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Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt

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ABSTRACT

Stabilization using lime and cement is a widespread technique that provides civil engineering applications for soils with poor geotechnical performance. This article describes the effects of a combined lime + cement treatment on both the characteristics and properties of a plastic silt. A multi-scale approach was implemented and the mechanical, microstructural and physicochemical changes were investigated. To carry out these tasks, unconfined compressive strength measurements were conducted. The modifications caused by this treatment on the microstructure could be characterized by means of scanning electron microscope (SEM) observations of the soil composition, through element distribution maps and mercury intrusion porosimetry (MIP) analyses. The physicochemical evolution has been monitored by X-ray diffraction (XRD) analyses. Within the silt, clay particles surround the coarsest particles in order to form millimeter-sized agglomerates, around which binders are deposited. During the curing period, the formation of C-(A)-S-H becomes readily apparent. These phases are detected in the form of a gel that provides continuity throughout the material; as such, the material displays a “honeycomb” type of microstructure. The mechanical properties of the treated soil are indeed affected by this microstructural organization. The post-treatment improvement in mechanical performance therefore proves to be significant.

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1. Introduction

Natural resource management is a critical challenge to be taken into account in any land development project, especially earthworks. The use of soils located within the project rights-of-way offers an alternative that allows conserving natural resources. To proceed with this alternative, soil stabilization using lime and/or hydraulic binders, etc. is a widespread technique employed to improve the workability and hydromechanical properties of soils (Osula, 1991, 1996; Bell, 1996; Wild et al., 1998; Kalkan and Akbulut, 2004; Cuisinier et al., 2009, 2011; Sariosseiri and Muhunthan, 2009; Le Runigo et al., 2011; Obuzor et al., 2011). Soil stabilization with lime and cement is a commonly used technique in earthworks and it has been under continuous development since its introduction in the middle of the past century. Lime is mainly used to dewater the soil in order to improve its workability and its bearing capacity. This lime modification is widely used for building embankment and subgrade of clayey soil since the effect is rapid and modifies the geotechnical characteristics of the soil like the plastic limit, the shear strength and the soil compaction characteristics. Later the pozzolanic reaction between the soil minerals and lime in presence of water leads to the formation of secondary cementitious products (C-S-H, C-A-S-H,…) increasing the soil cohesion and its resistance (Locat et al., 1990; Little, 1995; Bell, 1996; Boardman et al., 2001; Muller, 2005; Maubec, 2010; Le Runigo et al., 2011; Pomakhina et al., 2012). The effects of the pozzolanic reaction are mainly effective at long term. If the mechanical resistance of the material is essential at short term, the soil stabilization goes through the use of cement. Cement stabilization is quick, does not need mellowing time and provides a non-leaching platform (Sariosseiri and Muhunthan, 2009). Cement can be used for stabilization of a wide range of soils and the best performances of soils treated with cement have been observed on silt as well as on coarse-grained materials (Currin et al., 1976). However, in practice in France, a mixed treatment with lime and cement is used since the mixture allows to facilitate the workability without disturbing the effect of the cement in the gain of resistance at long term. The lime is first added to the soil and contributes to flocculation/agglomeration of the clay fraction while the second step of treatment with cement mainly contributes to increase the mechanical properties of the soil. This mixed treatment is classically used in the capping layer (LCPC–SETRA, 2000).

The addition of lime and cement exerts impacts on the material microstructure. The flocculation/aggregation of clay particles after adding lime or cement modifies, for one thing, the material particle size distribution (Osula, 1996) and, consequently, influences pore distribution over a very short term (Bin et al., 2007; Khattab et al., 2007; Russo et al., 2007), although this distribution is evolving during the curing period as well as in conjunction with both the pozzolanic and hydraulic reactions (Wild et al., 1986; Choquette et al., 1987; Locat et al., 1990; Le

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Runigo et al., 2009; Metelkova et al., 2012). Locat et al. (1990) followed up by representing the lime distribution in a soil sample. Transposition to a lime and cement-treated soil has not however ever been verified.

Many studies have been conducted in order to describe lime and/or cement effects on a soil. Yet to this day, none of these efforts has provided a complete description of the full set of physicochemical mechanisms and their impacts on both the microstructure and macroscopic behavior. With this backdrop, the objective of the present study is to describe the effects of adding lime and cement on the characteristics of a treated plastic silt by employing a multi-scale approach. The effects of this combined treatment on mechanical behavior will be monitored by means of unconfined compressive strength measurements. To explain performance trends, the effects of adding lime and cement on the soil's physical chemistry and microstructure will be characterized. Measurements or observations of the soil composition, pore size distribution and binder distribution, in addition to mineralogical analyses, will be introduced.

This study aims at bringing a description about the relationship between the binder addition and the mechanical performance evolution of the treated soil. From an engineer's point of view, this study shows how the soil fabric influences the mechanical behavior of the soil and how the respect of a classical procedure in the preparation of the specimens is fundamental in the mixing between the binders and the soil and the later development of the soil resistance.

2. Materials and methods

2.1. Soil samples tested

For purposes of this study, a plastic silty soil sampled in Héricourt (eastern France) has been selected. This soil sample was first sieved to 5 mm and homogenized; it contained a proportion of particles smaller than 80 μm equal to 60%. This soil exhibits a fraction lower than 80 μm superior to35% and a plasticity index to 18. According to the French soil classification, it ranges as soil A2 corresponding to fine sandy soil, silt, clays and marls with low plasticity. This silt is considered as a plastic silt. The composition of the <5 mm fraction was analyzed by means of X-ray diffraction. Results showed a breakdown as follows: quartz (55%), kaolinite (12%), feldspars (11%), illite (10%), smectite (4%), chlorite (1%), goethite (6.4%), and carbonates (0.6%). The main geotechnical and physicochemical characteristics of this Héricourt plastic silt are listed in Table 1.

2.2. Binders

The selected binder content reflects the level suggested in French guides for this type of soil given a conventional subgrade use, i.e. 1% lime + 5% cement, as expressed with respect to the dry soil weight. These dosages are of common practice in France for these types of soil (LCPC–SETRA, 2000). The quicklime introduced contained more than 93.1% of available CaO on a dry-weight basis. The cement used (CEM II/A-LL 42.5 R THIS CP2 NF) contained 12% of calcareous material and 87% clinker, which was composed of 60.8% C_3S, 7.7% C_2S, 15.7% C_3A, 9.9% C_4AF and 5.4% gypsum.

2.3. Sample preparation

The water content of the silt was adjusted up to the desired compaction water content. The wet soil was then left in an airtight container for at least two days in order to reach moisture equilibrium. The soil and lime were first mixed in a mechanical mixer for 5 min. The cement was then added and all ingredients were mixed together for another 5 min. The time interval between mixing the lime-treated soil and adding the desired amount of cement was set at 1 h. This same interval was respected before compaction. In both cases, the mixture was left in an airtight container. For the compaction step, the sequence adopted complied with the standard Proctor compaction procedure outlined in ASTM D698 at 98.5% of optimal density. The compacted cylindrical samples (50 mm in diameter, 100 mm high) were immediately sealed with cellophane film.

Table 2 summarizes the main sample characteristics following compaction. The samples were maintained under curing conditions, at constant temperature and water content for variable durations (1, 3, 7, 28, 90 and 300 days). The samples were placed into the curing chamber in a separate air-conditioned room at 20 °C and in a furnace at 50 °C. In the field, the mechanical effect of both pozzolanic reaction and cement hydration is mainly long term effects. One way to reach this long term effect in laboratory is to speed up the reactivity by the increase of the curing temperature. Several authors have demonstrated that the kinetics of these reactions and the combined increase of resistance speed up as temperature increases (Little, 1995; Al-Mukhtar et al., 2010; Maubec, 2010; Mooney and Toohey, 2010). Raising temperature thus appears to provide an alternative when evaluating long-term effects within the scope of laboratory experiments.

For each curing period, 4 specimens were prepared, 3 of which served to measure mechanical strength and perform physicochemical analyses, while the fourth was used for microstructural analysis.

3. Characterizations and analyses

At the end of each curing period, the unconfined compressive strength of the various samples was determined according to XP CEN ISO/TS 17892-7 and NF EN 13286-41.

The microstructure of treated and untreated silt was characterized by means of several techniques. Due to technical constraints, microstructure characterizations had to be performed using dry samples. The soil samples were then immersed in liquid nitrogen for freezing and placed in a freeze dryer for 72 h of sublimation. Quick freezing was preferred in order to minimize microstructural deterioration due to water departure (Delage and Pellerin, 1984).

Micro-level observations were recorded on fresh fractures and on Au-coated samples using an SEM equipped with an EDX analyzer. Secondary electron (SE) images were processed at an accelerating voltage of 15 kV and a working distance of 15 mm.

The mercury intrusion porosimetry (MIP) was selected to investigate the fabric of the samples because this method allows the measurement of a wide pore-size range, from a few nanometres up to several tens of micrometers, and permits the identification of different soil pore classes. In the MIP method, the mercury pressure is increased by steps, and the intruded volume of mercury is monitored for pressure increment. In the porosimeter, the mercury pressure is raised continuously from 0.008 to 410 MPa (intruding pore radius from 90 μm to

Table 1
Characteristics of the plastic silt of Hericourt.

Liquidity limit w_L (%) (NF P 94-051)	22
Plastic limit w_P (%) (NF P 94-051)	40
Plasticity index I_P (%) (NF P 94-051)	18
Particle density ρ_s (mg/m^3)	2.67
pH (NF ISO 10390)	5.7
Cation exchange capacity (NF X 31-130) (cmol+/kg)	7.41

Table 2
Characteristics for the untreated and treated silt of Hericourt compacted at the optimum Proctor.

	Untreated silt	Treated silt
Maximum dry density (mg/m^3)	1.72	1.66
Optimum moisture content (%)	17.9	20.0

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