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Changes in thermal conductivity, suction and microstructure of a compacted lime-treated silty soil during curing

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ABSTRACT

An experimental study was conducted to investigate changes of thermal conductivity, suction and microstructure of a lime-treated silty soil during curing. The soil samples were prepared with 2% lime and compacted dry (17%) and wet (22%) of optimum. The thermal conductivity, total suction and pore size distribution were determined at various curing times. Results show that the thermal conductivity of samples compacted on the dry side decreases slightly with curing time, while the curing time effect on the samples compacted on the wet side is insignificant. The total suction generally increases with curing time even though the soil water content was kept constant. The pore size distribution characteristics are mainly related to its moulding water content. As the samples are compacted on the dry side, the pore size distribution shows typical bi-modal characteristics, with a population of macro-pores and a population of micro-pores. By contrast, as the samples are compacted on the wet side, the pore size distribution shows typical uni-modal characteristics. It is found that the modal size of both the large and small pores decrease with curing time.

1. Introduction

Lime treatment is widely applied in geo-engineering constructions such as highway and railway embankments, levees and slopes. This technique effectively improves the workability and mechanical behaviour of soils, because lime can significantly modify soil properties through a series of physical-chemical reactions, including hydration, cation exchanges and pozzolanic reaction (Bell, 1996; Boardman et al., 2001; Prusinski and Bhattacharja, 1999; Umesha et al., 2009). Generally, lime hydration takes place shortly after adding lime into the soil, and this process consumes a large amount of water. The main product of this first step reaction is $Ca(OH)_2$. The followed ionization of hydration products provides sufficient Ca^{2+} ions, and induces cation exchanges that lead to soil flocculation/agglomeration. Note that the cation exchanges and the consequent flocculation process occur rapidly after lime addition, resulting in changes in aggregate size distribution, plasticity and workability of soil (Bell, 1989; Russo, 2005). Pozzolanic reaction usually takes a longer time and plays the major role in improving soil geotechnical behaviour, by increasing soil stiffness and shear strength (Bell, 1996; Consoli et al., 2009; Tang et al., 2011; Dong, 2013). Due to the time-dependence of lime-soil reactions, the geotechnical behaviour of lime-treated soil depends significantly on curing time (Locat et al., 1990; Bell, 1996; Little, 1999; AL-Mukhtar et al., 2012; DI Sante et al., 2014). Brandl (1981) and Liu et al. (2012) reported that the strength of lime-treated soil increased with increasing curing time. By performing bender element tests on lime-treated soils, Dong (2013) showed that there was a two-stage development for the shear modulus over time: stage 1 related to cation exchanges and stage 2 to pozzolanic reaction.

In most cases, lime-treated soils are exposed to natural environment or placed in shallow depth. They are unavoidably subjected to long-term cyclic climate loadings, i.e. temperature variations, drying and wetting, which can significantly affect their durability. Recent studies mainly focus on the effect of wetting and drying cycles on the mechanical behaviour of lime-treated soil (Khattab et al., 2007; Cuisinier and Deneele, 2008; Le Runigo, 2008; Tang et al., 2011), and little attention has been paid to the effect of temperature, which is also an important factor related to climate. Actually, temperature can also significantly affect the geotechnical properties of soil, such as Atterberg limits, stiffness, strength and volume change behaviour (Ctori, 1989; De Bruyn and Thimus, 1996; Sultan et al., 2002; Liu et al., 2012; Islam et al., 2013; Consoli et al., 2014). To assess the temperature effect, it appears essential to investigate soil thermal properties like thermal conductivity. Indeed,

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thermal conductivity is an important parameter in the modelling of the coupled thermo-hydro-mechanical behaviour of lime-treated soil under climate changes. It takes an important role in the heat transformation between the soil and the atmospheric air. However, most studies on thermal behaviour of treated soil involved cement stabilization in the past decades. Farouki (1981) reported that the addition of Portland cement into sand increased the thermal conductivity of the mixture in both wet and dry states. Adams and Jones (1995) observed that the thermal conductivity of cement stabilized soil was higher than that of lime-stabilized soil, and they explained that the former enhanced soil density while the later reduced it. Nevertheless, El-Rawi and Al-Wash (1995) indicated that the thermal conductivities of both soil-cement mixture and concrete decreased with curing time. Lee et al. (2014) tested the mixtures of the gold tailings and fly ash, showing a decrease of thermal conductivity of the mixtures with curing time. From these studies, it appears that the changes in thermal conductivity of lime-treated soil and especially the effect of curing time have not been well understood yet.

Due to the climate effect, field lime-treated soils are usually at unsaturated state. Thus, suction is a basic parameter to describe the state of soil-water-air system. For lime-treated soils, it was found that the cation exchanges and the induced flocculation can modify the water retention capacity of soil. Russo (2005); Tedesco and Russo (2008) observed an increase in water retention capacity by lime addition. Russo (2005) explained that in the low suction range, the soil water retention was controlled by the inter-aggregate porosity and addition of lime mainly reduced the interconnections between pores. Tedesco and Russo (2008) explained that the water retention capacity increase during curing was due to the larger amount of small-size pores. The cementation bonds between aggregates increased the frequency of ink-bottle pores. And the smaller the narrow openings of the link bottle pores, the higher the suction values needed to desaturate the soil. Cecconi and Russo (2008) attributed the increase in water retention to the reduction of interconnections of inter-aggregate pores and the increase of occluded intra-aggregate pores. Khattab et al. (2002) compared the water retention curve of a lime-treated clay with that of untreated one, and showed that the small increase of suction for the treated clay was due to water consumption by lime hydration. In longer term, pozzolanic reaction becomes dominant in lime-treated soils, creating cementitious compounds and giving rise to the modification of both microstructure and water retention capacity of soil.

To better understand the observed macroscopic behaviour of soil such as thermal conductivity, water retention capacity and stiffness, it is often required to perform soil microstructure investigation. Mercury intrusion porosimetry (MIP) is one of the most widely used techniques for this purpose. For lime-treated soils, due to the time-dependence of lime-soil interactions, their microstructure is time-dependent. Russo et al. (2007) performed MIP tests on lime-treated silt cured at different times, and highlighted the time-dependency of microstructure changes: the cation exchanges and pozzolanic reaction reduced the porosity and increased the quantity of small pores. Khattab et al. (2007) also studied the microstructure changes of a lime-treated expansive soil under wetting/drying cycles, and found that the total pore volume of treated soil increased drastically with wetting/drying cycles.

The above-mentioned studies show that different soil properties have been investigated for different cement/lime-treated soils, and there is no study on different soil properties with a fixed soil and a fixed treatment. This appears however essential to well understand different mechanisms involved in the treatment processes. In this study, the changes of thermal conductivity, suction and microstructure of a lime-treated unsaturated silty soil were analysed during curing time. Two groups of soil samples were prepared at dry and wet sides of optimum. The thermal conductivity, water retention capacity and pore size distribution of the samples at various curing times (from 1 to 90 days) were determined. Results allowed the coupled thermo-hydro-mechanical behaviour and the microstructure characteristics to be analysed.

2. Materials and methods

2.1. Test materials

The soil tested was taken from a site near Héricourt, France. This soil has a fine fraction (<80 μm) of 65%. Its geotechnical properties are reported in Table 1. According to French/European standard NF P 11-300 (1992), this soil belongs to category A2. It corresponds to a silt of high plasticity (MH) following the Unified Soil Classification System (USCS). The main minerals are quartz (55%), kaolinite (12%), feldspaths (11%), illite (10%), goethite (6.5%), montmorillonite (4%), chlorite (1%) and rutile (0.5%) (Deneele and Lemaire, 2012). In Fig. 1, both grain size distribution of natural soil and aggregate size distribution of soil powder used in this study are presented. The grain size distribution was obtained on the natural soil by the wet sieving method (NF P 94-056, 1996, for particles larger than 80 μm) and by the hydrometer method (NF P 94-057, 1992, for particles smaller than 80 μm). Natural soil was first air-dried, ground and then passed through the target sieve of 0.4 mm (D_{max}). The larger soil aggregates which could not pass through this sieve were ground again, until all soils passed through (Tang et al., 2011). Then the “aggregate size distribution” was determined by dry sieving method.

Quicklime was used as additive. It is the same lime used in the embankment construction at Héricourt, France. The main properties of this lime are presented in Table 2. In accordance with the lime treatment in the embankment construction at Héricourt, 2% lime by dry weight of soil was chosen as the lime dosage.

2.2. Sample preparation

After the soil powder was prepared ($D_{max} = 0.4$ mm), 2% quicklime powder was first mixed with dry soil. Then the soil-lime mixture was humidified by distilled water to reach different target water contents. According to the compaction curves of lime-treated soil determined from standard Proctor test (NF P 94-093, 1999) in Fig. 2 (where the curve of untreated soil is also shown), both the dry side ($w_{dry} = 17\%$) and the wet side of optimum water content ($w_{wet} = 22\%$) with the same dry density ($\rho_d = 1.65$ Mg/m^3) were considered. The water contents and dry density were chosen according to the values applied in the field for the embankment construction in Héricourt, France. After a mellowing period of 1 h, static compaction by 3 layers was performed to reconstitute the samples at the target dry density and different sizes to satisfy the requirements of different tests. For instance, the samples for thermal conductivity test had 50 mm in diameter and 75 mm in height; the samples for suction measurement had 38 mm in diameter and 100 mm in height; the samples for MIP test had 50 mm in diameter and 20 mm in height. Immediately after compaction, sample was carefully covered by plastic membrane and wrapped in a film. Then the sample was enveloped by scotch tape, confined in a hermetic box and cured in a chamber at a relative humidity of 100% and a temperature of 20 ± 2 °C.

Table 1
Geotechnical properties of the studied soil.

Property	Value
Specific gravity, G_s (NF P 94-054, 1991)	2.70
Liquid limit, w_L (%) (NF P 94-051, 1988)	51
Plastic limit, w_p (%) (NF P 94-051, 1988)	28
Plasticity Index, I_p (%) (NF P 94-051, 1988)	23
VBS (g/100 g) (NF P 94-068, 1998)	2.19
$CaCO_3$ content (%) (ASTM D4373-02, 2007)	1.4
Optimum moisture content (%) (NF P 94-093, 1999)	17.9
Maximum dry unit mass (Mg/m^3) (NF P 94-093, 1999)	1.76