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ScienceDirect

Soils and Foundations 57 (2017) 315–326

www.elsevier.com/locate/sandf

The influence of amorphous silica on the aging of a remoulded loessial soil

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Received 2 February 2016; received in revised form 28 December 2016; accepted 21 January 2017
Available online 17 May 2017

Abstract

A large number of soil formations in nature exhibit increments in stiffness and strength properties after deposition or even with aging after remoulding and compaction. Post-depositional diagenetic processes in the former case and various thyxotropic mechanisms in the latter case are usually postulated to explain the observed behaviour. Some horizons of the Argentinean loess formation show high shear strength properties in natural conditions and even with aging after remoulding, while others with similar origin and mostly identical physical-geotechnical parameters develop a sudden collapse as the soil is saturated. Samples of both types of loess were studied in this work to evaluate the reason for such behaviour. A battery of mechanical tests shows that the increments in strength and stiffness are time-dependent and that the values measured after 28 days of aging reach almost 70% of those corresponding to undisturbed specimens. Effective stress tests and suction control during aging confirm that the regain in strength is mostly due to a real cementation process and not to an increase in suction as is usually assumed. Mineralogical and chemical tests confirm the presence of amorphous silica which, in an alkaline environment as presented here, generates cementation reactions that bond the particles together and cause the development of a much stiffer structure.
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1. Introduction

Loess is an eolian formation consisting of one of the most abundant soils on the continental surface of the world. The Argentinean loess deposit is the largest deposit in the Southern Hemisphere. It has a thickness that varies between 20 and 60 m, and is mainly composed of platy-shaped silt and sand particles with a minor fraction of clay which is usually illite and montmorillonite. The combined effect of particle shape, origin and particle gradation renders a poorly accommodated and open structure. A more detailed review of the origin, structure and behaviour of the Argentinean loess at small and large strains can be found in literature (i.e., Rinaldi et al., 2001 and Rinaldi et al., 2007). The stability of the structure is governed by the combined effect of water suction and cementation. As the cementation is poorly developed, the soil may experience high volume changes when loaded or wetted, and then it is considered as a collapsible unstable soil. Research efforts in past decades have focused on understanding the collapse mechanisms, the relationship between collapse and the soil structure, evaluations of the collapsibility potential and the modeling of the stress-strain response. Concepts rooted in the field of unsaturated soil mechanics seem to correctly explain the behaviour of loess under static load conditions (i.e., Alonso and Gens, 1994).

Most natural soil deposits have some degree of cementation arising from post-depositional processes, such as chemical bonding and cement precipitation (Bennet et al., 1991; Mitchell, 1993). Iron oxide, amorphous silica and carbonates are usually the most stable cementing materials present in loess formations. Certainly, water acidity has a

Peer review under responsibility of The Japanese Geotechnical Society.
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http://dx.doi.org/10.1016/j.sandf.2017.05.001
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significant effect on cement stability. Highly acidic leachate (e.g., organic acids) dissolves carbonates, while alkaline waters promote the development of silica bonding in the presence of hydroxides. Usually, loess presents some degree of weak cementation which is difficult to perceive. However, certain layers of the loess formation show large amounts of cementing agents fully disseminated in the soil and precipitated at particle contacts, significantly increasing its shear strength and generating a true sedimentary rock (i.e., siltcretes and calcretes), also locally known as "tosca".

The important regain of stiffness and shear strength has also been noticed in engineering practice with aging in some loess samples after remoulding and compaction. In general, this effect was previously attributed to various thyxotropic mechanisms, including particle re-accommodation, water homogenization, water-meniscus development and salt precipitation at particle contacts, as has also been observed in many other soils, as reported in the former works of Moretto (1948), Seed et al. (1960), Trollope and Chen (1960), Day (1955) and Mitchell (1960). More recently, soil hardening with aging has been evaluated in the works of Mukabi and Tatsuoka (1999), Troncoso and Garcés (2000), Shibuya (2000) and Shibuya et al. (2001), among others. On the contrary, other loess samples have shown only a negligible regain of strength after remoulding even though they had similar origins and structures.

The different types of behaviour observed after aging in remoulded samples of loess originate the need to study the role of the different chemical and physical stabilizing processes that may take place in the soil after compaction. The potential stabilization effect after aging is of increased interest for evaluating and predicting the behaviour and stability of compacted embankments of loess without the addition of cements, such as lime or Portland cement.

The main goal of this work is to present the fundamental results and conclusions of an experimental study developed to evaluate the processes and mechanisms responsible for the increments in stiffness and shear strength of selected soil samples with aging after remoulding and compaction. Two types of loess samples were selected for this study which showed different kinds of behaviour, either in-situ or in the laboratory, after compaction. The gains in stiffness and undrained strength with time were evaluated in this work at small and large strain levels by means of unconfined compression tests, odometer tests and measurements of the shear wave velocity with bender elements. The roles of water suction and effective stress were also studied by means of suction measurements during aging and drained triaxial tests. The presence of potential reactive minerals was determined by means of X-ray spectrometry, X-ray diffraction, specific surface tests, grain size distribution and scanning electron microscopy (SEM). Finally, the pozzolanic chemical activity of silica minerals was monitored by measuring the electrical conductivity of prepared soil samples mixed with solutions of calcium hydroxide.

2. Soil parameters and sample preparation

Table 1 describes the fundamental geotechnical parameters for the selected samples in this study. The samples labelled as M correspond to a loessial type obtained at a depth of approximately 13 m in the city of Cordoba in Argentina. Under natural conditions, these samples are very stiff and the penetration resistance, in terms of the blow number (N) in a standard penetration test (SPT), is very high (usually $N > 30$ blows). The samples labelled as L correspond to a typical compressible loess obtained at a depth of 2.5 m with a penetration resistance, according to a standard penetration test (SPT), of $N < 5$. The L samples show a much lower natural water content ($w\% = 15.2\%$) with respect to the M samples ($w\% = 36.8\%$). Both types of samples are mainly composed of silt and show similar dry density and pH values. The M samples have a higher plasticity as well as a slightly higher fines content as can be observed from the grain size distribution curves displayed in Fig. 1. The specific surface was determined using the methylene blue aqueous absorption method (Santamarina et al., 2002). Table 1 presents the results. The larger fines content of the M samples reflects a higher specific surface value (69.7 m^2/g), whereas the value for the L samples (2.3 m^2/g) is a typical value for silts.

All tests were run at the natural water contents indicated in Table 1 since the main objective of this work was to evaluate the evolution of stiffness under the in-situ conditions. Undisturbed samples were trimmed from block specimens obtained from open trenches. The sides of the undisturbed cubic blocks were approximately 20 cm. The reconstituted samples were prepared by compaction in a three-piece split mould, 50 mm in inner diameter and 100 mm in height. The soil was mixed thoroughly with the required amount of tap water and then placed in a compaction mould in three layers. Compaction was performed with a 0.795-kg weight hammer falling from a constant height of 39 cm. The number of layers ($n = 3$) and the number of blows per layer ($bpl = 4$) were set so that the closest value of density to that corresponding to undisturbed samples could be attained. Table 2 shows the water content and the density obtained for the prepared samples. The observed differences were less than 1.0% in moisture content (w%) and 1.2% in dry density (γ_d), as displayed in the table. After compaction, the specimens were carefully conditioned in plastic bags and vacuum sealed. Aging was performed by storing the prepared specimens in a moisture-controlled cell, under 97% humidity and a temperature of 23 °C, for 0, 3, 7, 14, 21 and 28 days. In prior tests, the dimensions and the moisture content of all the samples were measured with the precision of 0.1 mm and 0.01 g, respectively, observing that no measurable volume changes occurred as a result of aging.

A series of tests was conducted to characterize the effect of aging in the stress-strain behaviour of the samples. The tests included oedometer tests, triaxial compression tests, shear wave velocity measurements and suction monitoring.

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