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Alçı İçeriği ve Kür Süresinin Kaolin Zemininin Dayanım Davranışı Üzerindeki Etkisi

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Öz

Alçı esaslı yapı malzemelerinin geoteknik uygulamalarda yeniden kullanımı, zemin iyileştirmesi için sürdürülebilir bir alternatif sunmaktadır. Bu çalışmada, sentetik alçının ($CaSO_4 \cdot ½H_2O$), düşük plastisiteli bir silt (ML) tipi kaolin zemininin fiziksel ve mekanik özellikleri üzerindeki etkileri deneysel olarak incelenmiştir. Zemin iyileştirme için, kuru zemin ağırlığına göre %2, %5, %8 ve %11 oranlarında alçı kullanılmıştır. Alçı katkısı ilave edilmiş ve edilmemiş numuneler üzerinde 1 ve 15 günlük kür süreleri sonunda Atterberg limitleri, standart Proctor ve serbest basınç dayanımı (UCS) deneyleri gerçekleştirilmiştir. Deneysel sonuçlar, alçı ilavesinin zeminin mühendislik davranışını önemli ölçüde değiştirdiğini göstermektedir. Düşük ve orta düzeyde alçı ilavesinin zemin plastisitesini azalttığı ve sıkışma özelliklerini iyileştirdiği, bunun da daha yoğun ve daha kararlı bir zemin yapısına işaret ettiği belirlenmiştir. Veriler, alçı içeriğinin optimum bir seviyeye kadar arttıkça belirgin bir dayanım artışı meydana getirdiğini ortaya koymuştur. Bu artış, zemin matrisi içerisinde dane bağlanmasının iyileşmesi ve puzolanik etkileşimlerin gelişmesiyle ilişkilendirilmektedir. Buna karşın, daha yüksek alçı oranlarında dayanımın azaldığı ve deformabilitenin arttığı gözlemlenmiş olup, bu durum aşırı bağlayıcı içeriğinin zemin dokusunu bozduğunu ve daha az etkili bağlanma oluşumuna neden olduğunu işaret etmektedir. Sonuç olarak elde edilen bulgular, yapı malzemesi olarak kullanılan alçının ML tipi zeminler için orta düzey oranlarda uygulandığında etkili bir stabilizasyon malzemesi olarak kullanılabileceğini göstermektedir. Ancak, uygulamada olası dayanıklılık sorunları ile uzun dönem performansın dikkatle değerlendirilmesi gerekmektedir.

Anahtar kelimeler: Alçı, Serbest basınç mukavemeti, Düşük plastisiteli silt, Koalin, Zemin iyileştirmesi

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Influence of Gypsum Content and Curing Time on the Strength Behavior of Kaolin Soil

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Abstract

The reusage of gypsum-based construction materials in geotechnical applications provides a sustainable alternative for soil stabilization. In this study, the effects of synthetic gypsum ($CaSO_4 \cdot ½H_2O$) on the physical and mechanical properties of a low-plasticity silt (ML) type kaolin soil were experimentally investigated. Atterberg limit, standard Proctor and unconfined compressive strength (UCS) tests were applied on untreated and treated soil samples by rates of 2%, 5%, 8%, and 11% gypsum by dry weight for curing periods of 1 and 15 days. The results of the experiments revealed a significant change in the mechanicai behavior of the soil by the usage of gypsum treatment. The soil plasticity decreased by low to moderate gypsum additive while an improvement was observed for the compaction characteristics pointing out a denser and more stable particle structure. A clear improvement has been observed for strength properties of the soil with increasing gyspum content up to an optimum level, pointing out an enhancement for interparticle bonding and pozzolanic interactions in the soil matrix. Besides, higher gypsum rates resulted in a strength reduction by increased deformability, pointing out a distortion in the soil fabric and the formation of less effective bonding at excess rate of binder contents. Consequently, the findings revealed that construction material type gypsum can serve as an effective stabilizing binder for ML-type soils when applied at moderate rates. However potential durability problems and long-term performance should be carefully considered in practical applications.

Keywords: Gypsum, Unconfined compresssive strength, Low plasticity silt, Kaolin, Soil treatment

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1. Introduction

In the last decade, urban transformation projects and post-earthquake reurbanization works increased heavily leading to an increase in the construction and demolition wastes (C&D) as well. It has been a universal problem to handle with the management of these waste materials for reusage to contribute to environmental sustainability. Among different type of C&D waste materials, the plasters and wallboards which are composed of mainly gypsum, is used so frequently and constitute a major portion in the worldwide. Previous studies declared that the storage of gypsum-based C&D wastes in the landfill areas results in soil contaminations and hydrogen sulfide gas emissions [1-3]. Hence, the recycling of these wastes has been heavily studied lately in geotechnical engineering applications. To be compatible with the mechanical and physical properties of gypsum utilized from the C&D wastes, this study used commercial powder type gypsum as an additive materal for kaolin type clay as a treatment material. Accordingly, this study aimed to define whether the gypsum additive is an effective metarial for the improvement of mechanical and physical properties of kaolin soil.

Many studies have been interested in the stabilizer performance of recycled gypsum obtained through C&D wastes for soil improvement. The gypsum material can be found in various structural forms as the natural form of gypum ($CaSO_4 \cdot 2H_2O$), bassanite ($CaSO_4 \cdot 1/2H_2O$) and andhydrit ($CaSO_4$), recycled form C&D wastes and as the man-made industrial side-product form such as phospogypsum and flue gas desulfurization gypsum. These alternative forms provide utilizing gypsum as a cementitious or adhesive binder for soil stabilization, hence reducing the dependence on high-carbon materials such as cement and lime, which are responsible for more than 4% of global CO_2 emissions [4]. By gypsum, the soil behavior is primarily altered through cation exchange, particle restructuring (flocculation and agglomeration), and by the formation of cementitious hydration substances [5, 6]. In the first stage of stabilization, calcium ions coming out of gypsum trigger the cation exchange mechanisms on clay surfaces and replace monovalent cations such as sodium and potassium, resulting in a thinner diffuse double layer and flocculation of soil particles [5]. Following this, hydration of calcium sulfate generates binding structures in the contact points of particles, thus contributing to early-age strength development [7-9]. This action is particularly important in high-plasticity clays, where the cation exchange capacity (CEC) controls the optimum gypsum content needed to achieve maximum strength [7-9]. Moreover, the strength and compaction characteristics of soil alter as well in addition to the change in plastic behavior. Gradually, these processes lead to rearrangement of soil microstructure by means of void reduction and increase of particle bonding. Hence, understanding the interaction between the relevant mechanisms plays a significant role in the accurate interpretation of both mechanical and microstructural behavior gypsum treated soils.

Yılmaz [10] studied on the stabilization of high plastic bentonite soils by the natural form of gypsum and stated that gypsum can improve soil strength and reduce plasticity. However, he declared that moderate water solubility and the swelling behavior of gypsum under wet conditions may pose durability concerns. Multiple studies investigated on the use of gypsum as a recycled construction waste or industrial side-products (in the form of phosphogypsum) with other additives such as fly ash and cement kiln dust to cure the strength and to increase stability of clayey soils. Degirmenci et al. [11] studied on the utilization of phosphogypsum together with cement and fly ash and revealed a decrease in plasticity index and improvements in compaction and unconfined compressive strength for clayey soils of medium to high plasticity. Ahmed et al., [12] and Khan [13] investigated the unconfined compressive strength (UCS) of natural and recycled (waste from plasterboard) gypsum-treated clays, revealing an increase in UCS with gypsum content up to an optimum level (ranging between 7%–15%), and beyond this a decrease or constancy in UCS. Jang et al. [14] studied the stabilization of soft marine clay with recycled gypsum board waste, revealing a significant early-period hardening. However, it was stated that prolonged mixing time led to a reduction in strength. Al-Adili et al. [15] used recycled gypsum which is collected from various construction sites and crushed by mechanically for testing. They noted that as the gypsum content increased in the clayey soil-gypsum mixture, liquid limit (LL) and plastic limit (PL) decreased up to 3% and 7% gypsum rates respectively and then increased, maximum dry density (MDD) decreased with increasing optimum water content (OWC), and the unconfined compressive strength has increased up to 5% gypsum content and then decreased. The strength improvement at lower ranges is attributed to cation exchange and flocculation, while the continued increase in some studies beyond the cation exchange capacity is explained by the pozzolanic reactions between calcium from gypsum and silica/alumina from clay minerals [6, 9]. Conversely, excessive gypsum addition may introduce soft, coarse recrystallized particles, leading to looser packing, increased pore volume, and reduced UCS [9], [16] In terms of compaction behavior, most studies agree that gypsum addition modifies both MD) and OM). For high-plasticity clays, gypsum tends to decrease MDD and increase OWC due to flocculated structure formation and larger pore volume [17]. In contrast, in low-plasticity or nonplastic soils, finer gypsum particles can fill interparticle voids, leading to higher density [18, 19].

According to the literature, the gypsum additive in soil stabilization is generally used with other binders such as concrete, lime or fly ash. However, the number of studies in which the gypsum is used alone as a stabilizing binder, and the evaluation of microstructural and mechanical behavior together especially for low plastic silt (ML) type soils, is quite limited. Hence, this study intended to investigate the effects of different gypsum rates as a stand-alone stabilization binder on mechanical behavior and explain the strength gain mechanism by revealing the microstructural changes utilizing from the Scanning electron microscopy (SEM), Energy dispersive spectrometry (EDS) and Fourier transform infrared spectroscopy (FTIR) analyses. Besides, while the previous studies are mainly focused on natural soils collected from various regions inholding changeable mineralogical properties and grain distributions, the current study maintains the mineralogy and grain distribution homogeneous and uniform respectively to reveal the effect of binder only. Though the binder used in this study is factory-processed, it is recyclable, contributing to environmental sustainability as well. The reusage of C&D wastes in the context of reurbanization works especially in earthquake prone regions, contributes to reducing the consumption of natural resources and provides an environmentally sustainable solution. From an economic perspective, the low cost of the binder material increases the suitability of the method for large scaled applications. Moreover, the soil stabilization by gypsum does not require any complicated equipments and advanced techniques, thus provides ease of application under field conditions. The absence of harmful and irritating effects on human health also constitutes an important advantage for practical applications. In this regard, the present study aims to make a significant contribution to the existing literature on the behavior of gypsum stabilized ML-type soils.

In the context of this study, the physical and mechanical effects of commercially available powdered gypsum used for plasterboard manufacturing, on kaolin clay were investigated through a series of laboratory experiments. For this purpose, the kaolin was mixed with varying proportions of gypsum (2%, 5%, 8% and 11%) by dry weight, followed by the determination of consistency limits through Atterberg limits test, compaction characteristics by standard Proctor test, and unconfined compressive strength (UCS) by uniaxial compressive tests. In addition, a curing period of 15 days was applied to determine the effect of aging on the strength development of the gypsum-treated soil. The findings of this experimental study aim to provide insight into the feasibility of using gypsum-based C&D waste for the stabilization of kaolin clays classified as low-plasticity clayey silt (ML) in the study.

2. Materials and Methods

2.1. Soil properties

In this study, low-plasticity silt type soil was used. The soil has a white-colored, high kaolinite content and ıt was purchased from commerial supplier. The kaolinite has a layered structure. And it consists of silica (SiO_4) tetrahedra bonded to Aluminum (AlO_6) octahedra. The soil type was characterized through sieve and hydrometer analyses (ASTM D6913 and ASTM D7928), specific gravity test (ASTM D854), Atterberg limits tests (ASTM D4318), and standard Proctor tests (ASTM D1557), (Table 1) [20-24]. The results of these tests and the particle size distribution curve show that the soil is composed by 78% silt and 22% clay pointing out a low-plasticity clayey silt (ML) soil class based on the Unified Soil Classification System (USCS), (Table 1 and Figure 1). The relationship between optimum water content (w_{opt}) and maximum dry density (ρ_{drymax}) obtained from the standard Proctor test is shown in Figure 2, pointing out the compaction parameters of ρ_{drymax}=1.34 gr/cm^3 and OWC=32%. Additionally, X-ray fluorescence (XRF) analysis indicated that the ML-type soil is predominantly composed of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), consistent with its high kaolinite content (Table 2).

Table 1. Physical soil properties of kaolin measured in this study

Property	Value	Property	Value
Silt (%)	78.00	ρ_{drymax} (gr/cm^3)	1.34
Clay (%)	22.00	OWC (%)	32
Liquid Limit-LL (%)	44.64	Spesific gravity (G_s)	2.55
Plastic Limit-PL (%)	37.02	USCS	ML

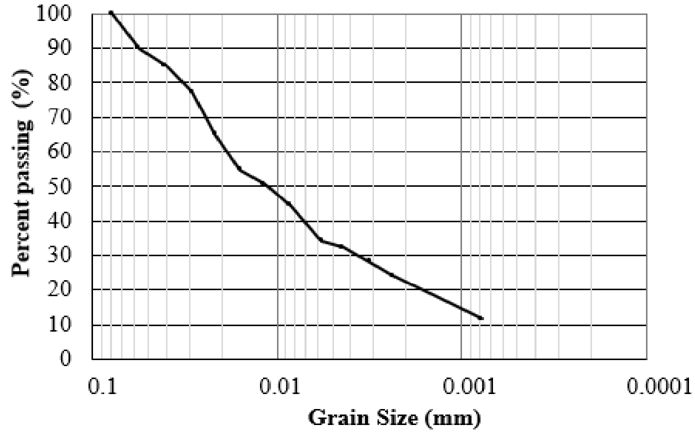


Figure 1. Particle size distribution curve of the kaolin soil

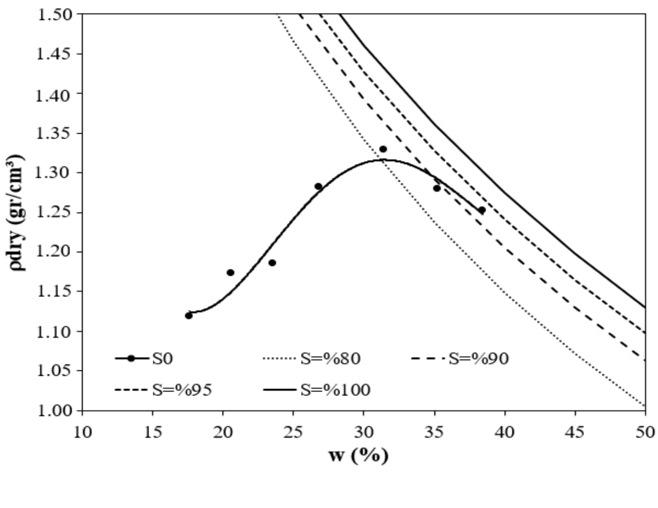


Figure 2. Standard compaction curve of the kaolin soil

Table 2. XRF analysis results of kaolin

Property	SiO_2	Fe_2O_3	CaO	Na_2O	Al_2O_3	MgO	TiO_2	K_2O	Cr_2O_3
Value (%)	71.00±2.00	0.40	0.15	0.10	20.00±2.00	0.05	0.50	0.35	0.35

2.2. Gypsum

Gypsum is available in various forms, including natural gypsum, synthetic gypsum, hemihydrate, and anhydrite. The selection of an appropriate gypsum type for the experimental study in the context of soil stabilization process is guided by several factors, including physical and chemical properties, environmental impact, and economic considerations. Among the different types, synthetic hemihydrate gypsum, which is pronounced as the construction gypsum, is produced by heating natural dihydrate gypsum ($CaSO_4 \cdot 2H_2O$) at elevated temperatures (approximately 150 °C) to convert it into the hemihydrate form ($CaSO_4 \cdot 2H_2O$) and often considered advantageous due to its uniformity, ease of handling, and predictable chemical composition. In the present study, the construction gypsum was selected for soil stabilization purposes based on its environmentally friendly characteristics, non-abrasive nature, chemical stability, and cost-effectiveness. Accordingly, a non-irritant, odorless, white-colored commercial gypsum was employed for soil-treatment. The physical, mechanical and chemical characteristics of gypsum are given in Table 3. The TS EN 13279-1 standard is the Turkish adaptation of the European norm EN 13279-1, and it serves as the fundamental European specification that defines the technical properties, material classification, and performance requirements of gypsum-based binders [25, 26]. The construction gypsum used in this study contains approximately 50% by weight calcium sulfate hemihydrate ($CaSO_4 \cdot 2H_2O$), a gypsum binder content of less than 50%, and various additional additives. It is white in color and exhibits a powder-like texture, with a maximum particle size of 1 mm, which is relatively close to that of the kaolin used (ranging from 0.075 mm to 0.002 mm) (Figure 3). The similarity in particle size between the soil and gypsum played a key role in achieving a uniform distribution of gypsum within the soil matrix.

Figure 3. ML type kaolin soil on the left and gypsum on the right

Table 3. Technical properties of the gypsum

Characteristics	Value	Units
Maximum grain size	1.0	mm
Compressive strength (28 days)	>2000	kPa
Flexural Strength	>1000	kPa
Calcium Sulfate hemihydrate $CaSO_4 \cdot ½H_2O$	49.5	%
Calcium Hydroxide $Ca(OH)_2$	0-2.0	%
Calcite $CaCO_3$	0.015-0.035	%
Tartaric Acid $C_4H_6O_6$	0.3-1.0	%
Gypsum Binder Content	<50	%

2.3. Sample preparation

To evaluate the effect of gypsum on the consistency, compaction, and strength–deformation behavior of ML soil, Atterberg limits, standard compaction, and unconfined compressive tests were performed. All specimens, including the untreated soil (0% gypsum) and gypsum-stabilized samples with contents of 2%, 5%, 8%, and 11%, were prepared following the same procedure. The soil was first passed through a No. 200 sieve and then oven-dried at 105 °C for 24 hours. After oven-drying, the soil was adjusted to the predetermined moisture content. For the untreated sample, it was mixed mechanically with distilled water only, whereas for the gypsum-treated samples, it was mixed with gypsum at proportions of 2%, 5%, 8%, and 11% by weight, along with water. The mixture of soil, gypsum, and distilled water was thoroughly blended for 15 min. until the surfaces of all soil particles were uniformly coated to provide a homogeneous distribution of gypsum and water through soil. The soil mixtures were cured for 24 hours in a desiccator after being placed inside a sealed bag, wrapped with stretch film and aluminum foil, and then enclosed in an additional sealed bag (Figure 4). This procedure enabled that all particles in the soil-additive mixture were uniformly saturated with moisture, brought to be ready for subsequent testing of Atterberg limits, standard compaction and unconfined compression.

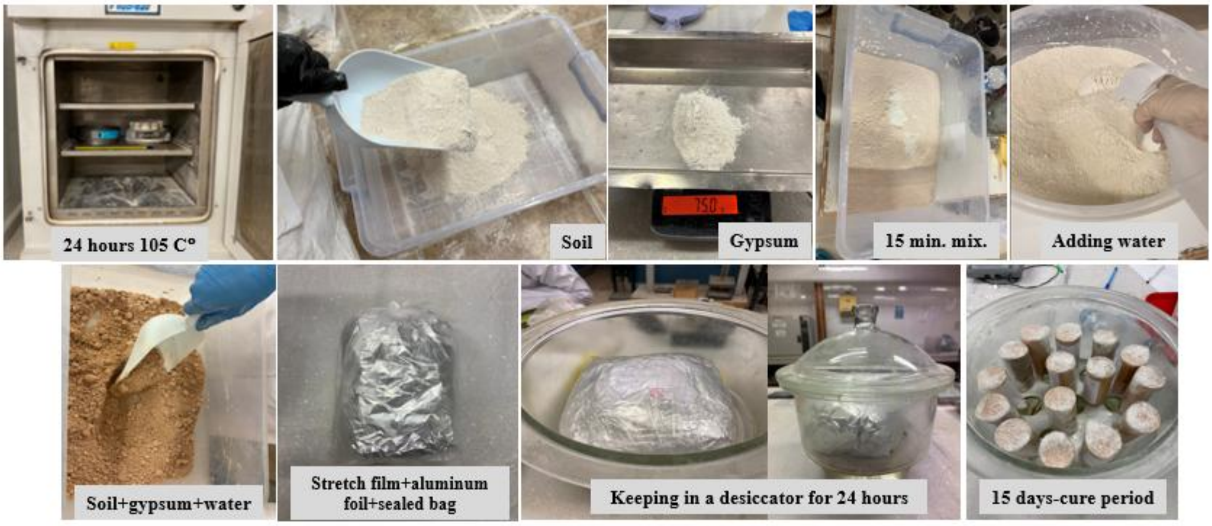


Figure 4. Sample preparation procedure

3. Experimental Studies

Following the sample preparation procedure, the consistency limits were determined for the untreated soil (0% gypsum) and for gypsum-stabilized samples containing 2%, 5%, 8%, and 11% gypsum by weight. The homogeneous mixtures were subsequently compacted using standard compaction energy to obtain compaction curves and determine the corresponding optimum moisture contents. To assess the unconfined compressive strength of both untreated and gypsum-stabilized samples, the soil-gypsum mixtures were compacted at their respective optimum moisture contents, and cylindrical specimens with dimensions of 36 mm x 80 mm were prepared for unconfined compressive testing. For each gypsum rate and curing period, three soil specimens were prepared to ensure the repeatability and reliability of the experimental results, hence the experiments were performed on these three specimens. The findings of this study are interpreted based on the average values; thus the reliability of experimental results was ensured. During the measurement of the compressive strength of the soil-gypsum mixtures, a curing procedure was applied. For this purpose, the cylindrical specimens unmolded from the compaction mold were wrapped with stretch film to prevent moisture loss and placed in a desiccator for curing period of 1 and 15 days (Figure 4). Upon completion of the relevant curing periods, the specimens were subjected to unconfined compressive test. At the end of the tests, the strength-strain relationships were investigated. Effect of gypsum content and curing durations are compared for each sample. The main reason for choosing 1- and 15-days curing periods in this study, is to evaluate the apparent early-age strength gain of gypsum based binders and the effects of short-term reactions. The gypsum binder shows a fast hydration process when exposed to water, hence significant changes occur in its inner microstructure in the first 24 hours. The curing period of 1 day was selected to observe early-age behavior and to evaluate the initial bonding mechanisms. Besides, 15 days curing period was selected to evaluate the difference between early-age strength gain and intermeadiate behavior, and to assess the continuity of stabilization effect. This period presents a time period that can be used efficiently in short and intermediate term engineering applications.

During the experiments, the results obtained from the untreated specimens (0% gypsum) were used as reference values. The data of the gypsum-treated samples containing 2%, 5%, 8%, and 11% gypsum were compared against these reference results. A specific labeling system was developed to compare the unconfined compressive test results of the soil–gypsum mixtures based on the gypsum content and curing duration (Table 4).

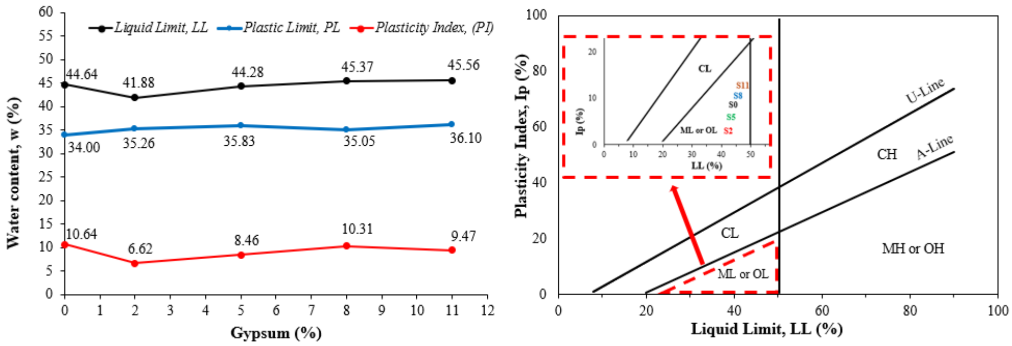
Table 4. Specimen test labeling scheme

Tests	Additive gypsum ratio (%)	Cure Durations (days)	
		1	15
Unconfined Compressive Strength	0	S0-1	S0-15
	2	S2-1	S2-15
	5	S5-1	S5-15
	8	S8-1	S8-15
	11	S11-1	S11-15

In the specimen test labeling scheme presented in Table 4, the first term represents the gypsum content incorporated into the soil, whereas the second term indicates the curing duration. Accordingly, "S8–15" denotes a specimen containing 8% gypsum that was cured for 15 days. Following the completion of the designated curing periods (1 and 15 days), unconfined compressive tests were performed on both untreated (0% gypsum) and gypsum-treated (2%, 5%, 8%, and 11% gypsum) specimens in accordance with ASTM D2166. During testing, a constant displacement rate of 1.27 mm/min was applied to determine the relationship between unconfined compressive strength (q_u) and axial strain. The results of experimental program are presented under several subsections below, taking into account the influence of gypsum additive content (%) and curing period on the consistency limits (e.g., Atterberg Limits), compaction characteristics and strength-strain behavior.

3.1. Effect on atterberg limits

Liquid limit and plastic limit tests were performed on gypsum-treated soil samples containing 2%, 3%, 5%, 8%, and 11% gypsum by weight (Figure 5a). As illustrated in Figure 5, the addition of 2% gypsum reduced the liquid limit by approximately 3%. However, higher gypsum contents (5%, 8%, and 11%) did not result in any significant change in the liquid limit and plastic limit. The plasticity index decreased by approximately 4%, 2%, 0.32%, and 1.17% with increasing gypsum contents, respectively. Notably, the only meaningful change in the consistency limits occurred at the 2% gypsum content, and the soil classification (ML) remained unchanged in the Casagrande plasticity chart (Figure 5b).



(a) (b)

Figure 5. Atterberg limit tests on untreated (0% Gypsum content) and Gypsum-treated soil samples (2%, 5%, 8%, and 11% additives)

3.2. Effect on compaction characteristics

The relationships between the optimum water content and the maximum dry density, determined under standard Proctor energy for both untreated and gypsum-treated soils, are presented in Figure 6 and Table 5. As shown in the experimental results, the addition of 2% gypsum to the kaolin reduced the optimum water content while increasing the maximum dry density. In contrast, higher gypsum contents of 5%, 8%, and 11% resulted in an increase in the previously reduced optimum moisture content and a corresponding decrease in the maximum dry density. Nevertheless, the optimum water content and maximum dry density of kaolin treated with 5% and 8% gypsum remain lower and higher respectively, than those of the untreated kaolin.

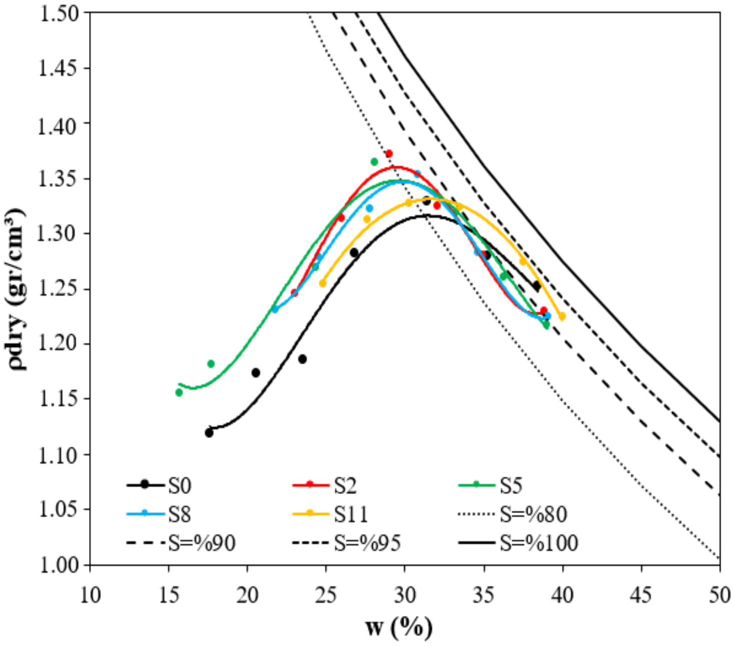


Figure 6. Standard compaction curves of gypsum-treated (2%, 5%, 8%, 11% additives) and untreated samples

Table 5. Compaction characteristics for gypsum-treated and untreated samples

Gypsum additive (%)	0	2	5	8	11
ρ_{drymax} (g/cm^3)	1.34	1.37	1.36	1.35	1.34
OWC (%)	32	29	30	31	32

3.3. Effect on strength-strain behavior

Unconfined compressive strength (UCS) tests were performed on soil specimens, prepared for each gypsum content (e.g., S0, S2, S5, S8 and S11 corresponding to 0%, 2%, 5%, 8%, and 11%), and subsequently subjected to curing periods of 1 and 15 days (Figure 7 and Figure 8), [27]. For each gypsum content, three replicate cylindrical specimens were taken from the same compacted mold to be tested under unconfined compression. The axial stress (σ) and strain (ε) relations for the specimens are presented both individually and as mean curves for 1- and 15-day curing periods, revealing very similar trends (Figure 7 and Figure 8). The initial portion of the compressive stress–strain curves (i.e., up to 1-2% strain) does not accurately reflect the fundamental mechanical properties, as the rough surfaces at both ends of the specimens prevented full contact with the loading platens during compression. The compressive stress was observed to increase approximately linearly with axial strains in the initial loading phases. Beyond the elastic region, the rate of stress increase accelerated; however, this trend gradually diminished as the specimens approached their peak strength, after which the stress decreased with further straining. All axial stress-strain curves exhibited a distinct strain-softening response following the attainment of peak strength (i.e., unconfined compressive strength, q_u). Moreover, increases in both gypsum content and curing duration influenced the stiffness of the elastic region. This led to variations in the initial stress-strain slope.

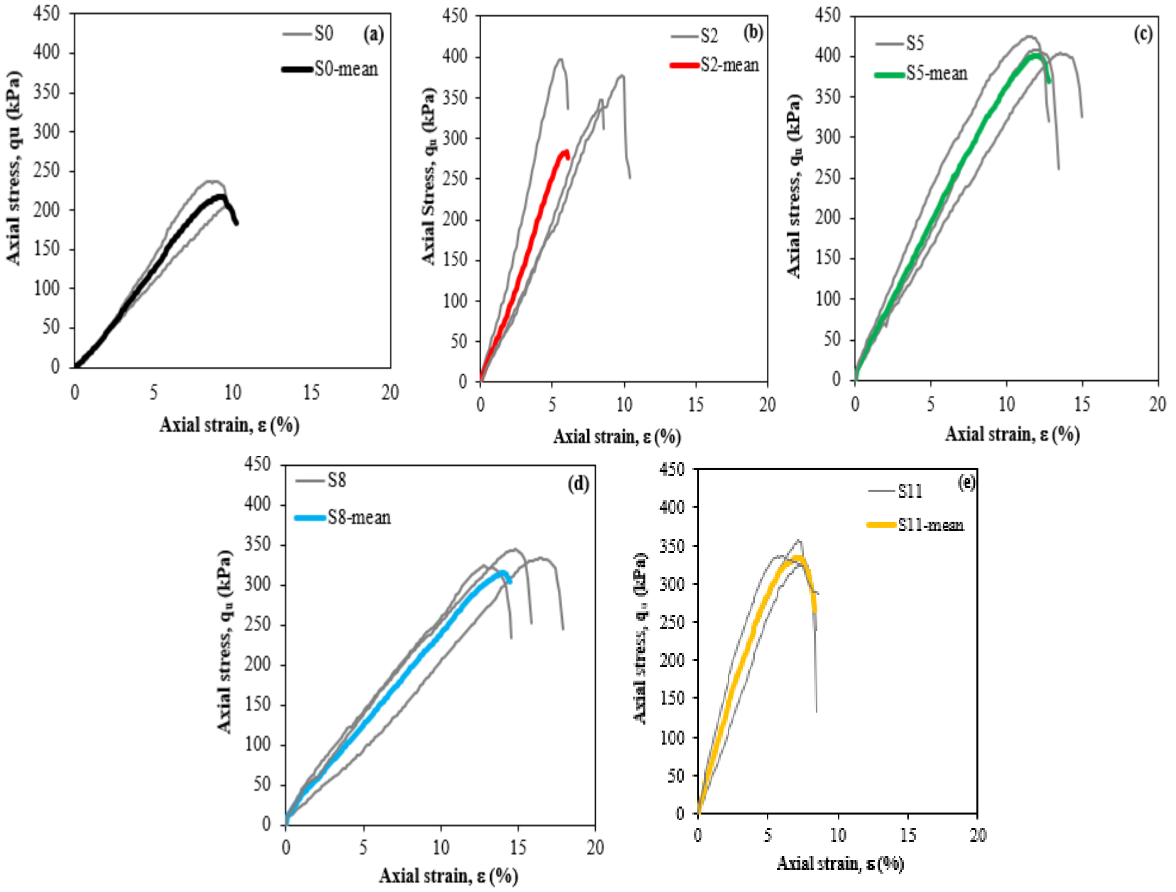


Figure 7. Stress-strain relations of the treated and untreated soils for 1-day curing period (a) without gypsum (S0); (b) S2; (c) S5; (d) S8; (e) S11

In Figure 7a, the mean unconfined compressive strength (UCS) of the untreated soil (S0) was measured as 221 kPa. This is corresponding to an axial strain of approximately 9.2%. The addition of 2% gypsum occured a substantial increase in strength. The strength reached average value of 376 kPa. The corresponding strain remained virtually unchanged at 8.5% (Figure 7b). The mixture containing 5% gypsum exhibited the highest strength (412.7 kPa). It is at a strain level of 12.3% and indicating that this rate of additive provides the most effective improvement in mechanical behavior (Figure 7c). When the gypsum content is 8%, the strength decreased to 333 kPa; however, this mixture reached the highest strain (14.5%) among the specimens cured for 1-day (Figure 7d). At a gypsum content of 11%, strength (345 kPa) and strain (7.3%) decreased (Figure 7e). These results suggest that increasing the gypsum content beyond an optimal level leads to higher stiffness and, consequently, more brittle behavior.

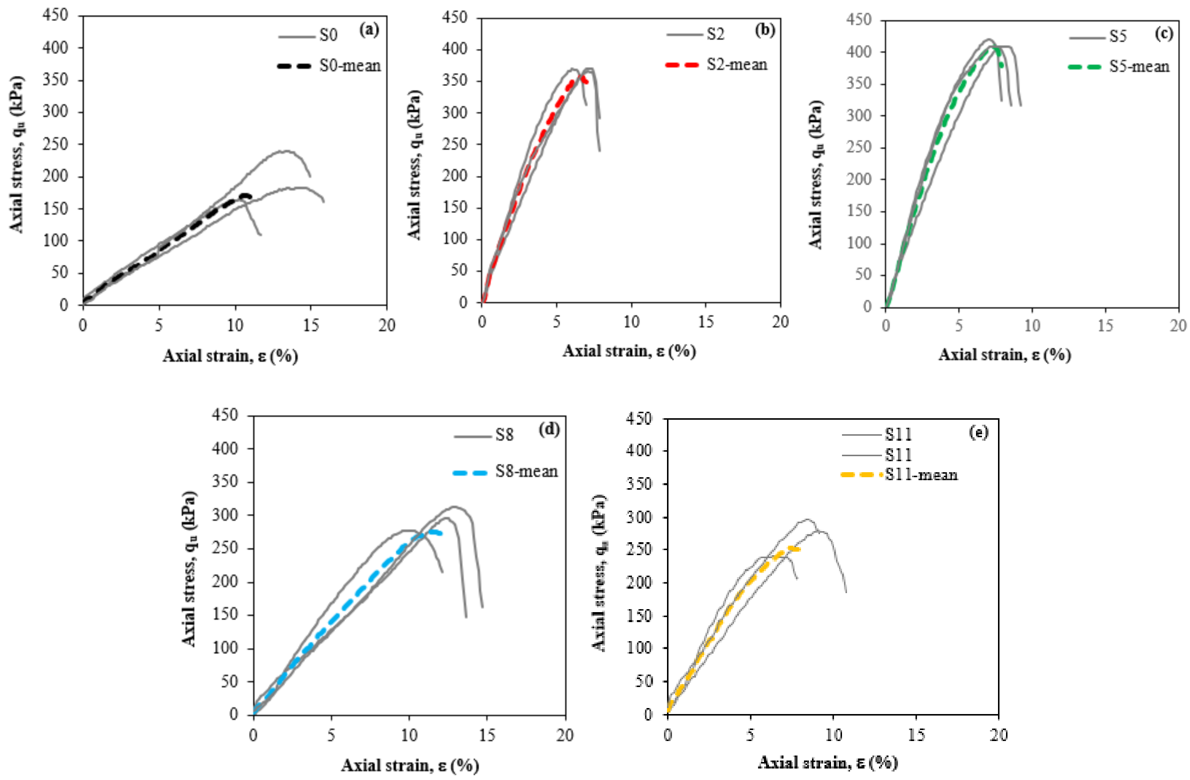


Figure 8. Stress-strain relations of the treated and untreated soils for 15-days curing period (a) without gypsum (S0); (b) S2; (c) S5; (d) S8; (e) S11

The stress-strain curves for the specimens cured for 15 days exhibit trends similar to those observed in the 1-day cured samples (Figure 8). The average unconfined compressive strength of the untreated soil (S0) is 196 kPa and an axial strain of 12.53% (Figure 8a). The average unconfined compressive strength of the addition of 2% gypsum soil (S2) is 196 kPa and an axial strain of 6.74%. This led to a substantial improvement (Figure 8b). The mixture containing 5% gypsum (S5) attained the highest strength, with an average value of 414 kPa and a corresponding strain of 7.49% (Figure 8c). When the gypsum content was increased to 8% (S8), the strength decreased to an average of 296 kPa, whereas the strain increased markedly to 11.72% (Figure 8d). The samples with 11% gypsum (S11) obtained an average value of 272 kPa, with a mean strain of 7.99% (Figure 8e). In general, these findings indicate that, after a 15-days curing period, moderate gypsum content (approximately 5%) provide the most effective enhancement in soil strength, while higher gypsum content tends to reduce strength.

3.4. Effect of cure treatment on the stress-strain behavior of gypsum treated kaolin

A comparison of the 1-day and 15-day curing results reveals the significant influence of curing time on the strength behavior of gypsum-treated soils (Figure 9 and Figure 10). For all gypsum contents, curing for 15 days led to notable variations in both strength and strain response. While the untreated soil exhibited a slight reduction in unconfined compressive strength after 15 days, gypsum-stabilized samples generally showed strength gains or maintained comparable values relative to the 1-day results (Figure 9a). The most substantial improvement with curing time was observed for the 2% and 5% gypsum mixtures (Figure 9b-9c). In both curing conditions, the 5% gypsum content consistently yielded the highest unconfined compressive strength, confirming the moderate gypsum addition provides optimal binding and pozzolanic interaction within the soil matrix. Conversely, higher gypsum contents (8% and 11%) exhibited reduced strength after prolonged curing, suggesting that excessive gypsum may disrupt soil fabric or increase brittleness, leading to diminished load-bearing capacity (Figure 9d-9e). Additionally, while moderate gypsum contents (2%-5%) showed reduced strain, indicating stiffer and more brittle behavior (i.e., lower plastic deformation capacity), higher contents (particularly 8%) tended to increase ductility after 15 days of curing (Figure 9f-9g). It is noteworthy that, 1-day curing period resulted in higher compressive strength and larger strains for gypsum contents ranging from 3% to 10%, indicating a more ductile response characterized by an increased deformation capacity. Overall, the comparative assessment highlights that curing time enhances the stabilization performance of gypsum at moderate contents, whereas excessive gypsum continues to have a detrimental effect on strength despite extended curing. In addition, the fracture patterns of the specimens were examined using the images taken before and after the tests (Figure 11 and Figure 12). The fracture patterns observed after 1- and 15-days of curing are presented in Figure 11 and Figure 12, respectively.

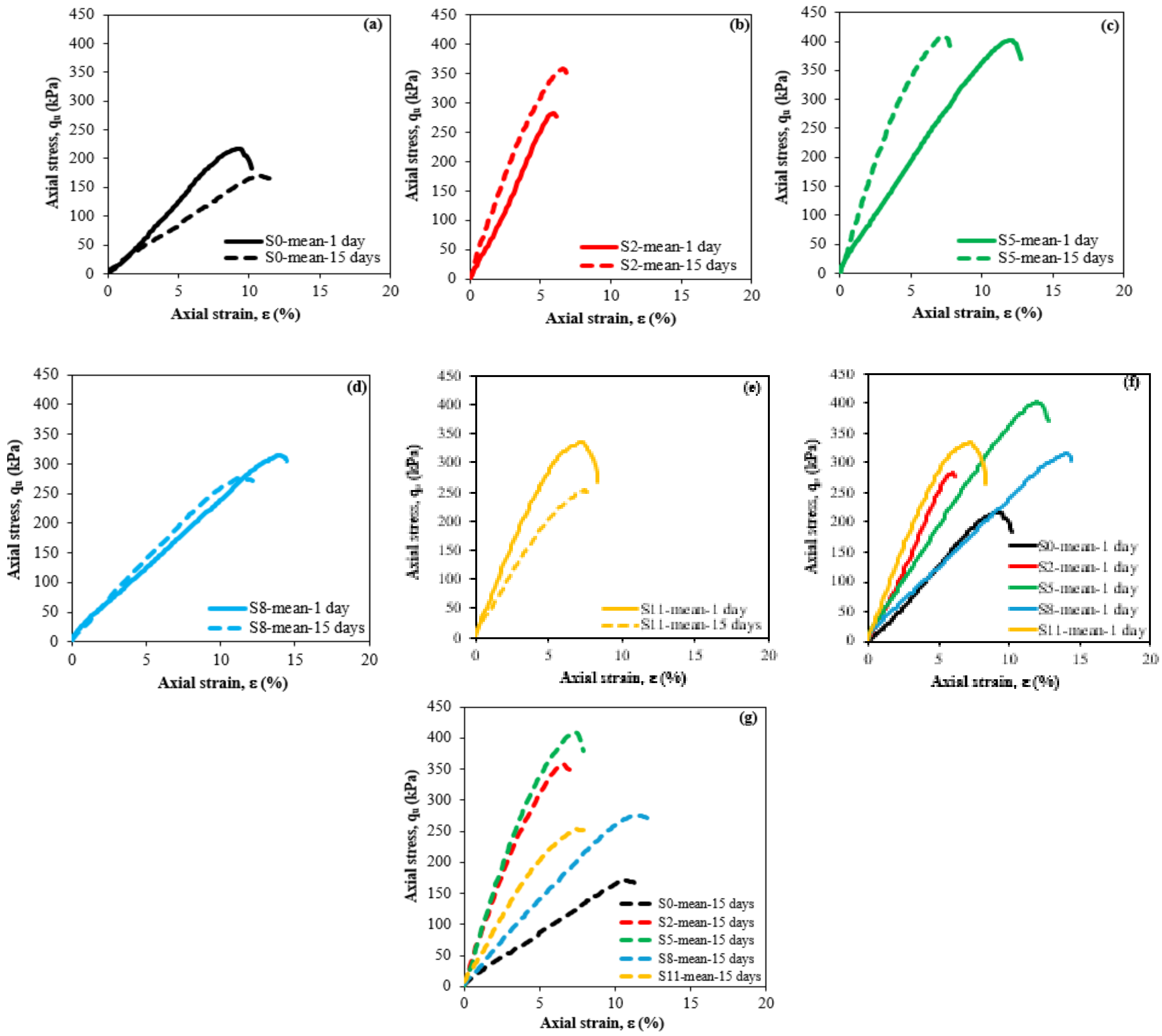
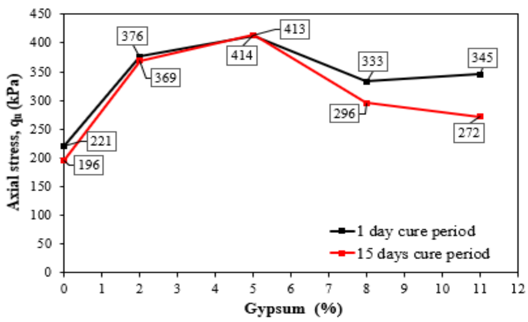
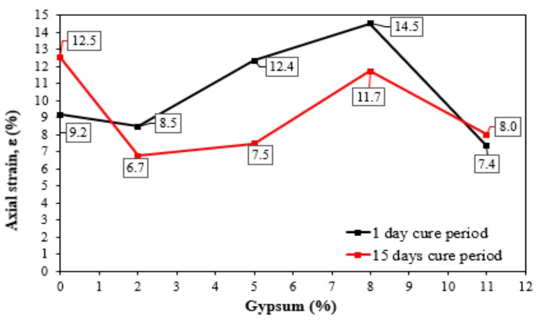


Figure 9. The effect of curing time on the stress-strain relations of treated and untreated soils



(a) Stress-gypsum rate relation



(b) Strain-gypsum rate relation

Figure 10. Stress-strain relations of different gypsum rates for 1-15 days curing periods

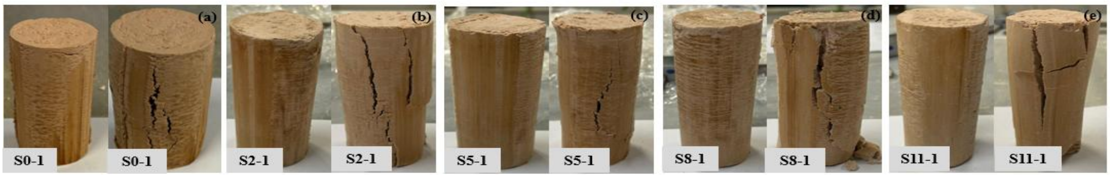


Figure 11. Before and after images of the treated and untreated soils for 1-day curing period (a) without gypsum (S0); (b) S2; (c) S5; (d) S8; (e) S11

Figure 12. Before and after images of the treated and untreated soils for 15-days curing period (a) without gypsum (S0); (b) S2; (c) S5; (d) S8; (e) S11

The failure planes for 2% and 11% gypsum additives are observed notably all along the soil specimens supporting the brittle behavior seen in Figure 11 and Figure 12. Besides, the cylindirical specimens of both 5% and 8% gypsum additives turned into a more elliptical form by the effect of compressive strength as a results of ductile behavior (Figure 11 and Figure 12).

4. Microscobic Analyses

The macrostructural changes observed in the experimental studies are primarily dependent on the microstructure of the soil. For this reason, the microstructure of soil-gypsum mixtures was examined in detail and correlated with the macrostructure. Chemical (Fourier transform infrared spectroscopy analyses, FT-IR and energy dispersive spectrometry, EDS) and microscopic (Scanning electron microscopy, SEM) analyses were performed on soil-gypsum mixtures. The analyses revealed the physical and chemical reactions between the soil and additive, grain-void layer structure, and elemental content of the samples.

4.1. Fourier transform infrared spectroscopy analyses (FT-IR)

FT-IR spectroscopy method can be used to determine the chemical structures of organic compounds. In this study, FT-IR analyses (Perkin Elmer Spectrum 100) were carried out on ML type soil, gypsum, and the kaolin-gypsum mixtures of S2, S5, S8 and S11 to identify atoms with different functional groups and chemical bonds. The chemical structures, functional groups and compounds of ML, gypsum and mixtures were determined and subsequently possible chemical and/or physical interactions between soil and different gypsum rates were investigated (Figure 13).

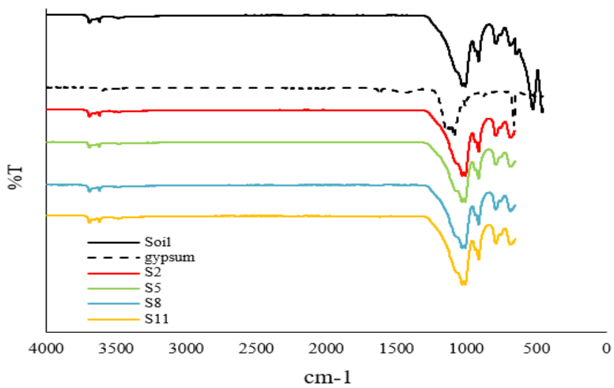


Figure 13. FT-IR spectra of gypsum, kaolin S0 and mixtures of S2, S5, S8 and S11

The soil used in this study is predominantly composed of silica and alumina, as confirmed by XRF analysis, which reveals high SiO_2 (~71%) and Al_2O_3 (~20%) contents (Table 2). In addition, minor amounts of Fe_2O_3, TiO_2, K_2O, and CaO are also detected. These oxide components suggest the formation of an aluminosilicate framework with possible Si–O–Al, Si–O–Fe, and Si–O–Ti structural linkages. The relatively low CaO content indicates that the soil does not contain a significant calcium-based binding phase. XRD analysis further supports this composition by indicating the dominance of silicate-based mineral phases. However, the absence of sharp and well-defined peaks corresponding to crystalline kaolinite suggests that the soil structure is not fully ordered, and may instead consist of partially amorphous or poorly crystalline aluminosilicate phases. This interpretation is also consistent with SEM observations, which indicate a heterogeneous and less ordered microstructure. The FT-IR spectrum of the soil (Figure 13) is in good agreement with the XRF findings. The bands observed in the range of 3600–3650 cm^{-1} are attributed to O–H stretching vibrations associated with structural hydroxyl groups and adsorbed water. These bands appear relatively broad, indicating a less ordered hydroxyl environment compared to well-crystallized clay minerals. A broad band in the 3400–3450 cm^{-1} region corresponds to hydrogen-bonded O–H stretching vibrations of physically adsorbed water molecules, while the band near ~1650 cm^{-1} is assigned to H–O–H bending vibrations, confirming the presence of moisture within the soil matrix. The most prominent bands are located in the 1000–1100 cm^{-1} range and are attributed to Si–O stretching vibrations. These bands clearly indicate the dominance of silicate structures in the soil and are consistent with the high SiO_2 content obtained from XRF analysis. At lower wavenumbers, bands observed in the 500–600 cm^{-1} range are associated with Al–O, Fe–O, and Ti–O vibrations, reflecting the contribution of minor oxide components to the overall structure. Additionally, bands in the 400–500 cm^{-1} region correspond to the bending vibrations of Si–O–Si and Si–O–Al linkages, indicating the presence of a complex and heterogeneous aluminosilicate network.

In the spectrum of pure gypsum, distinct bands are observed. The broad band in the 3400–3500 cm^{-1} range corresponds to O–H stretching vibrations of bound water related to the hydration of gypsum. The peak around ~1650 cm^{-1} is associated with the bending vibrations (H–O–H bending) of the bound water molecules. Sharp bands observed in the 1140–1110 cm^{-1} region reflect the symmetric and asymmetric stretching vibrations of the SO_4^{2-} group. Bands in the 670–610 cm^{-1} range correspond to bending vibrations of SO_4^{2-}, confirming the sulfate content of gypsum. A weak peak around 500 cm^{-1} is attributed to Ca–O bonds. No additional characteristic peaks are observed in the spectrum, indicating that the crystal structure of gypsum is typically identifiable by FT-IR.

The FT-IR spectra of gypsum-stabilized soil samples (S2, S5, S8 and S11) reveal clear changes as the gypsum content increases. In sample S2, the O–H stretching band at 3400–3500 cm^{-1} is still weak, and the H–O–H bending band at 1650 cm^{-1} is limited, while the Si–O stretching bands in the 1000–1100 cm^{-1} range remain dominant. This indicates that the spectral features are still mainly controlled by the soil matrix, with only minor contributions from gypsum. In S5, the O–H and H–O–H bands become more pronounced, and the SO_4^{2-} stretching bands around 1140–1110 cm^{-1} start to appear, reflecting an increasing influence of gypsum in the system. In S8, the O–H stretching and H–O–H bending bands are further intensified, and the SO_4^{2-} bending bands at 670–610 cm^{-1} become stronger, confirming the growing role of gypsum in the mixture. In S11, gypsum-related bands dominate the spectrum, whereas the silicate bands are still present but relatively weaker. This demonstrates a gradual shift from a silicate-dominated structure toward a gypsum-influenced system as the gypsum content increases. Across all samples, the broad O–H bands at 3400–3500 cm^{-1} and the peaks around 1650 cm^{-1} become more intense with higher gypsum content, corresponding to an increased presence of bound water and hydroxyl groups associated with gypsum hydration. Similarly, the SO_4^{2-} bending bands in the 600–700 cm^{-1} region show a clear increase in intensity. No new characteristic peaks are observed, indicating that no new crystalline phases are formed. The interaction between soil and gypsum is primarily physical, likely involving ionic interactions rather than the formation of new chemical bonds. Overall, the FT-IR results indicate that as the gypsum content increases, the system gradually transitions from a silicate-dominated structure to a gypsum-influenced one, with sulfate and hydroxyl groups becoming progressively more significant in the spectral response.

4.2. Scanning electron microscopy (SEM) analyses

SEM analyses were conducted to investigate the grain-void structure of materials. Due to the very small sample sizes used in SEM analyses (~2–3 g), obtaining a sample fully representative of the entire soil structure is challenging. For this reason, in this study, SEM (Zeiss EVO LS 10) examinations were performed on pure soil (S0) and soil with 5% gypsum (S5, representing the optimum gypsum ratio). The grain-void structures were observed at different magnifications (1 KX, 5 KX, and 10 KX), and the corresponding images for S0 and S5 are presented in Figure 14a–14d and Figure 14e–14g, respectively. In addition to visualizing the microstructure, energy dispersive spectrometry (EDS) analyses were performed simultaneously to identify the elemental composition of the samples, with results summarized in Table 6.

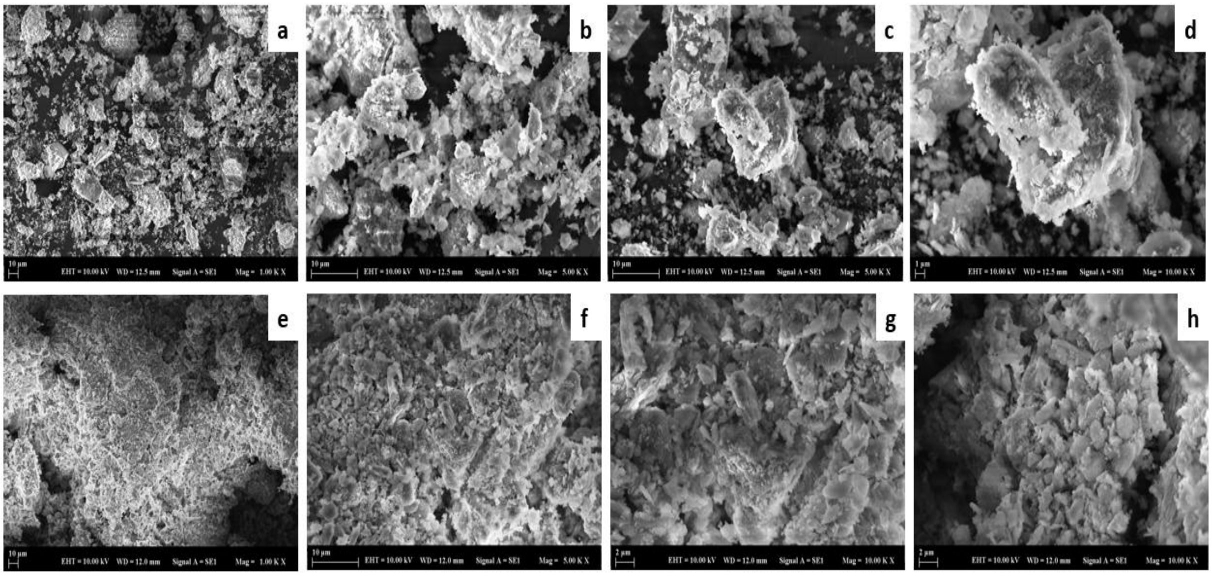


Figure 14. SEM analyses of S0 and S5

Figure 14a-14d shows that the S0 soil has a layered structure with voids between the layers, variable grain sizes, and a non-homogeneous soil with a wide range of grain sizes. Besides, the images of the S0 show an irregular and loosely packed grain-void structure. This corresponds to the particle size diameter distribution curve presented in Figure 1. At lower magnifications (1 KX) in Figure 14a, the soil particles appear heterogeneously distributed with noticeable interparticle voids, indicating a porous matrix. As the magnification increases (5 KX and 10 KX) in Figure 14b-14d, individual grains can be observed with rough, angular surfaces, and micro-voids are clearly visible between particles. This microstructure suggests limited particle cohesion in the untreated soil, which may correspond to lower compressive strength. In contrast, the SEM images of the S5 reveal a more compact and cohesive structure (Figure 14e-14h). The particles appear to be partially bonded, with reduced interparticle voids and a denser arrangement, especially evident at higher magnifications (5 KX and 10 KX). The gypsum addition seems to promote flake-like and sheet-like structures on the particle surfaces, suggesting early cementation and potential improvement in mechanical stability. Overall, the incorporation of 5% gypsum modifies the microstructure by reducing porosity and enhancing particle connectivity, which aligns with expected improvements in strength and durability.

Table 6. EDS results of S0 and S5

	S0		S5	
	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
O	48.9	62.8	50.4	65.8
Mg	-	-	0.1	0.1
Al	9.4	7.2	10.1	7.8
Si	40.1	29.3	22.3	16.6
S	-	-	6.3	4.1
K	0.4	0.2	0.5	0.2
Ca	0.2	0.1	9.9	5.2
Ti	0.3	0.1	0.1	0.1
Cr	0.2	0.1	0.1	0.0
Fe	0.4	0.1	0.3	0.1

The EDS results presented in Table 6 reveal the main elemental composition, which is consistent with the soil and gypsum compositions shown in Tables 2 and Table 3. In particular, Si, O, and Al were detected at high levels in both analyses. The high abundance of elements and their chemical bonds in the soil and gypsum are also consistent with the chemical bonds and functional groups identified in the FT-IR spectra. In addition, the FT-IR spectra support the chemical bonds of the observed elements and phases, reinforcing the SEM and EDS findings as well as the material's structural and chemical integrity. These mutually supporting observations enhance the reliability of the data and provide a comprehensive characterization of the material.

5. Results

The present study provides originality by means of using gypsum alone as a soil treatment additive compared to previous studies which mostly used gypsum with cement or another binder (e.g., additives). Hence this study aimed to contribute toward filling this gap, the experimental evidence for gypsum-alone stabilization effects on ML-type clayey soil. The results of the present study are compatible with the results of Al-Adili et al. [15] for CL soil, Al-Hokabi et al. [28] for ML soil, Zha et al. [9] for CH soils, investigated soil stabilization by gypsum-alone for clayey soils revealing a decrease and then increase in LL with increasing gypsum content. The reduction in LL and hence plasticity of soil is related to the cation exchange mechanism on clay particles where the cations such as sodium and potassium in clay structure are replaced by higher valence cations like calcium in the structure of gypsum, that resulted in thinner water diffusion around the clay particles [5]. Besides, especially the rate of additives in the structure of gypsum may increase the water absorption of low-plasticity soils [9]. For this study, these two mechanisms explain the initial decrease in LL and PI up to a certain range of gypsum content and then increase. The results obtained through compaction tests were evaluated as compatible with the trends declared in the literature. Especially in low plasticity soils, it has been stated that fine grained gypsum particles may fill the voids of soils resulting an increase in MDD [18, 19]. In this study, it was observed that the low rates of gypsum additives increased the MDD and decreased the OWC. Moreover, the decrease in MDD in higher rates of gypsum additive exhibits a compliant behavior with the literature in which the excess rates of gypsum resulted in the distortion of void structures [6, 29, 30]. Gypsum additive changes the mechanical soil properties as well by restructuring the soil particles (e.g., flocculation and agglomeration) and bonding the particles together (e.g., cementitious hydration and pozzolanic reaction) [6]. Especially pozzolanic reactions and hydration process contribute to the development of a hardened soil matrix, thereby increasing shear strength. Numerous previous studies primarily investigated on the clayey soils employing a curing period of 7 to 28-days, have reported two distinct trends in the strength behavior of gypsum-treated soils. The first trend indicates a continuous increase in unconfined compressive strength (q_u) with increasing gypsum content, whereas the second trend reveals the existence of an optimum gypsum content, generally within the range of 5%–15%, beyond which q_u decreases as the gypsum content continues to rise [8, 12, 13, 31]. In the present study, similarly the maximum strengths for 1-day and 15-day curing periods are consistent with the second trend, indicating that the optimum gypsum content was determined as 5%, beyond which the unconfined compressive strength (q_u) decreased with further gypsum addition. The optimum 5% gypsum rate defined in this study, is compliant with the lower limits for low plasticity ML-type soils, as reported in the literature, however it may vary due to soil mineralogy and cation exchange mechanisms [7, 8, 9], [12, 13]. Besides, the curing period of 15 days was found to slighlty reduce the q_u values once the optimum gypsym content was exceeded, exhibiting a trend that is broadly consistent with previous studies. The microstructural analyses results also demonstrate findings that are consistent with the mechanisms reported in the literature. Especially in SEM analyses of 5% gypsum included soil sample, the observed void reduction and increase in interparticle bonding show similarities with the development of a denser microstructure declared by the previous studies [8, 9]. These microstructural changes are believed to play a key role in the strength increase observed in the UCS tests. Furthermore, the increase in sulfate bands observed in the FTIR analyses is associated with gypsum hydration and consistent with the binder formation mechanisms reported in the literature.

The results obtained in this study presents practical insights that can be used in ground improvement design. Especially, defining the optimum gypsum content as 5% may help in selecting an economical and effective stabilization rate for low-plasticity ML-type soils. The strength increase at low rates of gypsum binder together with the development of a dense microstructure, provide an advantage for increasing the soil bearing capacity. Also, the soil stability is improved by by limiting the deformations under seismic loading. The results of this study may be used as a guideline for engineering design of short-and intermediate-term ground improvement applications for shallow foundations and enbankments in low-plasticity soils. Finally, the utilization of gypsum from C&D wastes in ground improvement contributes to sustainable engineering by reducing traditional binder usage and promoting recylable materials.

6. Conslusions

The transformation of gypsum-based plasterboard materials, commonly used as interior design components of the constructions, into C&D waste following urban renewal projects has promted consideration of their reuse in soil stabilization from a sustainability perspective. This study aimed to investigate the change of physical and mechanical properties of low-plasticity silt (ML) type kaolin soil by commercially used powdered synthetic hemihydrate gypsum ($CaSO_4 \cdot 1/2H_2O$) sold in construction markets. Within the context of this study, 2%, 5%, 8% and 11% rate of gypsum additives were used for treatment of kaolin soil for 1 day and 15 day curing periods, meanwhile applying Atterberg limits, standard Proctor and unconfined compressive tests. Through these assessments, the optimum gypsum content that yields effective soil improvement was identified, and the influence of curing duration on the mechanical response of the treated soil was determined.
The conclusions of this study are summarized as follows:

(1) This study contributes to the existing literature since it reveals short and intermediate period strength gain behavior on ML-type soils stabilized solely with gypsum through mechanical and microstructural analyses. In particular, microstructural evaluations supported by SEM, EDS and FTIR analyses provided valuable insights into the underlying the strength gain mechanisms.
(2) Despite the shorter curing periods of 1 and 15 days compared to the commonly used 7-28 days, the strength development trends observed in this study are consistent with the literature findings. The maximum strength was achieved at 5% gypsum content, confirming the comparability of the observed behavior with reported mechanisms.
(3) Consistency limit tests indicated that the liquid limit (LL) and plasticity index (PI) decreased with the addition of gypsum up to 5% content and then increased. Besides, the plastic limit (PL) increased continuously with increasing gypsum content. Accordingly, the highest decrease in PI and LL were obtained at gypsum contents of 2% and 5% in descending order.
(4) The highest maximum dry density and the lowest optimum water content was observed at gypsum contents of 2%, 5% and 8%, respectively, in descending order. This behavior can be attributed to the filling of interparticle voids in the low-plasticity soil by the finer gypsum particles, leading to a denser packing structure. In contrast, a higher gypsum content of 11% did

not lead to significant change in the compaction characteristics. This is because largely filled interparticle voids tend to form weak clusters rather than contributing to a denser packing arrangement.

(5) For both curing durations (1 and 15-days), the unconfined compressive strength increased with increasing gypsum content, reaching a peak value at 5% gypsum. The strength (q_u) declined with further gypsum addition beyond 5% gypsum. While moderate gypsum contents (2-5%) were associated with lower axial strains, reflecting a more brittle response, higher gypsum contents (particularly 8-11%) led to increased strain values, indicating a tendency toward more ductile behavior. According to the results of consistency limits tests, compaction characteristics and stress-strain response, the optimum gypsum content for kaolin was identified as 5%. The microstructural observations through SEM analyses are in compliance with the mechanical behavior obtained by UCS tests as well. Especially the increase in particle bonding and void reduction by pozzolanic and cementitious interactions is consistent with the highest strength values obtained at this gypsum rate. This findings suggests that low to moderate gypsum addition promotes cation exchange and flocculation mechanisms, resulting in microstructural curing hence development of enhanced strength. In contrast, excessive gypsum contents (8%-11%) and extended curing periods, results in alteration of the soil fabric adversely, leading to a reduction in unconfined compressive strength.

(6) Although moderate gypsum addition improves the short-term strength of kaolin including rapid strength gain and potential for sustainable reuse of gypsum-based construction waste, its use as a soil improvement material should be carefully evaluated due to durability concerns. Gypsum's moderate solubility and the swelling potential of anhydrite by wetting may cause long-term strength loss and deformation. Therefore, gypsum-based stabilization appears more suitable for controlled or short-term applications where moisture exposure is limited and long-term durability requirements are not critical.

7. Acknowledgement

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8. Author Contribution Statement

In this study, Author 1 and Author 2 contributed to the conception of the idea and the design of the experimental program; Author 1 was responsible for the implementation of the experimental studies; Author 2 conducted the literature review; Author 3 and Author 4 carried out the experimental work; Author 1 prepared and organized the graphs and figures; Author 1 and Author 2 evaluated and interpreted the obtained results; and Author 2 reviewed the manuscript in terms of writing quality and content.

9. Ethics Committee Approval and Conflict of Interest

"There is no conflict of interest with any person/institution in the prepared article. Additionally, ethics committee approval is not required for this study."

10. Ethical Statement Regarding the Use of Artificial Intelligence

"No artificial intelligence-based tools or applications were used in the preparation of this study. The entire content of the study was produced by the author in accordance with scientific research methods and academic ethical principles."

11. References

[1] K. Yang, Q. Xu, T. G. Townsend, P. Chadik, G. Bitton, and M. Booth, "Hydrogen sulfide generation in simulated construction and demolition debris landfills: Impact of waste composition," *J. Air Waste Manag. Assoc.*, vol. 56, no. 8, pp. 1130–1138, 2006.

[2] M. Mirabi, M. Hadadkazarji, and M. Abbasi, "Recycling of construction and demolition gypsum wastes as stabilizer of soft clay soil and effects of drying–rewetting frequency on the treated soil stability," *Environ. Resour. Res.*, vol. 9, no. 2, pp. 117–132, 2021.

[3] D. Kuttah and K. Sato, "Review on the effect of gypsum content on soil behavior," *Transp. Geotech.*, vol. 4, pp. 28–37, 2015.

[4] C. Spaulding, F. Masse, and J. Labrozzi, "Ground improvement technologies for a sustainable world," *Civ. Eng.*, vol. 78, no. 4, pp. 54–59, 2008.

[5] J. K. Mitchell and K. Soga, *Fundamentals of Soil Behavior*, 3rd ed. New York, NY, USA: John Wiley & Sons, 2005.

[6] N. Latifi, F. Vahedifard, S. Siddiqua, and S. Horpibulsuk, "Solidification–stabilization of heavy metal–contaminated clays using gypsum: Multiscale assessment," *Int. J. Geomech.*, vol. 18, no. 11, 2018.

[7] I. Yılmaz and B. Civelekoglu, "Gypsum: An additive for stabilization of swelling clay soils," *Appl. Clay Sci.*, vol. 44, nos. 1–2, pp. 166–172, 2009.

[8] A. K. Jha and P. V. Sivapullaiah, "Role of gypsum on microstructure and strength of soil," *Environ. Geotech.*, vol. 3, no. 2, pp. 78–89, 2016.

[9] F. Zha, B. Qiao, B. Kang, L. Xu, C. Chu, and C. Yang, "Engineering properties of expansive soil stabilized by physically amended titanium gypsum," *Constr. Build. Mater.*, vol. 303, Art. no. 124456, 2021.

[10] I. Yılmaz, "Gypsum and anhydrite: Some engineering problems," in *Proc. 15th Int. Conf. Soil Mech. Geotech. Eng.*, vol. 2, 2001, pp. 1203–1206.

[11] N. Değirmenci, A. Okucu, and A. Turabi, "Application of phosphogypsum in soil stabilization," *Build. Environ.*, vol. 42, no. 9, pp. 3393–3398, 2007.

[12] A. Ahmed, K. Ugai, and T. Kamei, "Laboratory and field evaluations of recycled gypsum as a stabilizer agent in embankment construction," *J. Geotech. Geoenviron. Eng.*, vol. 137, no. 10, pp. 975–984, 2011.

[13] S. H. Khan, "Use of gypsum and bagasse ash for stabilization of low plastic and high plastic clay," *J. Appl. Res. Ind. Eng.*, vol. 6, no. 3, pp. 251–267, 2019.

[14] H. Jang *et al*., "Hardening performance of reclaimed gypsums for stabilizing agent to improve soft clayey ground," *J. Mater. Cycles Waste Manag.*, vol. 19, pp. 654–663, 2017.

[15] A. Al-Adili, N. M. Salim, and K. Y. Al-Soudany, "Response of soft soil mixing with recycled gypsum (plasterboard) as stabilized agent for soil underneath oil tank as a case study," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 579, 2019.

[16] T. E. Helle, S. Nordal, P. Aagaard, and O. K. Lied, "Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay—Ulvensplitten, Norway," *Can. Geotech. J.*, vol. 53, no. 3, pp. 410–422, 2016.

[17] T. Kamei, A. Ahmed, and K. Ugai, "Durability of soft clay soil stabilized with recycled bassanite and furnace cement mixtures," *Soils Found.*, vol. 53, no. 1, pp. 155–165, 2013.

[18] I. P. Hastuty, "Comparison of the use of cement, gypsum, and limestone on the improvement of clay through unconfined compression test," *J. Civ. Eng. Forum*, vol. 5, pp. 131–138, 2019.

[19] M. S. Eisa, M. E. Basiouny, A. Mohamady, and M. Mira, "Improving weak subgrade soil using different additives," *Materials*, vol. 15, Art. no. 15134462, 2022.

[20] ASTM D6913/D6913M-17, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*. West Conshohocken, PA, USA: ASTM Int., 2017.

[21] ASTM D7928-17, *Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis*. West Conshohocken, PA, USA: ASTM Int., 2017.

[22] ASTM D854-14, *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*. West Conshohocken, PA, USA: ASTM Int., 2014.

[23] ASTM D4318-17, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. West Conshohocken, PA, USA: ASTM Int., 2017.
[24] ASTM D1557-12, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort*. West Conshohocken, PA, USA: ASTM Int., 2012.
[25] EN 13279-1, *Gypsum Binders and Gypsum Plasters—Part 1: Definitions and Requirements*. Brussels, Belgium: Eur. Comm. Stand. (CEN), 2014.
[26] TS EN 13279-1, *Gypsum Binders and Gypsum Plasters—Part 1: Definitions and Requirements*. Ankara, Türkiye: Turkish Standards Inst. (TSE), 2014.
[27] ASTM D2166/D2166M-16, *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. West Conshohocken, PA, USA: ASTM Int., 2016.
[28] A. Al-Hokabi, M. Hasan, M. Amran, R. Fediuk, N. I. Vatin, and S. Klyuev, "Improving the early properties of treated soft kaolin clay with palm oil fuel ash and gypsum," *Sustainability*, vol. 13, no. 19, Art. no. 10910, 2021.
[29] K. A. Bhardwaj and S. Kumar, "Stabilization of soil with calcium chloride using gypsum," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 7, pp. 117–124, 2019.
[30] R. K. Dutta and J. S. Yadav, "The impact of variation of gypsum and water content on the engineering properties of expansive soil," *Transp. Infrastruct. Geotechnol.*, vol. 9, no. 5, pp. 631–652, 2022.
[31] Y. Abdolvand and M. Sadeghiamirshahidi, "Soil stabilization with gypsum: A review," *J. Rock Mech. Geotech. Eng.*, vol. 16, no. 12, pp. 5278–5296, 2024.