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Improving the Properties of Gypsum Soil Using Cement and Lime Mixtures

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ABSTRACT

Soil is the medium in which the agricultural and non-agricultural activities are carried out and it is the base of food production for human beings. Gypseous soils are one of the most troublesome soil types, and can cause severe damage to building foundations because it's a collapsible soil. This failure happens when water gets to the gypseous soil grains and dissolves the gypsum bonds. Gypsum soils are highly soluble, and are poorly structurally stable and thus pose serious problems for construction and agriculture. These soils typically experience over settlement and loss of supporting capacity when they come into contact with water. Application of lime and cement stabilization has shown potential in solving these issues. The characteristics of gypsiferous soils, the conventional stabilizing materials (limestone and cement), and conventional methods of treatment are reviewed and the effect of these treatments on the behaviour of gypsiferous soils is examined. The physical and chemical characteristics of gypsum soils are briefly discussed, as well as the chemical reactions and equations that occur when cement and lime are added to gypsiferous soil; and selected previous studies that used these stabilizers were presented.

1. Introduction

Gypsum-containing soil is known as gypseous soil, and it is typically hard when unsaturated due to the interaction between soil particles and gypsum. When the ground becomes wet, the cementitious gypsum bonds between soil particles dissolve, resulting in a dramatic increase in soil compressibility and collapse potential [1]. Numerous problems are associated with these soils, including gypsum's high water solubility, which is considered one of the primary obstacles to their productive exploitation, as well as nutrient scarcity resulting from low organic matter content. The most important factors are water quality, temperature, ionic strength, gypsum crystal size and method of irrigation [2]. The high concentration of gypsum is one of the key issues that affect the agricultural productivity due to the poor chemical and physical properties. In addition to problems associated with the formation of hardened subsurface layers that impede root growth, the weak soil structure and low organic matter content reduce its water-retention capacity and interfere with water movement due to gypsum's high solubility (2.06 $g \cdot L^{-1}$) [3]. Serious problems such as soil particle leaching and gypsum salt dissolution caused by water flow through gypseous soil lead to significant alterations in physical and chemical characteristics [4]. Furthermore, the dissolution of calcium and soluble sulfate creates cavities beneath structural foundations, causing abrupt settlement and failure, and resulting in significant volumetric changes [5]. Increasing soil stability and reducing deformation are the primary objectives of soil reinforcement to

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prevent settlement and erosion. Studies have shown that higher gypsum concentrations and void ratios increase the collapse potential of gypseous soils, whereas higher initial water content and drying reduce it [6]. When dry, gypsum soils typically exhibit stiff behavior. However, fluctuations in water content caused by changes in the water table or water infiltration can substantially affect these soils. Gypsum dissolution may create voids and fissures that increase soil permeability. Moreover, pore water pressure is lower than pore air pressure in unsaturated conditions, and these soils behave as multi-phase systems. The primary geotechnical concern is that moisture reduces pore pressure, inducing effective stress changes, volume changes, and a reduction in shear strength. Water can also cause a decrease of inter-particle bonds, weakening the soil matrix and increasing the density [7]. Moreover, the fine dust particles produced in the process of cement manufacturing are also dangerous to all living beings, hence in the construction industry more effective and sustainable alternatives must be found [8]. Cement is commonly used for the stabilization of gypseous soil because of its positive impact on engineering properties, but it has many economic and environment related issues, such as high price, energy consumption, dust generation, CO_2 emission, health hazards, damage to vegetation and soil, and heavy metal content [9]. Their production is a major contributor to global greenhouse gas emissions, where almost 4% of the anthropogenic CO_2 produced comes from lime and cement manufacturing [10]. Soil stabilization is the process of modifying soil behavior for engineering purposes and is generally carried out to achieve the following goals: 1) increase strength, 2) modify permeability, and 3) reduce settlement [11]. Human activities contributing to soil collapse include water impoundment, irrigation, lawn watering, alteration of natural drainage patterns, and wastewater disposal [12].

2. Previous Studies

Al-Hadidi, M. T., and AL-Maamori, Z. H., 2019 [13] This study focuses on the deliberate treatment of gypseous soil with a soil-cement mixture. Collapsibility and settlement tests were performed on gypseous soil imported with a gypsum content from the Karbla Governorate (42.55%). Wight mixed the soil with different proportions of cement (2%, 3%, 5%, 8%, 10%, 13%, and 15%) and crushed it as much as possible. Dry density: 16.5 $kN/m3$ with 12.8% O.M.C. The tests conducted experimentally were carried out in a flume that has a constant velocity of 0.148 m/sec. The outcomes showed that (10) % cement reduces collapsibility by (86.54%), while the gypsum content of the soil remains nearly unchanged after 28 days. Aside from that, the minimum cure time, according to study, is 14 days.

Eliaslankaran, Z., et al 2021 [14] This study looked into the geotechnical behavior of soil that was taken from the Bagan Lalang coast and treated with lime, cement with rice husk ash (RHA) to create an inexpensive substitute mixture with eco-friendly qualities. Tests conducted in the lab were performed to examine the soil's physical characteristics (Compaction characteristics and Atterberg limits), as well as mechanical characteristics (direct shear and unconfined compressive strength (UCS) tests), in order to determine the effect of different stabilizer/pozzolan ratios on the coastal soil and the best conditions for each mixture. Examining the shear behavior of coastal soil was one of the study's objectives. and to determine the highest axial compressive stress that, in the absence of any limiting pressure, the treated specimens can tolerate. In contrast to the natural soil, the soil treated with a 1:2 ratio of lime and rice husk ash (LRHA) (8% lime content) showed a significant rise in shear stress at 200 kPa of normal tension.

Bahmyari, H., et al 2021 [15] This paper presents a wide range of a lab studies on the shear strength properties and collapse behavior of collapsible soils with various initial structures. This study also clarifies the critical role of chemical stabilization in Collapsible soils' mechanical characteristics and workability by varying the percentages of various stabilizer agents. The effect of curing time and agent concentration on the collapsibility, unconfined compressive strength, undrained shear strength, and consistency of treated collapsible soils was investigated. The findings revealed that cement performed better than natural pozzolan and lime. in terms of enhancing collapsible clays' engineering qualities and strength. The results showed suggests mixing soil with cement significantly reduced collapsibility while increasing un-drained shear strength by up to five times.

Al-Teameemi, H. K., and Al-Rubaiee, A. K., 2022 [16] This study investigates the impact of adding lime on gypseous soil's engineering characteristics collected from a portion of the Najaf-Karbla plateau (52, 48, 72% gypsum). This study also demonstrates a rise in the soil's gypsum content to the northwest of the study area. The three samples had optimal moisture content and maximum dry density (2.065, 2.025, and 2.003) of 15%, 14%, and 15%, respectively. The ideal moisture content rises and the maximum dry density falls as the hydrate lime ratio rises. The findings demonstrate that applying more than 3% hydrated lime to gypscous soil renders it non-plastic. Cohesion Force increases as the percentage of lime is increased from 3% to 6%, then declines as the proportion of lime is increased to zero when the addition is 9%. This is because lime strengthens molecular cohesion up to a maximum of 6%, after which it falls to zero at 9% of lime is added. The outcomes of a liquid limit change, and the soil becomes more liquid limit when it is treated because the hydrated lime significantly rises fluid boundaries, and it gets clear that the limit of fluidity.

Shivanshi, Jha, A. K., et al 2022 [17] Soil treatment with lime is a popular method for improving its properties. However, long-term viability of soil treated with lime in a variety of environmental circumstances, including chemical contamination, remains a concern. Lime-treated soil contaminated with different sulphatic water concentrations took longer to initiate swelling and reach its peak than untreated soil. It is due to the ease with which sulphatic water migrates and thus interacts with the ions in untreated soil, as opposed to the compacted matrix of soil treated with lime.

Ebailila, M., et al, 2023 [18] This research evaluates two calcium-based stabilizers for viability (Portland cement-C and lime-L) in soil stabilization. The outcomes showed that stabilizing pure kaolin with Portland cement produced the highest UCS and the lowest linear expansion when compared to lime and magnesium oxide. This is because Portland cement contains a higher concentration of Si+4 and Al+3 ions, which supply the oxides required for the nucleation and growth of hydrates, which are primarily responsible for the system's interlocking. The sulfate (gypsum) content in kaolin soil stabilized with calcium-based binders (lime and Portland cement) resulted in an increase in UCS and linear expansion due to ettringite formation, which was more pronounced in quicklime-stabilized samples.

Rodiah, F., and Ramadhani, S., 2025 [19] The intention of this study is to evaluate the efficacy of two clay soil stabilization techniques: MgCl + cement and lime stabilization. The study's findings show that stabilizing clay soil with MgCl + cement outperforms lime. The ideal moisture content is decreased when MgCl+ cement is added while increasing unrestricted compressive strength and clay soil cohesion. At higher concentrations, the MgCl and cement mixture is more efficient in increasing unconfined compressive strength and undrained cohesion, though lime increases density more steadily. If the primary goal is to achieve high strength and material stability, a mixture of MgCl and cement is recommended, particularly at a 10% concentration. Lime is still a good choice, though, for applications that call for high density and a high moisture content.

AlNaddaf, H. Q. et al, 2025 [20] Collapsible sandy gypseous soils from two sites: Karbala, which has an 18% gypsum content (G1), and Tikrit University, which has a 66% gypsum content (G2) are the subject of the study. The sand replacement method was used to determine the field dry density of the samples, which were representative of disturbed soils. The results were 1.61 g/cm3 for

G1 and 1.6 g/cm3 for G2. Under both saturated and unsaturated conditions, G1 and G2 showed comparatively high indexes of brittleness for untreated soils, indicating their propensity to fail suddenly after reaching peak deviatoric stress. Because G2 had a increased gypsum levels, which caused the soil's structure to dissolve, the brittleness was more noticeable. In G2, where brittleness was successfully reduced despite the elevated gypsum content, Cement's stabilizing effect was especially noticeable. The performance and dependability of gypseous soils are improved by cement stabilization, especially when gypsum dissolution and cyclic loading present serious difficulties.

3. Chemical and Physical Characteristics of Gypsum

Nearly all engineering challenges encountered by civil engineers in building and construction are caused by subsurface soil characteristics. Gypseous soil is one of the most problematic soil types; in certain regions, gypsum content can reach up to 70%. Gypsum is among the highly soluble salts in water [12]. It may occur naturally in building soils (referred to as gypseous, gypsiferous, or sulfate-bearing soils), or it may be added in small amounts to non-gypsiferous soils to improve their properties or to reduce the volume of gypsum-containing waste disposed of in landfills. Consequently, researchers worldwide have investigated the effects of adding lime and cement to enhance soil properties. Gypsum soils, also known as gypsiferous soils, are soils with high calcium sulfate dihydrate ($CaSO4•2H2O$) content. These soils are found in arid and semi-arid areas and have their own set of problems related to low fertility, structure instability and dissolution under certain conditions. The treatment technique should vary depending on the intended use of the gypsum soil: construction or agriculture. Gypsum soils can be effectively stabilized, irrigated and amended to achieve a significant improvement in performance. Table 1 [21] shows some of the chemical and physical properties of gypsum. The mechanical properties of the gypsiferous soil such as impact resistance, shear strength and plasticity index in response to different levels of compost addition have also been assessed. Results showed that compost application significantly enhanced shear performance and decreased penetration resistance, particularly in soils with low gypsum content [22]. Typical objectives of ground improvement techniques include increasing shear strength and bearing capacity, raising density, reducing permeability, minimizing deformations (settlement, heave, and distortion), improving drainage, accelerating consolidation, reducing imposed loads, providing lateral stability, enhancing liquefaction resistance, and transferring loads to deeper, higher-capacity strata [23]. These techniques are beneficial for numerous applications, including the following [24]:

1- Enhancing mechanical characteristics, like compressive and shear strengths.
2- Limiting shrinking and decreasing the potential for swelling and volume instability.
3- The plasticity index (PI) is declining.
4- Reducing the permeability.
5- Minimizing settlement, deformation, and compaction of the soil.
6- Reducing the size of silt and clay particles.
7- Growing the resilient modulus.
8- Making it more resilient to weathering, erosion, wet-dry cycles, and freeze-thaw cycles.

Table 1: Chemical and Physical Characteristics of Gypsum [21]

Chemical and Physical Characteristics of Gypsum	
Layers	Gypsum is composed of layers that are parallel of (SO4)2 groups that are tightly bound to $(Ca)^{+2}$. These layers are distinguished by sheets of (H2O) molecules with weak interactions between the H2O molecules in adjacent sheets.
Colures	Gypsum is either colorless or, because of impurities, can be white, gray, red, brown, or have various shades of yellow.

Hardness	Gypsum is easily scratched by fingernails due to its hardness of 2. It's also important to keep in mind that the hot liquid (HCl) can dissolve gypsum.
Monoclinic Structure	In a vacuum up to 1.33 Pa of pressure during thermal disintegration (<200 °C), Gypsum single crystals' original monoclinic structure may change into a hexagonal and ultimately an orthorhombic structure.
Specific Gravity	The specific gravity is 2.32.

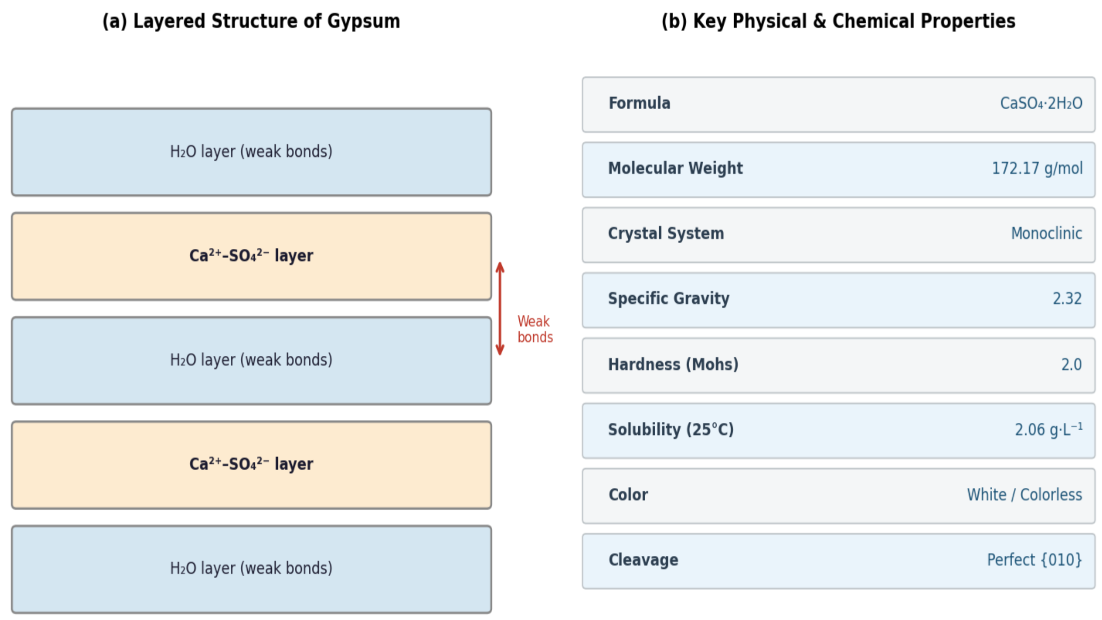

Figure 1. Layered structure and key chemical/physical properties of gypsum ($CaSO_4 \cdot 2H_2O$)

4. Chemical Reactions of Cement and Lime

4.1 Portland Cement Stabilization

Portland cement contains four primary clinker compounds: tricalcium silicate (C3S), dicalcium silicate (C2S), tricalcium aluminate (C3A), and tetracalcium aluminoferrite (C4AF). These are the essential molecules that contribute to the structural strength of the hardened cement paste. The main hydration products include hydrated calcium silicates (C2SHx and C3S2Hx), hydrated calcium aluminates (C3AHx and C4AHx), and calcium hydroxide (Ca(OH)2). When Portland cement components come into contact with water, a series of reactions occur, including the following [25]:

$$2(3CaO\cdot SiO2)+6H2O=3CaO\cdot 2SiO2\cdot 3H2O+Ca(OH)2, \quad (1)$$

$$2CaO\cdot SiO2 + 4H2O = 3CaO\cdot 2SiO2\cdot 3H2O + Ca(OH)2, \quad (2)$$

$$4CaO\cdot Al2O3\cdot Fe2O3 + 10H2O + 2Ca(OH)2 = 6CaO\cdot Al2O3\cdot Fe2O3\cdot 12H2O, \quad (3)$$

$$3CaO\cdot Al2O3 + 12H2O + Ca(OH)2 = 3CaO\cdot Al2O3\cdot 12CaOH2\cdot 12H2O, \quad (4)$$

$$3CaO\cdot Al2O3 + 10H2O + CaSO4\cdot 2H2O = 3CaO\cdot Al2O3\cdot Ca(OH)2\cdot 12H2O. \quad (5)$$

The following reactions are mostly for tricalcium silicate (C3S), the essential component of Portland cement:

$$C3S + H2O \rightarrow C3S2Hx + Ca(OH)2, \quad (6)$$

$$Ca(OH)2 \rightarrow Ca{++} + 2OH-, \quad (7)$$

$$Ca{++} + 2OH- + SiO2 \rightarrow CSH, \quad (8)$$

$$Ca{++} + 2OH- + Al2O3 \rightarrow CAH, \quad (9)$$

When pH < 12.6, then the subsequent response takes place:

$$C3S2Hx \rightarrow C3S2Hx + Ca(OH)2. \quad (10)$$

When C3A hydrates on its own, it quickly combines with water to form calcium aluminate hydrate platelets:

$$2C3A+21H \rightarrow C4AH13 + C2AH8. \quad (11)$$

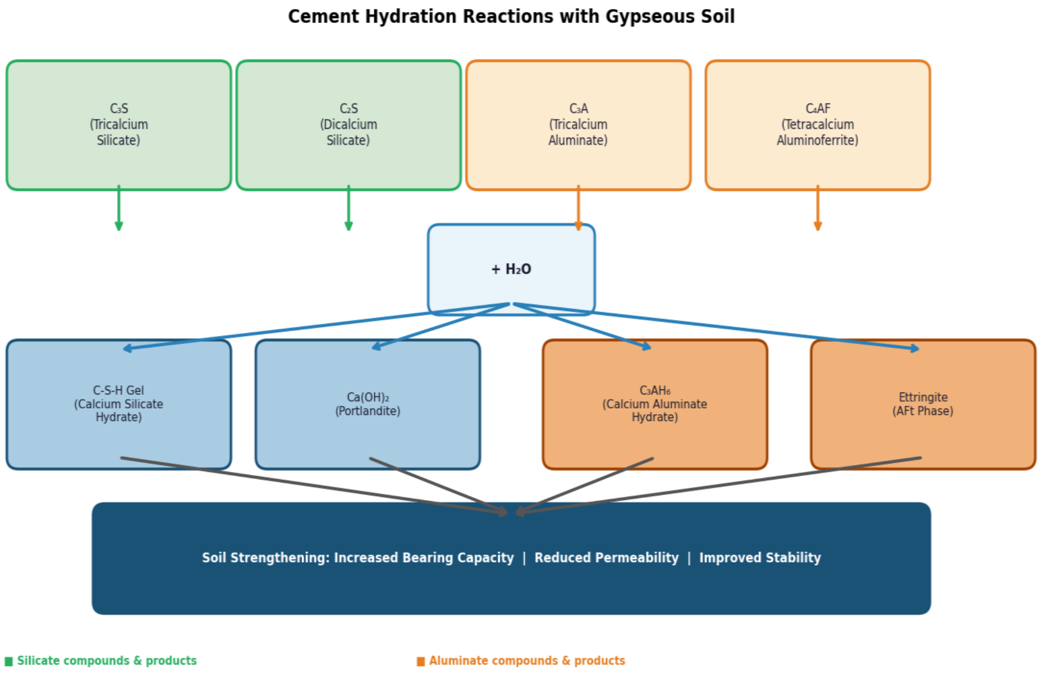

Figure 2. Flowchart of Portland cement hydration reactions and their products in gypseous soil stabilization

Lime treatment is one of the most commonly used methods for improving the engineering properties of gypsum-rich soils and mitigating the challenges associated with high gypsum content. The reaction between lime and gypsum and other soil components will change the soil's chemistry, structure and behavior. Lime is normally provided in the form of quicklime (CaO) or hydrated lime (Ca(OH)2). Lime is added to gypsiferous soils with the intent to provide a desired engineering benefit. The important factors that influence the result are the amount of lime, moisture in soil, mixing and curing method. The correct lime treatment approach for a specific construction project must be determined through proper soil testing, soil laboratory analysis and engineering design [26]. The cement industry accounts for about 10% of anthropogenic CO2 emissions [27]. There are four main sources of CO2 emissions in the cement industry: the decarbonation of limestone, transport, energy and fossil fuel combustion. Figure 3 [28] shows the relative contribution of each source to anthropogenic CO2 emissions [29].

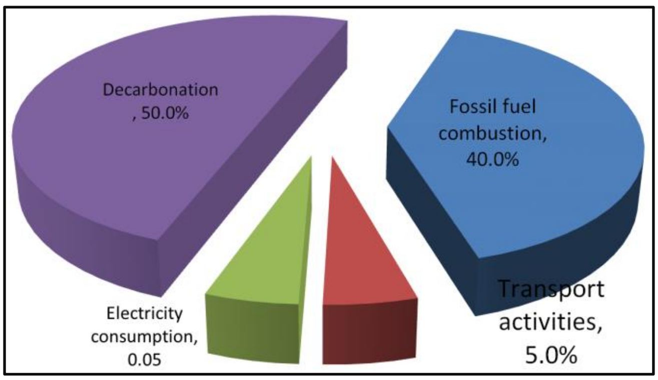

Figure 3. The cement industry sources of CO2 emissions [28]

4.2 Lime Stabilization

Grounded limestone is used for soil stabilization and is obtained by burning limestone. May be used as a pulverized quicklime (calcium oxide, CaO), milk-of-lime solution or hydrated lime (calcium hydroxide, Ca(OH)2). The binary mixes of lime and other additives showed that the soil compressive strength has been significantly increased than the hydrated lime alone as there are more efficient chemical interactions with the formation of calcium silicate hydrate (CSH) gel, which in turn increased the compressive strength and improved California Bearing Ratio (CBR) value. Quicklime (CaO) is obtained by calcining limestone (CaCO3) at about 1100 °C and liberating large amount of CO2. Approximately 40% of the limestone mass is lost as gas during calcination, predominantly as CO2. CaO exists in various forms, some readily available for chemical reactions and others chemically bound to other compounds, resulting in a difference between total and reactive CaO content. Typically, approximately 90% of burned lime consists of reactive CaO [30]

$$CaCO_3 \rightarrow CaO + CO_2 \quad (12)$$

When burned lime and water come into contact, hydrated lime is created:

$$CaO + H_2O \rightarrow Ca(OH)_2 + heat \quad (13)$$

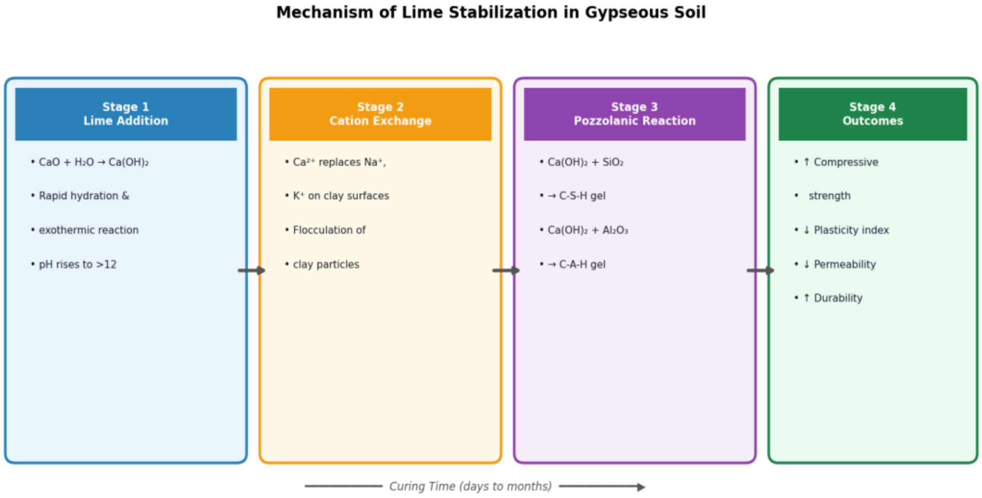

Figure 4. Four-stage mechanism of lime stabilization in gypseous soil, from hydration to long-term pozzolanic reaction

5. Stabilization of Gypsum Soils for Construction

The durability over time of stabilized soils is directly impacted by environmental factors like freeze-thaw cycles and wetting-drying cycles [31]. Thus, it is crucial to choose stabilizing agents that offer high chemical stability, resistance to harsh environments, and environmental compatibility in addition to improving mechanical performance [32]. In contemporary geotechnical practice, the long-term stability of stabilized soils under actual environmental conditions continues to be a significant challenge [33]. Gypsum-rich soils present significant construction risks due to their solubility and susceptibility to settlement. The principal stabilization approaches for gypsum soils used in construction are summarized in Table 2 [21]. Selecting the most appropriate soil stabilization technique is a complex task that requires engineers to consider technical requirements, financial constraints, available resources and equipment, field experience, and test results. In general, techniques for stabilizing or improving soil can be divided into the following categories: 1) Stabilization by mechanical means 2) Stabilization of electricity 3) Stabilization of

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temperature 4) Cooling stabilization, 5) Drainage stabilization, 6) Stabilization by chemicals, 7) Stabilization of lime, 8) Cement stabilization, 9) Stabilization of bitumen and 10) Stabilization of Geogrid [34]. One very effective mechanical method for stabilizing the soil is soil improvement or reinforcement. Chemical the process of enhancing the engineering qualities is called stabilization of undesirable soils by using admixtures, particularly emulsions, and chemicals as stabilizing agents in addition to modifiers, water-retaining agents, waterproofing agents, and other chemicals [35].

Table 2: Chemical and Physical Characteristics of Gypsum [21]

Stabilization of Gypsum Soils	
Lime and Cement Stabilization	Hydrates of calcium silicate, which hold dirt particles together, are created when lime reacts with soil.Cement makes the soil suitable for roads and foundations by increasing strength and decreasing permeability.
Bituminous Coatings	By acting as waterproofing agents, bitumen or asphalt emulsion layers stop water intrusion and gypsum dissolution.
Geotechnical Applications	The soil is stabilized and water movement is decreased when impermeable layers are placed beneath foundations.

In addition to the conventional chemical stabilizing agents previously discussed, road practitioners have consistently worked to investigate and create novel chemical stabilizing agents in order to improve both technical efficacy and commercial efficiency. Here are a few examples of cutting-edge chemical soil stabilizers: [36]

1- **Ionic stabilizer:** The water content's electrolyte concentration in matrix of soil changes when ionic stabilizer is added. The double-water layer thickness and inter-particle distance decrease when fewer water molecules are drawn to soil particles, which causes the clay particles to flocculate.

2- **Enzyme-based soil stabilizer:** Organic encapsulation is the most commonly accepted theory regarding the enzyme-based soil stabilization mechanism.

3- **Microbial induced calcite precipitation (MICP):** The creation of materials that bind particles through microbial reactions is known as bio-cementation or bio-mineralization. One of the most well-known techniques is microbially induced calcite precipitation. To efficiently fill the gaps, link the dirt particles together, and strengthen the soil, Calcium carbonate crystals are precipitated in the voids by MICP using microorganisms.

4- **Biopolymer soil stabilizer:** Biopolymers are polymers that are either produced intentionally by microbial action or bio-derived monomers, or they are derived from natural resources. Biopolymers are therefore regarded as environmentally benign.

5- **Synthetic polymer stabilizer:** Polyurethane (PU), polyvinyl alcohol (PVAO), polyvinyl acetate (PVA), polyacrylamide (PAM), polyethylene (PE), polypropylene (PP), polystyrene (PS), and styrene copolymer, and polyvinyl chloride (PVC) are common synthetic polymer stabilizers that can be found in powder, fiber, or liquid form.

6- **Polymer modified cementitious (PMC) stabilizer:** Soil stabilizers that work well include cement and cementitious chemicals. However, the main disadvantages of the treated soils are their brittle behavior and propensity to fracture under traffic loads. Pavement technologists use a variety of polymers to modify the property against internal crack formation and reinforce cementitious-stabilized soil substrate by implementing the concept of composite material.

7- **Nanotechnology for soil stabilization:** Nanotechnology is a multidisciplinary field of study that examines the structure and phenomena of materials at the nanoscale. When measurements of the material size range are scaled down to the microscale or nanoscale, many materials' properties change. Nanotechnology makes it possible to create novel materials and applications with distinctive properties, which have an impact on a variety of industries.

6. Classification of Soil Stabilization Technique

In geotechnical science, the gypseous content of the soil is crucial for determining volume change, soil properties, and strength. Three distinct terms are used to classify soils based on their gypsum content. The first is "gypsiferous soil," which contains a minor proportion of gypsum. The second is "highly gypsiferous soil," which has an intermediate gypsum content. The third is "gypseous soil," which refers to soils with the highest gypsum percentages. Gypseous soil is classified as slightly gypseous (3–10%), moderately gypseous (10–25%), highly gypseous (25–50%), and gypseous (more than 50%) based on its gypseous content. Gypseous soil stabilizations are categorized according to stabilization technique, as shown in Table 3 [37]. Thermal and chemical stabilization techniques can improve the gypseous loess soils' strength, stability, and durability. Thermal stabilization is the process of bringing specific noticeable changes into the soil through heating or cooling methods. Chemical stabilization techniques, on the other hand, add chemicals to improve characteristics of the soil. Enhanced power and control over volume variations, decreased plasticity index, deformability, and settlement are just a few advantages of these stabilization techniques [9].

Table 3: Methods of Treatment of Gypseous Soils [37]

Methods of treatment		Types
Mechanical stabilization	This technique, which entails altering the soil's properties or other features, is regarded as the outdated method of stabilizing soil.	• Compaction process • Soil Reinforcement • Adding Materials for Graded Aggregate. • The use of mechanical remediation.
Chemical processes	This treatment approach relies on the incorporation of materials to gypseous soil, such as cement, clinker, silica fume, and cutback asphalt, that interact physically and improve the soil.	-
Soil stabilization by using polymers	Compared to other treatment trends, using polymers for treatments should be substantially less harmful to the environment.	-

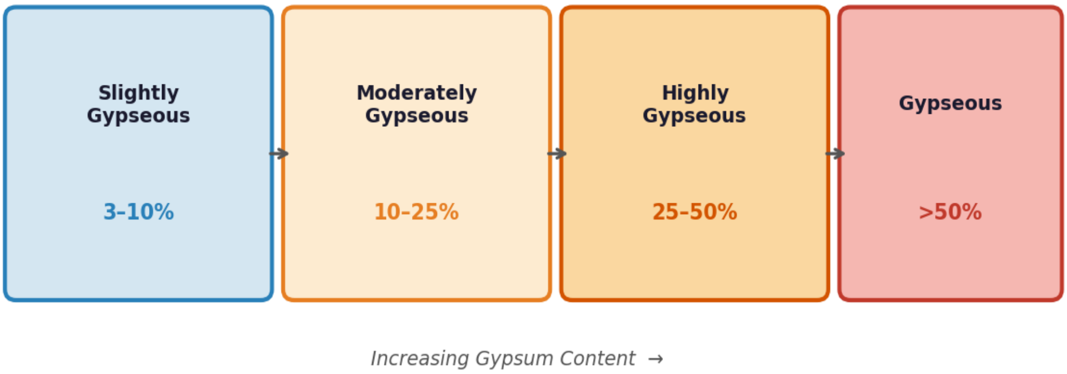

Figure 5. Classification of gypseous soil based on gypsum content [37]

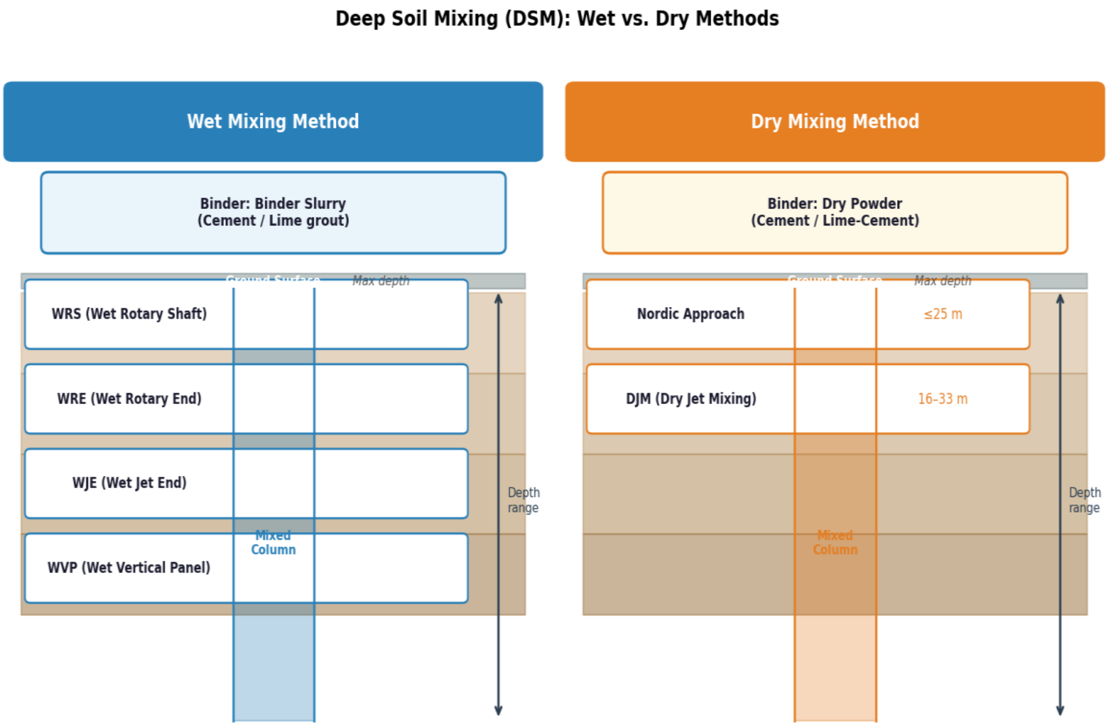

Figure 6. Comparison of wet and dry deep soil mixing (DSM) methods used for gypseous soil stabilization

7. Types of Deep Mixing

Deep soil mixing (DSM) employs two primary methods: wet mixing and dry mixing. In wet mixing, a binder slurry is mechanically injected and blended into the soil, whereas dry mixing introduces the binder in dry powder form [24].

7.1 Wet Mixing

The wet method is generally considered more appropriate for fine-grained sands, silts, and soft clays with relatively low moisture content. Wet mixing techniques can be broadly classified into four categories. This approach is particularly recommended for stratified soils containing alternating layers of stiff and soft materials or thick homogeneous soil layers [38–41], as described below:

- ✓ **Wet rotary shaft (WRS):** equipment that physically mixes the injected slurry with the surrounding soil using one shaft or multiple shafts and blades. Columns, panels, or blocks of mixed soil down to 30 meters are typical uses.

- ✓ **Wet rotary end (WRE):** apparatus with a single mixing tool and a single shaft. Common uses include high-volume mass stabilization to depths of up to 15 m or columns, panels, or blocks of mixed soil down to 40 m.
- ✓ **Wet jet end (WJE):** equipment with one or more shafts, blade tips, and high-pressure ports for slurry jetting assistance. Columns, panels, or blocks of mixed soil down to a depth of 25 meters are frequently used.
- ✓ **Wet vertical panel (WVP):** Chainsaws and other vertical cutting tools are mounted on a cutter post in the center. Common applications are continuous walls up to 50-m deep are commonly built.

7.2 Dry Mixing

Dry soil mixing (DSM) methods introduce dry binder materials directly into the soil, relying on existing soil moisture to hydrate the resulting in situ mixture. Although a variety of binders can be used, cement, lime-cement blends, and other cementitious materials that chemically interact with the soil are the most widely adopted. Compressed air is used to inject the dry binder into the ground, where it is thoroughly mixed using specially designed auger tools to treat the soil to the specified depth. The two primary dry mixing techniques are the Nordic approach and Japanese dry jet mixing (DJM). The DJM equipment can build columns to a depth of 16 – 33 m, with one or two mixing shafts [24].

8. Conclusion

Gypseous soils are an important type of problematic soils which can adversely affect building foundations. Their most important problem is collapsibility, which is the result of water coming in contact with gypseous soil grains and dissolving the gypsum bonds. These soils are very soluble and have poor structural integrity, which poses severe problems in construction and agriculture. The engineering properties of gypsiferous soils is improved significantly with cement or lime treatment in all the studies examined.

Cement or lime application to a gypseous soil modifies its mechanical characteristics including shear strength, compressive strength, swelling and volumetric instability, shrinkage, decrease of the plasticity index (PI), decrease of the permeability, refinement of clay and silt particle size, decrease of settlement and deformations, and increase of long-term durability through increase of resistance to erosion, weathering, freeze-thaw cycles and wet-dry cycles.

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Conflict of Interest

The authors want to emphasize that this article's publication does not create a conflict of interest.

Author Contribution Statement

The authors helped to collect and synthesize much of the literature, and studied the topic in detail from several angles, providing a helpful reference paper for anyone working in the gypseous soil stabilization field.

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