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# Impact of wetting–drying cycles on the microstructure and mechanical properties of lime-stabilized gypseous soils

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ABSTRACT

Gypseous soil is a problematic soil due to its high water sensitivity. Its behavior depends on its gypsum content and it loses much of its strength when saturated. Lime stabilization is a traditional technique used to stabilize soils in civil engineering works, mainly road construction. In order to assess the long-term stability of lime stabilized gypseous soils, the effect of wetting–drying cycles on the mechanical behavior of fine-grained soil with different gypsum contents (0, 5, 15 and 25%) was investigated. The soil samples were stabilized with 3% lime and subjected to different curing times of up to 28 days, then exposed to 6 wetting–drying cycles of 96 h each. Results showed that the strength of the compacted soil samples increased with curing time and that the maximum unconfined compressive strength was reached for the soil samples with 5% gypsum. While the wetting–drying cycles had a detrimental effect on the compressive strength and P-wave velocity of the soil samples, these effects varied with gypsum content. Greater loss in strength occurred in soil samples with 25% gypsum. These changes can be explained by the increase in water content during these cycles, crack propagation during drying and gypsum dissolution during wetting. Mineralogical and microscopic studies showed the formation of Ca-hydrates composed of different proportions of Ca, Si, and Al, responsible for the increased strength of stabilized soil samples. Ettringite was also found in stabilized soils and acts in the opposite direction to reduce the strength of soil samples. The durability of the tested gypseous soils treated with 3% of lime against wetting–drying cycles is not guaranteed. To ensure the durability of these problematic soils against environmental conditions, other percentages of lime and another stabilizer such as cement need to be tested.



## 1. Introduction and scientific background

Durability can be defined as the ability of the materials to retain their stability and integrity and to maintain adequate long-term residual strength to provide sufficient resistance to climatic conditions (Dempsey and Thompson, 1968). In addition to the mechanical and mineralogical properties of the soil, its durability under severe climatic conditions is a vital parameter when evaluating in situ the use of soil as a construction material. Climatic conditions, namely wetting–drying cycles, are considered to be one of the most destructive actions that can induce damage to infrastructures such as highways and pavements (Allam and Sridharan, 1981; Sobhan and Das, 2007). During these cycles most of the engineering properties of soils, especially their strength, are severely affected and as a result crack propagation and stability failure occur (Al-Obaydi et al., 2010; Al-Zubaydi, 2011).

Gypseous soils are currently used in geotechnical applications especially in the construction of infrastructures such as highways and pavements (Aiban et al., 1998; Razouki and El-Janabi, 1999; Rollings et al., 1999; Adams et al., 2008). The amount of gypsum in a soil is crucial in determining the properties, especially volume change and strength that are required for all geotechnical applications. Smith and Robertson (1962; see also FAO, 1990) found that a gypsum content of less than 10% does not significantly affect the soil characteristics (structure, texture and water retention). Moreover, several studies showed that the onset of problems associated with gypseous soils depends on the initial sulfate level in the soil prior to chemical stabilization (Hunter, 1988; Petry and Little, 1992; Adams et al., 2008; Aldaood et al., 2014a). Based on their studies, researchers have determined various initial amounts of sulfates (i.e. gypsum) at which problems such as a reduction in strength and an increase in swelling can be expected. In fact, fine-grained soils, especially gypseous soils, are usually known as environmentally susceptible and considered to be problematic, because they lose the engineering properties required for use in geotechnical structures when exposed to environmental conditions such as freezing–thawing (Saetersdal, 1981; Czurda and Hohmann, 1997; Aldaood et al., 2014b) and wetting–drying cycles (Hunter, 1988; Al-Obaydi et al., 2010; Little et al., 2010; Tang et al., 2011). However, the results of research into the effects of wetting–drying cycles on the stability of stabilized fine-grained soils are very disparate and depend on the soil type, percent of stabilizer, test methods and curing conditions (Shihata and Baghdadi, 2001; Khattab et al., 2007; Al-Obaydi et al., 2010; Al-Kiki

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**Table 1**
Some physical and index properties of natural soil.

| Property | | Value |
|---|---|---|
| Liquid limit (%) | | 29 |
| Plastic limit (%) | | 21 |
| Plasticity index (%) | | 8 |
| pH | | 8.0 |
| Electrical conductivity (mS/cm) | | 0.4 |
| Natural moisture content in situ (%) | | 18.5 |
| Specific gravity Gs | | 2.66 |
| Standard compaction | Max. dry density (kN/m$^3$) | 17.7 |
| | Optimum moisture content OMC (%) | 11 |
| Grain size distribution | Sand (%) | 17 |
| | Silt (%) | 64 |
| | Clay (%) | 19 |
| USCS | Group symbol | CL |
| | Group name | Sandy lean clay |
| Unconfined compressive strength (MPa) | | 0.19 |
| Wave velocity (m/s) | | 618 |

et al., 2011; Tang et al., 2011). Al-Obaydi et al. (2010) studied the durability of gypseous soil with 23% gypsum content, stabilized with cement and waste lime, and subjected to 12 wetting–drying cycles. The samples were cured for 7 days before testing. They determined that the natural soil samples showed no durability against wetting–drying, while the soil strength was enhanced with cement and waste lime additions. They concluded that the degree of deterioration due to wetting–drying cycles is dependent on the treatment used: the deterioration of samples stabilized with waste lime is more pronounced compared with samples stabilized with cement.

Lime stabilization is one of the most economical techniques for improving the engineering behavior of clayey soils (Ingles and Metcalf, 1972; Little, 1995; Paige-Green, 2008; Lemaire et al., 2013). The addition of lime to a soil causes two basic sets of reactions, one being a short-term reaction while the second is a long-term reaction (Little, 1995). The immediate effect of lime addition is to cause flocculation and agglomeration of the clay particles caused by cation exchange at the surface of the soil particles. The result of this short-term reaction is mainly to enhance workability and plasticity (Little, 1995; Mathew and Rao, 1997). The long-term reactions may require weeks, months or even years for completion, depending on the rate of chemical decomposition and hydration of the silicates and aluminates. This results in the formation of cementitious materials, which bind the soil particles together and improve the mechanical properties of the lime treated soil.

Limited information is available on the durability of lime stabilized gypseous soils, mainly with a controlled amount of gypsum in the tested soil. Thus, the main objectives of the present research were to:

- Analyze the performance of gypseous soil containing a wide range of gypsum content, under the effect of curing times and wetting–drying cycles.
- Assess the durability behavior of lime stabilized gypseous soils against wetting–drying cycles. In order to compare the results obtained, a single percentage of lime was used that corresponds to the optimal value for natural fine-grained soil.

The durability of untreated and lime treated gypseous soil was assessed based on geotechnical and microscopic analysis. On the geotechnical level, unconfined compressive strength and P-wave velocity measurements were investigated. pH, electrical conductivity, volume change and water content variations were also examined. On the microscopic level, mineralogical and micro-structural changes due to reactions between soil, lime and gypsum in the soil samples were analyzed at the end of curing times and wetting–drying cycles.

## 2. Materials and testing methods

### 2.1. Materials

In this study, three components were used for sample preparation: fine-grained soil, lime and gypsum. The fine-grained soil was obtained from a site near Jossigny in Paris, France. Samples were taken at a depth of about (1.5–2.0 m) below ground level. Before testing, the soil samples were oven dried for 2 days at 60 °C and gently disaggregated using a hammer then passed through ASTM #4 sieves. Laboratory tests such as Atterberg limits, specific gravity, hydrometer analysis and compaction were performed. Table 1 presents some indices and engineering properties of the soil, using the relevant tests according to the ASTM standard. The liquid limit was 29%, with a plasticity index of 8% and the specific gravity of the solid was 2.66. Based on the Casagrande plasticity chart and according to the Unified Soil Classification System (USCS), the soil was classified as a low plasticity clay soil (CL). The grain size distribution was 17% sand, 64% silt and 19% clay.

The quick lime used in this study, supplied by the French company LHOIST, was a very fine lime which passed through an 80 µm sieve opening. The activity of the lime used was 94%. The gypsum (dehydrate calcium sulfate, $CaSO_4 \cdot 2H_2O$), supplied by the Merck KGaA company, Germany, was a very fine gypsum which passed through an 80 µm sieve opening and had a purity of more than 99%.

### 2.2. Sample preparation

In order to conduct a precise parametric study, all the tested samples were prepared in the laboratory. As studies reported in the literature showed that the gypsum content in nature varies widely, in order to control the exact percentage of gypsum in the different samples tested and study a wide range of gypsum soil behavior, samples were prepared with three percentages of gypsum: 5, 15 and 25% by dry weight of soil. The natural and gypseous soil samples were treated with 3% lime (the minimum and appropriate amount of lime required for stabilization, giving a pH value of 12.4), based on the method of Eades and Grim (1966). To prepare the samples, the soil was thoroughly mixed with the predetermined amount of gypsum and lime in a dry state until the mixture had a homogeneous and uniform appearance. In order to investigate only the effect of gypsum content, all the materials were added using the complementary substitution method. Thus, to prepare the gypseous soil samples with a gypsum content of 5%, 95% of soil was mixed with 5% of gypsum; to prepare the lime-treated gypseous soil


**Fig. 1.** Disintegration the soil samples during soaking.