseous subgrades are vulnerable to differential settlement, surface cracking, cavity formation, and sudden collapse failure modes that develop progressively and often without adequate warning. In Iraq alone, the annual cost of rehabilitation and reconstruction of roads damaged by subgrade gypsum dissolution has been estimated to represent a substantial portion of the national infrastructure maintenance budget (Fattah et. al., 2012). Similar problems have been documented in Saudi Arabia, Libya, Oman, Iran, and parts of southern Russia and China, and United States (Al-Dabbas et. al., 2010).

The engineering challenges posed by gypseous soils constitute one of the most persistent and consequential geotechnical problems confronting infrastructure development in arid and semi-arid regions (Abdalhusein et. al., 2022). Resulted in, extensive research has been conducted on the behavior of gypseous soils under various conditions of wetting, soaking, and leaching for natural and treated gypseous soils. For instance, Ismael (1993) conducted laboratory and field leaching tests on gypseous sandy silt soils and concluding that leaching increased permeability, void ratio, and compressibility. In addition, Razouki and Kuttah, (2004) quantified the effect of soaking-drying cycles on the resilient modulus of gypseous subgrade soils. Moreover, Al-Obaidi, (2007) investigated leaching behavior using the permeability-leaching oedometer test, comparing results from standard oedometer and Rowe cell apparatus. Furthermore, Jha and Sivapullaiah, (2017) conducted oedometer tests to evaluate the compressibility of soils containing different gypsum contents and curing durations. Their results showed that compressibility increased with gypsum content but decreased with prolonged curing. The permeability coefficient increased as the void ratio change became larger. More recently, Faris (2020) focused on the effects of the gypsum content, wetting- drying cycles, static and moving water on gypsum dissolution and its effect on soil stability, mass loss, porosity, and soil permeability.

On the other hand, for gypseous treated soils, Fattah et. al., (2012) investigated the treatment of collapsibility using dynamic compaction. Alsafi et. al., (2017) used activated fly ash to immobilize the gypsum in soil to improve its strength and to reduce its collapse potential. The target was to stabilize gypseous clayey sand with silt that has a gypsum content of 13%. Al-Taie et. al., (2019) found that gypsum leaching significantly reduced the cohesion and increased the compressibility of gypseous soil, while chemical treatment with calcium chloride decreased permeability, leaching strain, and gypsum dissolution, thereby preserving the soil's shear strength characteristics. Faris (2020) used three additives: activated fly ash, asphalt emulsion, and Portland cement to identify the most suitable stabilizing agent for improving the mechanical properties of gypseous soils. Al-Wattar and Al-Kifae, (2024) found that adding locally available clayey soil effectively reduced the permeability and leaching effects of gypseous soils, thereby improving their resistance to wetting-induced deterioration and instability. Emad and Salman, (2024) demonstrated that adding nano-clay and nanometakaolin (1–3%) to gypseous soil reduced its collapse potential and improved shear strength, density, and permeability characteristics, with greater improvements observed at higher nanomaterial contents and longer curing periods used in

their study. Ali and Karkush, (2025) investigated the effects of nano-silica and nano-clay on gypsum dissolution during the leaching of gypseous soils. It was found that nanomaterials can reduce gypsum dissolution, and leaching-induced settlement. On the other hand, for unsaturated soils. Kamil et. al., (2023); Al-Naddaf et. al., (2025) reported that cement treatment effectively mitigated gypsum dissolution and collapse potential while enhancing the shear strength, stiffness, and cohesion of unsaturated gypseous soils.

Numerous studies have examined soils containing gypsum at various contents to evaluate the influence of gypsum on soil behavior and engineering properties. However, none of the previous studies have quantified the minimum gypsum content after prolong leaching process and its effect on soil engineering properties. The minimum gypsum content after leaching is addressed by the concept of Critical Gypsum Content (CGC) which is the gypsum percentage below which further gypsum dissolution produces only minor changes in the engineering properties of the soil because most of the soluble gypsum responsible for cementation has already been removed.

2. Methodology

2.1 Materials

Four types of soils with different gypsum contents (14%, 19%, 24%, and 31%) designated as S1, S2, S3, and S4 respectively were collected from four different locations at south and southwest of Mosul city-Nineveh-Iraq as illustrated in Fig. 1. The soil properties were presented in Table 1. It shows that the soil classifications range from clayey silt, low plastic clay to high-plasticity clay.

2.2 Testing setup and Leaching test procedure

The leaching process was conducted on undisturbed soil samples using different methods. Their field densities and water contents were measured and presented in Table. 1. Leaching tests were performed in 3-in consolidation cell, and direct shear box, with water replacement every 12 hours. Fig. 2 illustrates the testing setup of the two different testing methods.

2.3 Testing program

Table 2 summarizes the testing program used to evaluate the effects of leaching on the engineering properties of the four soils. Chemical analyses, including Total Soluble Salts (T.S.S.) and gypsum content (G) were conducted periodically during the leaching process to monitor gypsum dissolution. Geotechnical tests such as consolidation, and direct shear were performed before and after

leaching to assess changes in compressibility, and shear strength. Further, the hydraulic tests represented by soil permeability tests from the oedometer tests were conducted during leaching to assess the effect of gypsum dissolution on the soil hydraulic conductivity.

3. Result and discussions

3.1 Monitoring of T.S.S during leaching

The T.S.S. was monitored during leaching for the tested four soil types. Throughout the leaching process the values of the T.S.S. were recorded every 3-day. So that the removal gypsum from soil samples were progressively tracked during leaching until gypsum content reaches its critical values (CGC). Fig.3 illustrates the T.S.S. with time for the four tested soil types. It shows that the T.S.S. decreases during leaching indicating that the highest gypsum dissolution occurs at the beginning of the leaching process. Results show that S3 exhibits the highest T.S.S. throughout the leaching process. Quantitively, the initial T.S.S. is 7700 mg/L and it remains high at the first few days of leaching process. After two weeks of leaching, the values of T.S.S. decrease sharply to about 4800 mg/L. Thereafter, the decrease becomes more gradual and equilibrates at 2100 mg/L after 70-days of leaching. S3 soil contains the highest amount of soluble gypsum thus, the reported initial T.S.S. is the highest too. The significant reduction in T.S.S. reflects intense gypsum dissolution during the leaching process, whereas the gradual decreases in T.S.S. at later stage of leaching indicates that most dissolved gypsum content has already been removed from the soil during leaching process. Similarly, Asghari et. al., (2018); Al-Riahi et. al., (2024) reported that soils with higher gypsum content exhibited higher T.S.S. during leaching because of the availability of more calcium sulphates dissolute and remove by flowing water. Soil 4 exhibits the second highest dissolvable gypsum. The T.S.S. starts initially at 4900 mg/L and decreases gradually to 1600 mg/L after 65-day of continuous leaching at which the CGC has been reached. It is also noted that although S4 contained higher gypsum content, it exhibits less soluble gypsum than S3. Soil S2 exhibits relatively low T.S.S values compared with S3 and S4. The T.S.S decreases from 1300 mg/L to 750 mg/L during approximately 60 days. This reduction indicates a lower gypsum content and dissolution as the dissolution rate is controlled by gypsum content and leaching condition. In general, soils contain lower gypsum content exhibit lower initial T.S.S. Recent microstructural studies confirmed that lower gypsum-content soils release fewer dissolved ions and experience less severe structural changes during leaching (Al-Riahi et. al., 2024). Finally,

soil S1 exhibits the lowest T.S.S values among all tested soils. The T.S.S decreases from nearly 1200 mg/L to around 350 mg/L within 30 days and then it remains approximately constant. This fast levelled off trend indicates that only a small amount of soluble gypsum was available for dissolution. Once the readily soluble fraction has been removed, the leachate reaches a relatively stable chemical composition.

Fig. 3 also indicates a critical gypsum content (CGC) stage occurred when the T.S.S curve levelled off with time of each soil. The time at which each sample reached its Critical Gypsum Content (CGC), beyond which T.S.S values remain stable regardless of continued leaching. S1 reaches this condition after approximately 27–30 days, whereas S4, S3 and S2 requires about 50–65 days. This behavior is expected because soils with greater gypsum contents require longer periods for dissolution (Faris 2020; Fattah et. al., 2022). Fig. 4 presents the normalized T.S.S reduction (% of initial value). The normalized analysis reveals that S1 achieves the greatest percentage reduction (70.8%), reaching its CGC in only 27 days. S3 shows 72.7% reduction during 66 days. S2 demonstrates the smallest percentage reduction (44.4%) despite having long leaching period (63 days). Fig. 5 presents the dissolution rate of gypsum during leaching confirms that the significant reduction in T.S.S. occurs during the first 15-18 days of leaching for the four soil types. Soil S3, for instance, presents a dissolution rate of 200 mg/L during leaching and decreases to nearly zero at the CGC.

Fig. 6 presents the comparison between the initial and final (at CGC) T.S.S, for the four soil types. Results show that as the leaching proceeds, the T.S.S. decreases, indicating continuing the gypsum dissolutions. The reported maximum initial T.S.S. is 7700 mg/L for S3 and it decreases to 2100 mg/L at CGC at which only 9.3% of the gypsum remains undissolved. Similarly, for soil S4, the T.S.S. decreases from initial value of 4900 mg/L to 1600 mg/L at CGC resulted in only 6.1% of the gypsum remains undissolved. Further, for soil S2, the T.S.S. decreases from initial value of 1300 mg/L to 800 mg/L at CGC where the remain gypsum content is 11.1%. Finally, the lowest initial value of the T.S.S is 1200 mg/L and reaches to 300 mg/L at CGC at which the remain gypsum after leaching is only 5.2%.

Fig. 7 shows the relationship between the soil plasticity (PI) and the critical gypsum content (CGC) for the four soil types. it is noticed a positive correlation between the PI and CGC. The CGC increases from 5.2% for S1 (PI = 12%) to 11.1% for S2 (PI = 26%), indicating that the higher

the plasticity of the soil, the higher the residual the gypsum content after prolong leaching where it terminates at CGC. This behavior may be attributed to the finer pore spaces and low permeability of highly plastic soils, which reduces the dissolution of gypsum during the leaching process (Al-Wattar and Al-Kifae, 2024).

The collected quantitative results of the percentages of initial and at CGC parameters such as T.S.S and gypsum content (G) are presented in Table 3. The table shows that the initial T.S.S. ranges between 1200 to 7700 mg/L and it decreases to 350 to 2100 mg/L at CGC for the four soil types. Thus, the reduction in T.S.S. ranges between 44.4 to 72.7%. In addition, dissolved gypsum ranges from 7.9 to 24.9% during a period of time ranges between 27 and 66 days. These results show the variations of dissolution rate, time and the magnitude of residual gypsum among the different soils used in this study.

3.2 Effect of leaching on geotechnical soil properties

The progressive dissolution of gypsum during leaching, as tracked by T.S.S reduction, directly impacts all engineering properties of the gypseous soils. This section presents the changes observed in strength, compressibility, and permeability characteristics.

3.2.1 Shear Strength Parameters

Table 4 shows a noticeable decrease in the shear strength parameters of the tested gypseous soils after leaching to the CGC. The effective cohesion (c') exhibits significant reductions ranging from 54.8% to 68.8%, with the highest reduction observed in S1 and S3. The reduction can be attributed to gypsum dissolution which negatively affected the initial cementing bonds (Al-Taie et. al., 2019; Ping et. al., 2023). However, the effective angle of internal friction ($\emptyset'$) exhibits slight reductions of 12.1%–14.8%, decreasing from initial values of 32°–34° to 28°–29°, respectively. Results show that leaching mainly affects the soil's cohesion while it is a less pronounced influence on soil friction. Quantitively, Fig 8 presents the normalized final shear strength parameters at the CGC relative to their initial values before leaching. Quantitative ratios of normalized cohesion ranges from 0.31 to 0.45, indicating that only 31–45% of the initial cohesion remains after leaching, whereas the normalized angle of internal friction ranges from 0.85 to 0.88, meaning that only less than 15% of the friction angle was degraded during leaching. These findings are consistent with previous studies on gypseous soils, which reported that water infiltration and gypsum dissolution remove interparticle cementation, and consequently cause a significant

reduction in cohesion while the friction angle remains unaffected or decreased only slightly. Al-Taie et. al., (2019) found that leaching induced a large reduction in cohesion whereas the friction angle remained approximately constant, attributing this behavior to the dissolution of gypsum bonds and the development of a looser soil structure. Similarly, Abd (2022) reported that soaking and wetting of gypseous soils caused cohesion to nearly disappear and significantly reduced shear strength due to gypsum dissolution. Recently, microstructural investigations further confirmed that water–gypsum reactions generate new pores and weaken the soil skeleton, leading to a nearly linear decrease in cohesion with continued dissolution, while changes in friction angle are comparatively smaller because the granular framework of the soil is partially preserved.

3.2.2 Compressibility

In the pre-leaching state, gypsum forms a semi-rigid framework that resists compression, yielding low Cc values of (0.10-0.14) as presented in Table 5. As dissolution proceeds, the gypsum starts dissolving, and the soil transitions toward an uncemented state resulted in increasing in the Cc values. The results present in Table 5 clearly demonstrates that leaching significantly increases the compressibility of the gypseous soils. After prolong leaching (at CGC), soil compression index (Cc) increases to 0.30–0.38, corresponding to increasing factors of 2.4–3.5 times. The greatest increase is observed in sample S4 (G = 31% and PI=14%), where Cc increases from 0.11 to 0.38 (3.5-time), while the smallest increase occurs in S2 (2.4-time) where (G=19% and PI=26%) as illustrated in Fig.9. Similarly, the table shows that the void ratio increases from approximately 0.58–0.68 before leaching to 0.90–1.05 after leaching (at CGC), and the coefficient of compressibility (av) increases from about 2.4–3.2 $\times 10^{-4}$ m²/kN to 7.2–9.5 $\times 10^{-4}$ m²/kN. These changes indicate that leaching dissolved gypsum bonds and soluble salts that originally cemented the soil particles, producing additional voids and weakening the soil skeleton (Al-Sharrad 2023). Fig. 10 confirms the susceptibility of soil to collapse due to increasing void ratios during leaching process till reach the CGC. Consequently, the soil structure becomes looser and more susceptible to compression under applied loads. Quantitively, Fig. 10 shows that the void ratios increase by as much as 1.75-time for S4 (G=31% and PI=14%), while for soil S2 (G=19% and PI=26%), the void ratios increase only by 1.4-time at CGC. This behavior is consistent with recent studies showing that gypsum dissolution during leaching destroys interparticle cementation, increases pore volume and void connectivity, and causes significant increases in compression index. It is important to note from the current finding that not only gypsum content plays a significant role for the soil

behavior, but also the soil PI. For instance, despite soil S2 contains higher gypsum content than soil S1, it exhibits less compression susceptibility due to its higher PI. Al-Riahi et. al., (2024) reported that leaching of gypseous soils increased the compression index and volume compressibility due to the removal of gypsum cementation and development of a more open soil fabric. Similarly, Abbas et. al., (2026) emphasized that gypsum dissolution created additional voids and induced substantial settlement and collapse, while Fattah et. al., (2022); Hussein et. al., (2023) observed that continuous leaching weakened particle bonding, and increased soil compressibility and collapse susceptibility. Therefore, the results confirm that leaching transforms gypseous soils from relatively stable cemented materials into highly compressible and settlement-prone soils, particularly when the gypsum content approaches the critical gypsum content range.

3.2.3 Permeability

Results of permeability tests are presented in Fig. 11 and Table 6. Fig. 11 and Table 6 demonstrate that leaching causes a substantial increase in the coefficient permeability of all gypseous soils as gypsum dissolution progresses toward the critical gypsum content (CGC). The initial coefficient of permeability (K) values was very low, ranging from 1.8×10^{-8} to 4.0×10^{-8} m/s. However, after leaching, the coefficient of permeability increases significantly to values between 1.0×10^{-7} and 1.4×10^{-6} m/s. The increase factor varies from 5.6 times in sample S2 (G = 19%) to 35 times in sample S4 (G = 31%), while samples S3 and S4, which contain higher gypsum contents, exhibits the most pronounced increases (27.1 and 35.0, respectively). These results indicate that the dissolution of gypsum cementation creates interconnected pores, channels, and voids within the soil sample, thereby enhancing water flow through the soil mass Fattah et al., (2022). As shown in Fig. 11, the longer stabilization periods observed for the higher gypsum-content soils (51–66 days) further suggest that a greater amount of soluble gypsum required dissolution before a new equilibrium condition was reached. This finding confirms the previous findings reported by Al-Riahi et al., (2024) who concluded that gypsum dissolution altered the soil microstructure by increasing pore connectivity and permeability, and reported by Fattah et al., (2022) who found that continuous leaching progressively enlarged void spaces and accelerated seepage through the soil mass. Similarly, Asghari et. al., (2018) observed that soils with higher gypsum contents experience higher increase in permeability because larger quantities of dissolved gypsum leave behind extensive pore networks. Therefore, the results confirmed that the coefficient of permeability is highly sensitive to gypsum dissolution and that soils with greater gypsum

contents are more vulnerable to the formation of highly permeable and potentially collapsible structures after leaching.

Fig.12 presents the values of the initial and final coefficients of permeability. It is noticed that the effect of leaching on the coefficient of permeability is very pronounced. The red 45° line represents the condition where the initial and final coefficient of permeability are equal. It is noticed that all data points plotted well above this line, indicating that the coefficient of permeability at the CGC is substantially greater than the initial values. Moreover, the points for all soil types are clustered near the vertical axis, showing that relatively small initial coefficient of permeability increases to much larger final values, in some cases especially for higher gypsum contents, the increase in the coefficient of permeability increases by more than an order of magnitude. This behavior confirms that gypsum dissolution during leaching progressively removes the cementing bonds between soil particles, creating additional voids and interconnected flow channels that significantly enhance the coefficient of permeability (Al-Otaibi 2020).

4. Conclusions

1. The experimental evidence conclusively demonstrates that gypseous soils possess a Critical Gypsum Content (CGC), a residual gypsum fraction that is inaccessible to dissolution regardless the duration of water exposure.
2. The dissolution rate is highest during the initial 15-18 days, when surface-accessible and pore-lining gypsum crystals are removed, and decays asymptotically toward zero as the CGC is approached. Maximum dissolution rates of 200 mg/l/day were recorded for S3 (G=24%) during the initial leaching phase. Resulted in the CGC values for the four tested soils range from 5.2% (S1, G=14%) to 11.1% (S2, G=19%), and the time required to achieve CGC ranges from 27 days (S1) to 66 days (S3).
3. The effective cohesion (c) reveals severe reduction of 54.8-68.8% across all samples upon reaching the CGC. Confirming that the primary source of cohesion in gypseous soils is the inter-particle cementation provided by gypsum crystals. The residual cohesion at CGC is attributable solely to clay mineral bonding with a positive dependence on soil PI.
4. The effective angle of internal friction ($\emptyset'$) decreases by only 12.1-14.8%, confirming that gypsum leaching only slightly affecting the frictional soil skeleton.
5. The Compression Index (Cc) increases by a factor of 2.4 to 3.5 times during leaching to CGC, with S4 (G=31%, PI=14%) exhibiting the maximum increase from 0.11 to 0.38 and S2

(G=19%, and PI=26%) exhibiting the minimum increase from 0.14 to 0.33 with a positive dependence on soil PI.

6. At the CGC, the coefficient of permeability increases by 5.6-time for (S2) and by 35.0 for (S4) during leaching which is function to the initial gypsum content and soil PI. Such increase in soil permeability explains the progressive and often abrupt nature of gypseous structure failures observed in the field.

Authorship Contribution Qutayba Al-Saffar**:** Conceptualisation, Writing – original draft. Mohammed Jaro: Experiments Formal analysis. Muwafaq Awad: Writing – review & editing. Zeena AlKazzaz: experiments. Abdulnasser Ali: experiments.

Conflict of Interest The authors declare they have no known competing financial interests and prepared the manuscript ethically, citing all sources, data, and references appropriately.

Data Availability All data, models, and code generated or used during the study appear in the submitted article.

Funding The authors gratefully acknowledge the support provided by the College of Engineering, University of Mosul, particularly the Department of Civil Engineering, during the data collection, analysis, and documentation phases of this research. The study was conducted within the scientific research plan of the Department of Civil Engineering for the 2025–2026 academic year and was officially registered under No. 9/16/6217 on 15 June 2026

5. References

Abbas, H. A., Al-Riahi, S. M. H., & Fattah, M. Y. (2026). Mitigating infrastructure risks in gypseous soils: combining random forest modeling with monte carlo simulation. Discover Civil Engineering, 3(1), 42.

Abd, A. H. (2022). Preliminary Study on the Reduction in Shear Strength Parameters of Gypseous Soil upon Wetting. Civil and Environmental Engineering, 18(1), 195-199.

Abdalhusein M, Akhtarpour A, Mahmood M. (2022). Unsaturated behaviour of gypseous sand soils using a modified triaxial test apparatus. Int J Geotech Eng;16(6): 743–758. https://doi.org/10.1080/19386362.2022.2033483.

Al Wattar, Z. H., & Al-Kifae, A. A. (2024). Optimizing gypseous soils permeability utilizing clayey soils, both treated and untreated. In IOP Conference Series. Earth and Environmental Science (Vol. 1374, No. 1, p. 012011). IOP Publishing.

Al-Dabbas, M.A., Schanz, T. and Al-Badran, Y. (2010). Engineering geological mapping of the Iraqi Western Desert. Iraqi Bulletin of Geology and Mining, 6(1), pp. 51-66.

Aldaood A, Bouasker M, Al-Mukhtar M. (2015). Effect of long-term soaking and leaching on the behaviour of lime stabilised gypseous soil. International Journal of Pavement Engineering. 2;16(1):11-26.

Ali, S. D., and Karkush, M. (2025). Studying leaching of gypseous soil improved with nanomaterials. Journal of Engineering, 31(7), 99-110.

Al-Kaabi, F.H. (2007). "Distribution of gypseous soils in Iraq at depths 250-1500mm." National Center for Construction Laboratories, Iraq.

Al-Layla, M. T., & Al-Saffar, Q. N. (2014). Improving the engineering properties of the gypseous soil using dynamic compaction method. Al-Rafidain Engineering Journal, 22(2), 109-122.

AlNaddaf, H. Q. A., Kouzegaran, S., Akhtarpour, A., & Fattah, M. Y. (2025). Effects of Cement Treatment on the Behavior of Unsaturated Gypseous Soils. Transportation Infrastructure Geotechnology, 12(5), 140.

Al-Obaidi, Q.A. (2007). Leaching behavior of gypsiferous soils using the permeability-leaching oedometer test. PhD Thesis, University of Technology, Baghdad.

Al-Otaibi FA(2020). Variation of Sabkha Soil Permeability Associated with Ions' Dissolution during Distilled Water Leaching Jordan. J Civil Eng.;14(4):525–36.

Al-Riahi, S. M. H., Pauzi, N. I. M., Fattah, M. Y., & Abbas, H. A. (2024). Leaching-induced alterations in the geotechnical and microstructural attributes of clayey gypseous soils. Ain Shams Engineering Journal, 15(7), 102865.

Alsafi, S., Farzadnia, N., Asadi, A., & Huat, B. K. (2017). Collapsibility potential of gypseous soil stabilized with fly ash geopolymer; characterization and assessment. Construction and Building Materials, 137, 390-409.

Al-Sharrad, M. A. (2023). Collapsibility and leaching behavior of an artificial sandy gypseous soil. Bulletin of Engineering Geology and the Environment, 82(12), 445.

Al-Taie, A. J., Albusoda, B. S., Alabdullah, S. F., & Dabdab, A. J. (2019). An experimental study on leaching in gypseous soil subjected to triaxial loading. Geotechnical and Geological Engineering, 37(6), 5199-5210.

Asghari, S., Ghafoori, M., & Tabatabai, S. (2018). Changes in chemical composition and engineering properties of gypseous soils through leaching: An example from Mashhad, Iran. Bulletin of Engineering Geology and the Environment, 77(1), 165–175.

Emad, R., & Salman, A. D. (2024). Shear Strength and Collapsibility of Gypseous Soil Improved by Nanomaterials. In IOP Conference Series: Earth and Environmental Science (Vol. 1374, No. 1, p. 012004). IOP Publishing.

FAO, I. (2006). ISRIC: world reference base for soil resource in world soil resource report no. 103. FAO, Rome, Italy.

Faris, M. K.(2020). Evaluating the Stabilization of Gypseous and Gypsiferous Sands Using Different Chemical Additives to Mitigate Gypsum Dissolution. (Doctoral dissertation). Retrieved from https://scholarcommons.sc.edu/etd/6140

Fattah, M. Y., Al-Musawi, H. H., & Salman, F. A. (2012). Treatment of collapsibility of gypseous soils by dynamic compaction. Geotechnical and Geological Engineering, 30(6), 1369-1387.

Fattah, M. Y., Al-Shakarchi, Y. J., & Al-Numani, H. N. (2008). Long-term deformation of some gypseous soils. Engineering and Technology Journal, 26(12), 1461-1483.

Fattah, M. Y., Obead, I. H., & Omran, H. A. (2022). A study on leaching of collapsible gypseous soils. International Journal of Geotechnical Engineering, 16(1), 44-54.

Hussein, A. H., Muhauwiss, F. M., & Abdul-Jabbar, R. A. (2023). Collapsibility of Gypseous Soil Treated with Pectin-Biopolymer through Leaching. Journal of engineering, 2023(1), 6379835.

Ismael, N. F. (1993). Laboratory and field leaching tests on coastal salt-bearing soils. Journal of geotechnical engineering, 119(3), 453-470.

Jha, A. K., & Sivapullaiah, P. V. (2017). Volume change behavior of gypseous soil. Journal of Materials in Civil Engineering, 29(10), 06017010.

Kamil, K. S., Abdulkareem, A. H., & Mahmood, N. S. (2023). Using a Laboratory Model Test to Evaluate Collapsibility of Gypseous Soils Improved by Sludge. In E3S Web of Conferences (Vol. 427, p. 01004). EDP Sciences.

Karkush, M. O., Al-Shakarchi, Y. J., & Al-Jorany, A. N. (2008). Leaching behavior of gypseous soils. Journal of Engineering, 14(04), 3077-3089.

Mahmood, M. R., Fattah, M. Y., & Khalaf, A. (2020). Experimental investigation on the bearing capacity of skirted foundations on submerged gypseous soil. Marine Georesources & Geotechnology, 38(10), 1151-1162.

Nashat, I.H. (1990). "Engineering properties of gypseous soils." MSc Thesis, University of Baghdad, Iraq.

Ping, S., Wang, F., Wang, D., Li, S., Yuan, Y., Feng, G., & Shang, S. (2023). Multi-scale deterioration mechanism of shear strength of gypsum-bearing mudstone induced by water-rock reactions. Engineering Geology, 323, 107224.

Razouki, S.S. and Al-Omari, R.R. (2007). "Pavement design on gypsiferous subgrade." Proceedings of the Institution of Civil Engineers - Transport, 160(TR2), pp. 57-65.

Razouki, S.S. and Kuttah, D.K. (2004). "Effect of soaking-drying cycles on resilient modulus of gypsiferous subgrade soils." Transportation Research Record, 1874, pp. 38-45.

Silva, A. H. N. D., Sousa, M. G., Araújo Filho, J. C. D., Corrêa, M. M., Otero, X. L., Ferreira, T. O., ... & Souza, V. S. D. (2025). Gypsic soils in the Brazilian Semiarid. Revista Brasileira de Ciência do Solo, 49, e0240138.

LIST OF TABLES

Table 1. Geotechnical soil properties

Table 2 Tests program before and after leaching

Table 3. Collected data during leaching test

Table 4 Effect of leaching on shear strength parameters

Table 5 Initial and at CGC compression index and void ratios

Table 6 Initial and at CGC coefficient of permeability

LIST OF FIGURES

Fig. 1 the locations of the soil samples collected for this study.

Fig. 2 Testing setup of leaching **a.** standard consolidation method, and **b.** direct shear method.

Fig. 3 Total soluble salts (T.S.S) during leaching process

Fig. 4 The normalized Total soluble salts (T.S.S) to the initial values during leaching process

Fig.5 Rate of T.S.S dissolution of gypsum during leaching

Fig. 6 Initial and final T.S.S. for the four tested soils

Fig. 7 Critical gypsum content **(**CGC) versus Plasticity Index (PI).

Fig. 8 Normalized shear strength parameters

Fig. 9 Effect of leaching on soil compression index (Cc)

Fig. 10 Effect of leaching on soil void ratio (e)

Fig. 11 coefficient of permebility with time during leaching process

Fig. 12 Comparison of initial and final permeability coefficients of gypseous soils at the CGC.

501 **Table 1.** Geotechnical soil properties

Sample	Field moist density (g/cm^3)	Field water content (%)	Gypsum (%)	L.L (%)	P.L (%)	P.I (%)	Classification
S1	15.0	11.2	14	32	19	12	CL-ML
S2	18.2	13.4	19	54	28	26	CH
S3	17.6	12.1	24	46	25	21	CL
S4	16.1	10.3	31	34	20	14	CL

502

503 **Table 2** Tests program before and after leaching

Test	Standard	Purpose	Frequency
T.S.S Analysis	Chemical	Total soluble salts monitoring	Every 3 days
Gypsum Content	BS 1377	Residual gypsum determination	Each cycle
Consolidation	ASTM D2435 / Rowe cell	Compressibility (Cc, av)	Before/after leaching
Direct Shear	ASTM D3080	Shear strength (c, phi)	Before/after leaching
Permeability	ASTM D5084	Hydraulic conductivity (k)	During leaching
Atterberg Limits	ASTM D4318	Consistency limits	Before/after leaching

504

505 **Table 3.** Collected data during leaching test

Parameter	S1 (G=14%)	S2 (G=19%)	S3 (G=24%)	S4 (G=31%)
Initial T.S.S (mg/l)	1,200	1,350	7,700	4,900
Final T.S.S at CGC (mg/l)	350	750	2,100	1,600
T.S.S Reduction (mg/l)	850	600	5,600	3,300
T.S.S Reduction (%)	70.8%	44.4%	72.7%	67.3%
Time to Reach CGC (days)	27	63	66	51
Initial Gypsum Content (%)	14	19	24	31
Critical Gypsum Content (Residual) (%)	5.2	11.1	9.3	6.1
Gypsum Removed (%)	8.8	7.9	14.7	24.9

506

507

508

509

510

511

512 **Table 4** Effect of leaching on shear strength parameters

Soil Type	c Initial (kPa)	c at CGC (kPa)	c Reduction (%)	Initial ∅′(deg)	∅′ at CGC (deg)	∅′ Reduction (%)
S1 (G=14%)	48	15	68.8%	32.5	28.0	13.8%
S2 (G=19%)	62	28	54.8%	34.5	29.5	14.5%
S3 (G=24%)	55	18	67.3%	33.8	28.8	14.8%
S4 (G=31%)	52	20	61.5%	33.0	29.0	12.1%

513

514 **Table 5** Initial and at CGC compression index and void ratios

Sample	Cc Initial	Cc at CGC	Cc Increase Factor	Void Ratio Increase	av x10^-4 Increase (m^2/kN)
S1 (G=14%)	0.10	0.30	3.0	0.58 to 0.90	2.4 to 7.2
S2 (G=19%)	0.14	0.33	2.4	0.68 to 0.95	3.2 to 8.0
S3 (G=24%)	0.12	0.38	3.2	0.62 to 1.02	2.8 to 9.0
S4 (G=31%)	0.11	0.38	3.5	0.60 to 1.05	2.5 to 9.5

515

516 **Table 6** Initial and at CGC coefficient of permeability

Sample	Initial k (m/sec)	Final k at CGC (m/sec)	k Increase Factor	Time to Stabilize (days)
S1 (G=14%)	2.10 x 10^-8	1.50 x 10^-7	7.1	27
S2 (G=19%)	1.80 x 10^-8	1.00 x 10^-7	5.6	63
S3 (G=24%)	3.50 x 10^-8	9.50 x 10^-7	27.1	66
S4 (G=31%)	4.00 x 10^-8	1.40 x 10^-6	35.0	51

517

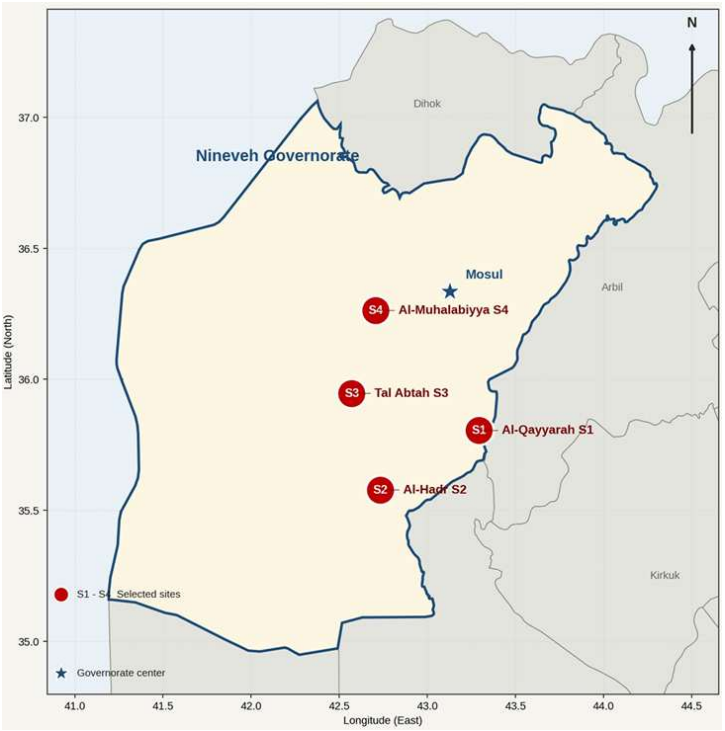
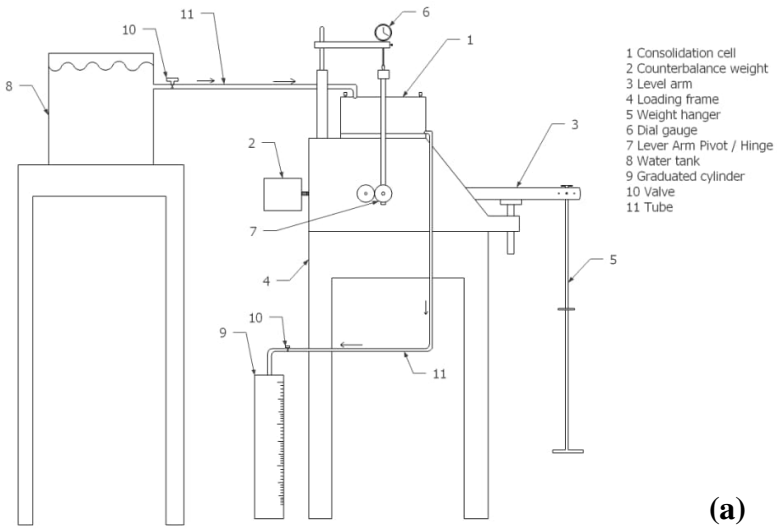
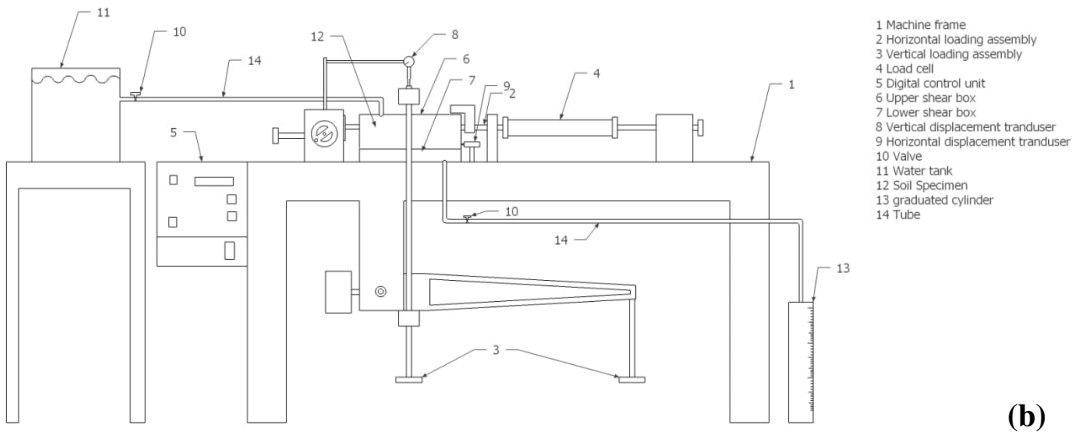


Fig. 1 the locations of the soil samples collected for this study.



(a)



(b)

Fig. 2 Testing setup of leaching **a.** standard consolidation method, and **b.** direct shear method.

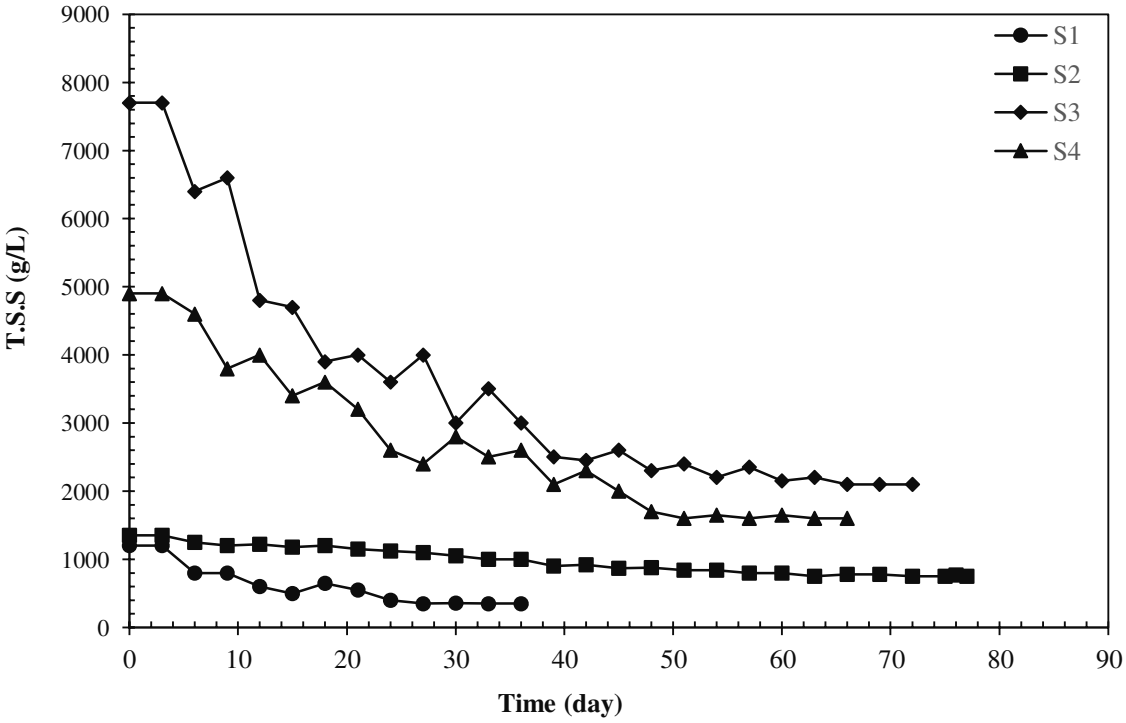
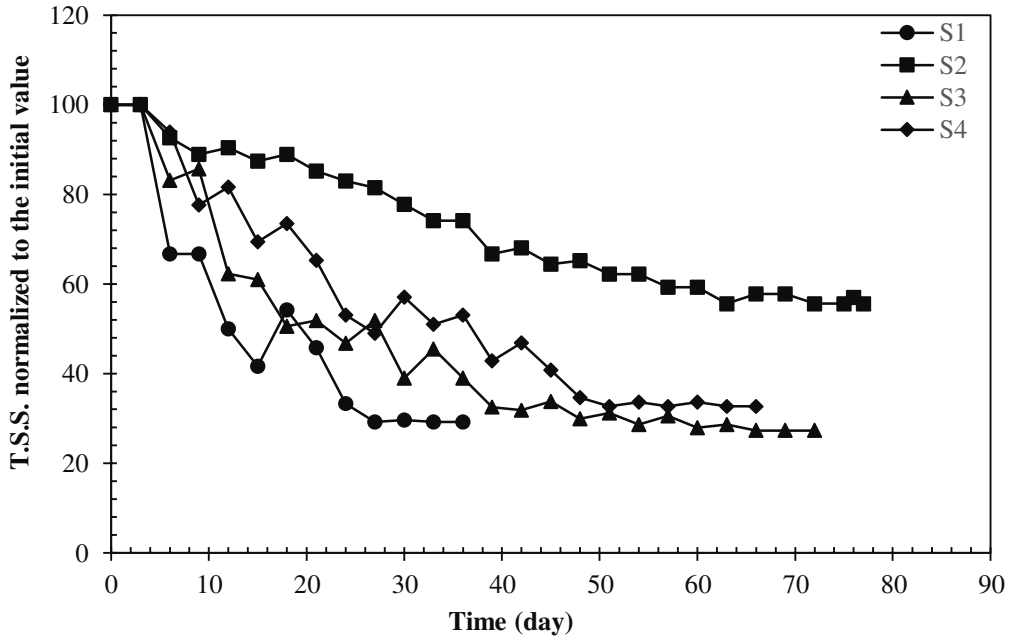
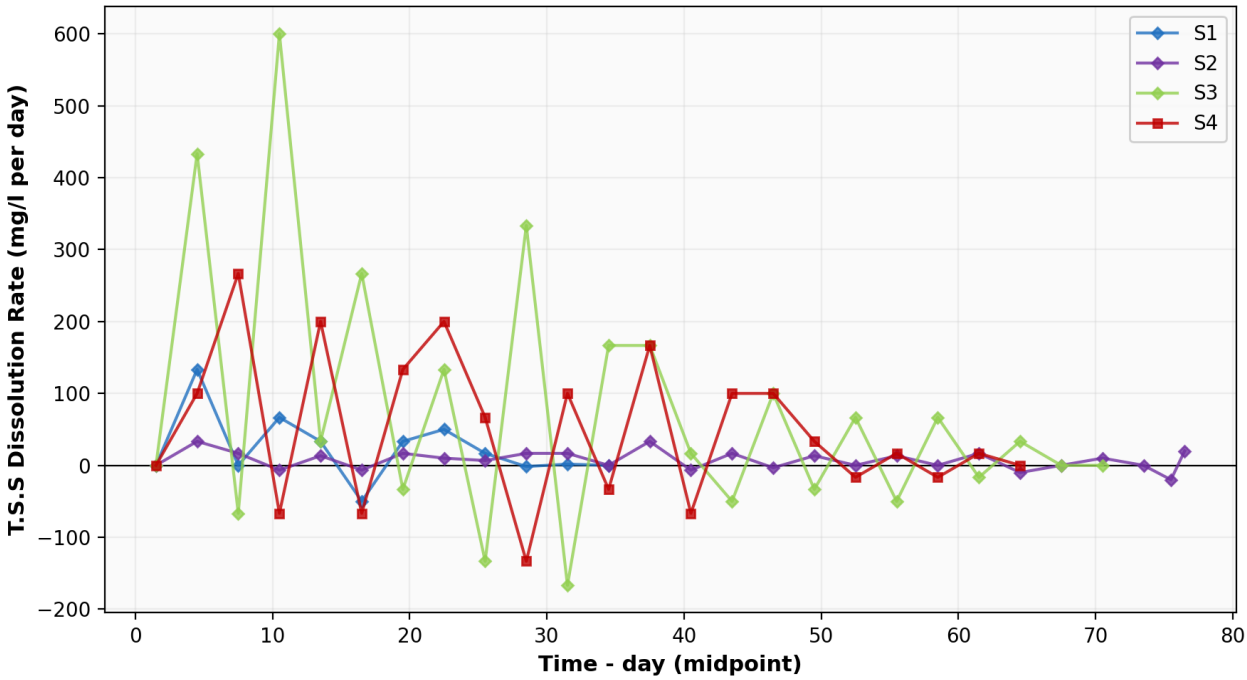


Fig. 3 Total soluble salts (T.S.S) during leaching process

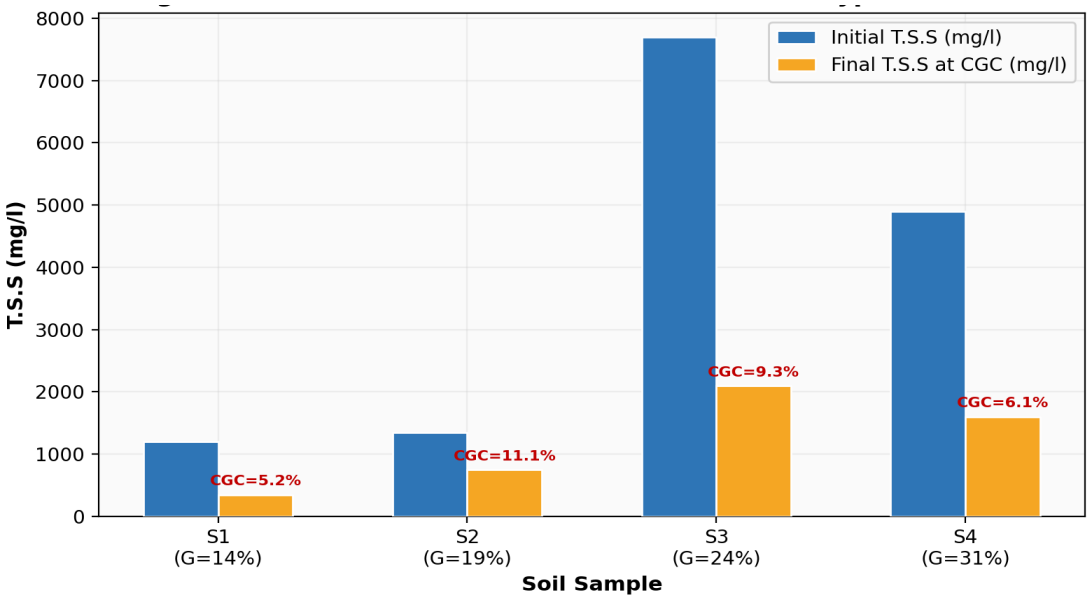


532
533 **Fig. 4** The normalized Total soluble salts (T.S.S) to the initial values during leaching process

534

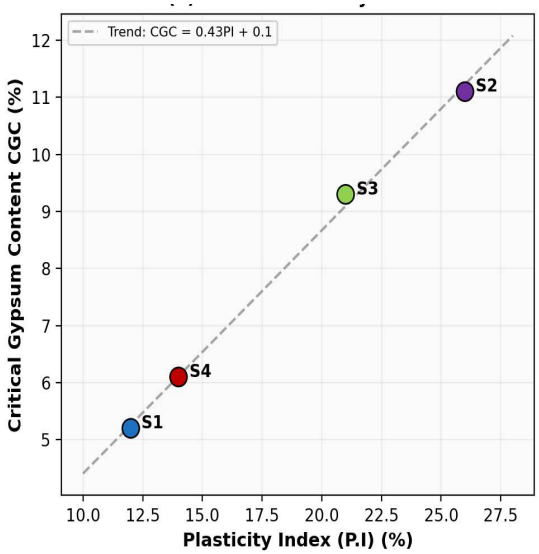


535
536 **Fig.5** Rate of T.S.S dissolution of gypsum during leaching
537

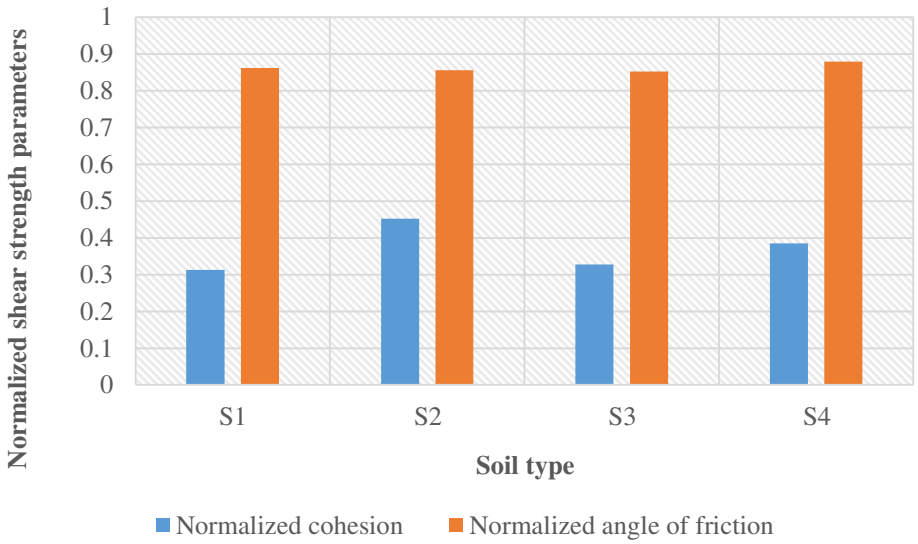


538 **Fig. 6** Initial and final T.S.S. for the four tested soils

539



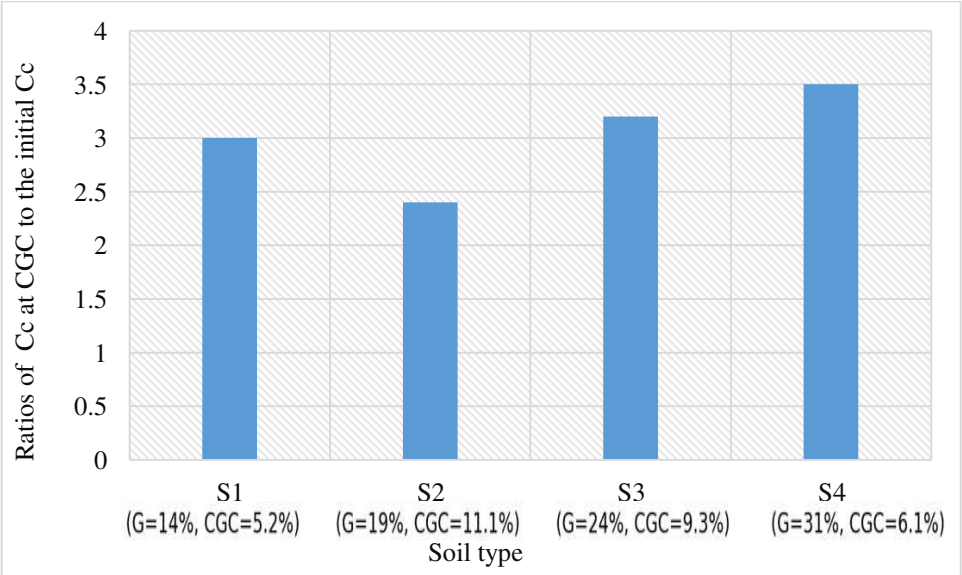
540
541 **Fig. 7** Critical gypsum content (CGC) versus Plasticity Index (PI).
542



543
544 **Fig. 8** Normalized shear strength parameters

545

546



547
548 **Fig. 9** Effect of leaching on soil compression index (Cc)
549

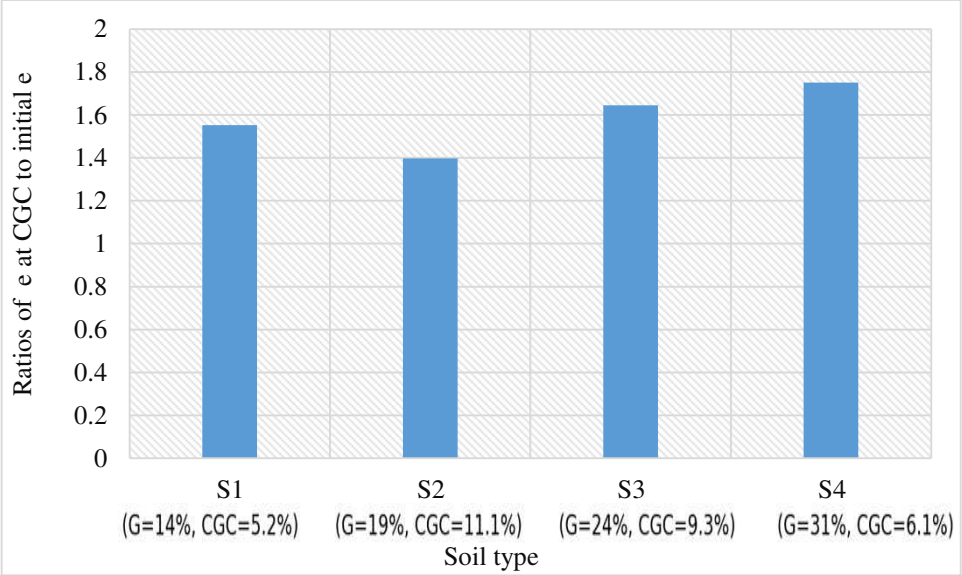


Fig. 10 Effect of leaching on soil void ratio (e)

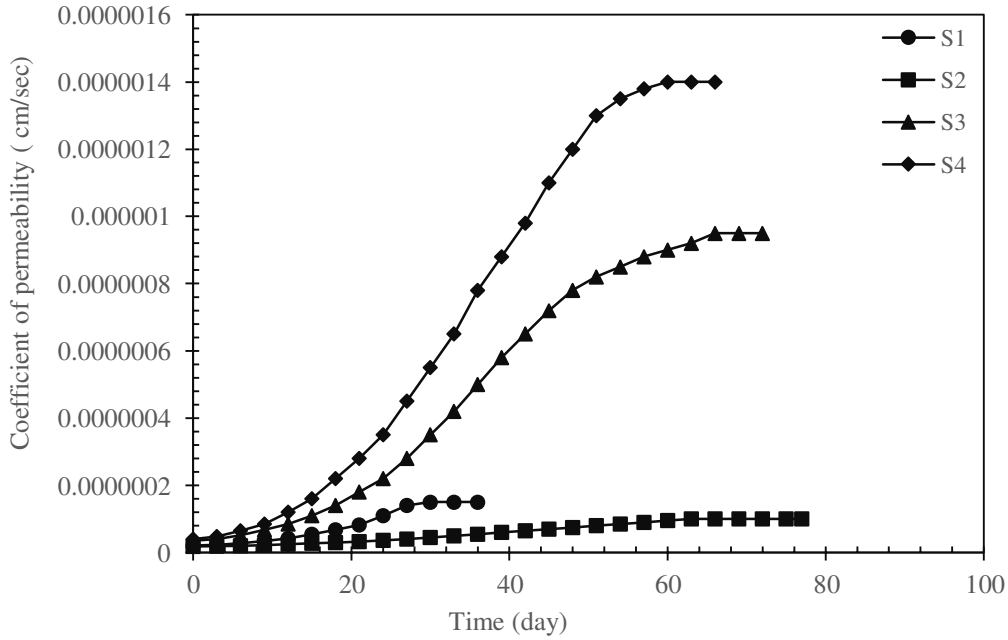
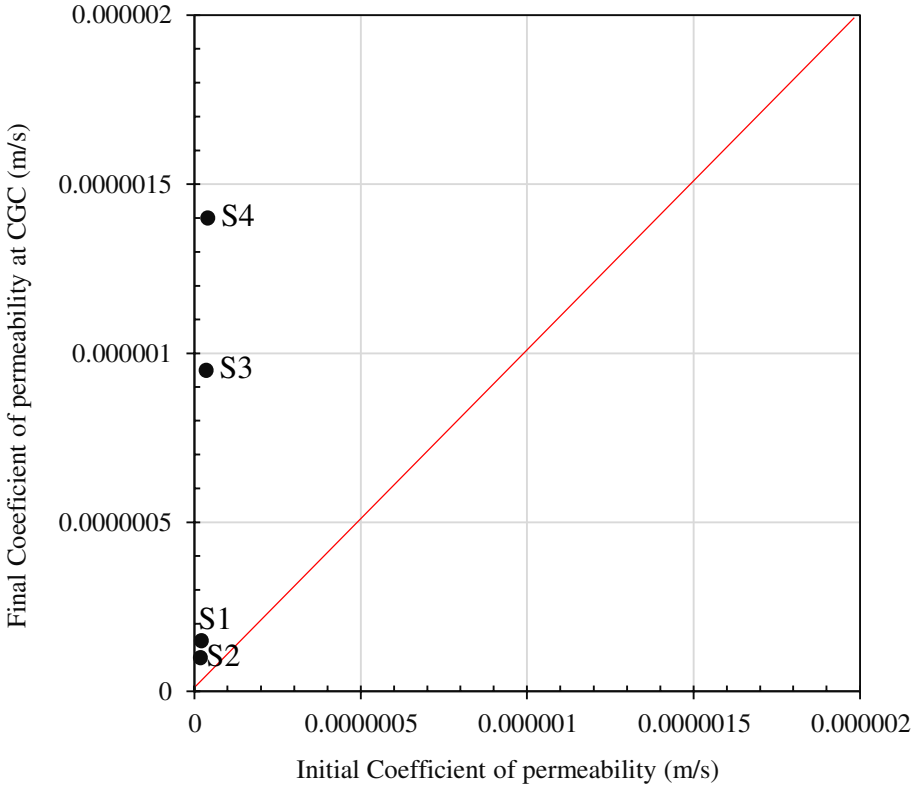


Fig. 11 coefficient of permebility with time during leaching process

560



561
562 **Fig. 12** Comparison of initial and final permeability coefficients of gypseous soils at the CGC.
563

564