Construction and Building Materials 158 (2018) 454–463

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Laboratory investigation and field evaluation of loess improvement using nanoclay – A sustainable material for construction

Alireza Tabarsa [a,*], Nima Latifi [b], Christopher L. Meehan [c], Kalehiwot Nega Manahiloh [d]

[a] Faculty of Engineering, Golestan University, Golestan 49138-15759, Iran
[b] Department of Civil and Environmental Engineering, Mississippi State University, MS 39762, USA
[c] Bentley Systems Incorporated Chair of Civil Engineering, Department of Civil and Environmental Engineering, University of Delaware, 301 DuPont Hall, Newark, DE 19716, USA
[d] Department of Civil and Environmental Engineering, University of Delaware, 301 DuPont Hall, Newark, DE 19716, USA

HIGHLIGHTS

- Potential for effective loess stabilization using nanoclay.
- Investigation of nanoclay content effect on the stabilized loess strength.
- Laboratory evaluation was performed using various engineering tests.
- Field modification of loess was conducted in an exposed channel.

ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form 3 August 2017
Accepted 16 September 2017

Keywords:
Loess soil
Nanoclay
Natural material
Soil improvement
Unconfined compressive strength
Construction
Sustainable material

ABSTRACT

Loess soils are aeolian deposits of primarily silt sized soil particles, which are often lightly cemented. The wind-blown depositional process of loess formation yields a relatively loose soil structure that is particularly sensitive to changes in hydro-mechanical loading conditions, and the silt particles that comprise loess deposits are often easily eroded by water or wind. The main irrigation channels of Gonbad dam, located in northeastern Iran, are constructed on loess deposits and have experienced significant cracking and other forms of damage that can be attributed to subsidence and erosion of the loess soil. This study investigates the potential for effective loess stabilization using nanoclay, an engineered nanomaterial, both in the laboratory and in the field at the Gonbad dam irrigation channel site. To evaluate the effects of nanoclay stabilization, varying fractions of nanoclay ranging from 0.2% to 3% by mass were added to the natural loess soil. In the laboratory, representative specimens were prepared and subjected to a variety of tests, including Atterberg limits, standard Proctor compaction, unconfined compressive strength, unconsolidated undrained triaxial compression, wetting-induced collapse, and pinhole dispersivity. Results from the laboratory tests revealed that the addition of nanoclay altered the plasticity, strength, and stiffness behavior of the specimens. Also, the dispersivity and relative wetting-induced collapse behavior of the natural loess were impacted by the addition of nanoclay. In-situ investigation was performed at a selected section of the irrigation channel, to explore the effectiveness of nanoclay for improving the loess soil. Results of this pilot field study indicated that loess soils that had been stabilized with 2% nanoclay showed notable improvement. The field and laboratory obtained results were observed to be in general agreement.

1. Introduction

Loess is an aeolian sediment formed by the accumulation of primarily silt sized soil particles, and often a small amount of clay, typically in the 15–20% range [1–3]. In some cases, a significant amount of sand-sized particles can also be present, and light calcium carbonate cementation of particles is commonly observed [4–6]. The wind-blown depositional formation of loess soils tends to yield a relatively loose soil structure with a low density [7–9]. This loose, unstable state is often maintained by the weak cementation that develops due to the formation of calcium carbonate (calcite) between the sides of vertical root holes and at the interparticle contacts [2]. It is common for loess soils to plot near the A-line on the USCS plasticity chart, and for loess soils in the field to have a fairly low natural water content, given the arid nature

* Corresponding author.
E-mail address: a.tabarsa@gu.ac.ir (A. Tabarsa).

https://doi.org/10.1016/j.conbuildmat.2017.09.096
0950-0618/

of their depositional environment [7,10]. It is estimated that loess covers about 10% of the earth's surface [6,11,12]. Large loess deposits are found in parts of Asia, Africa, Europe, and South America. In the United States, loess soil is found in the mid- and south-western portions of the country, and in Alaska [2,13–17].

Given their open, unstable soil fabric, unsaturated loess deposits tend to experience significant volumetric compression when subjected to loading [18,19]. This soil collapse can be induced by loading of the soil via construction of a new structure on top of a loess deposit [20,21]. Changes in the degree of saturation and the related suction can also lead to failure of the soil structure. This phenomenon is commonly referred to as "wetting induced collapse". The changes in the degree of saturation can arise from precipitation events, irrigation, a change in groundwater level, or even a leaking pipe [9,22–24]. Mechanical loading followed by wetting can be particularly problematic when building civil engineering structures on loess deposits.

The Gonbad dam is located in northeastern Iran, in a semi-arid region that contains significant loess soil deposits [25]. A considerable length of the irrigation channel running from Gonbad dam has suffered damage resulting from relatively large, non-uniform subsidence of the foundation soil. Considering the amount of water that can seep through the concrete joints and cracks of the lined canal into the foundation loess, the observed subsidence can be attributed to wetting induced collapse. In the 1960s, similar patterns of field behavior were observed for a large canal constructed in the San Joaquin Valley of California [2].

Treating loess soils with stabilizing additives has the potential to reduce settlements associated with hydro-mechanical loading [26]. Moreover, depending upon the stabilization technique used, the strength, stiffness, plasticity, dispersivity, and erodibility of the loess could also be improved. Traditional chemical stabilizers include cement, lime, fly ash and bituminous materials. New and non-traditional stabilizers include liquid polymers, enzymes, resins, acids, silicates, and ions and lignin derivatives [27–40]. In addition, several recent studies have improved the engineering properties of problematic soils using different types of geopolymers [41–45]. Recently, there is an emerging interest in the use of nanotechnology and nanomaterials for a wide variety of applications, including soil stabilization [46–48]. This study explores the use of nanoclay, an engineered nanomaterial, for improving the engineering properties of loess soils. Samples retrieved from the foundation soil of an irrigation channel near Gonbad dam were utilized to examine the effectiveness of nanoclay stabilization. A variety of traditional geotechnical engineering tests were conducted on the stabilized nanoclay specimens, including Atterberg limits, standard compaction, unconfined compressive strength, unconsolidated undrained triaxial, collapse potential and pinhole tests. The results from this study were then utilized for field stabilization of loess at the Gonbad dam irrigation channel site.

2. Nanoclay stabilization

In the last decade, the use of nanotechnology and the production and usage of nano-scale particles has increased significantly, leading to advancements in many disciplines, including medicine, materials science, and engineering [49,50]. Concurrently, the application of nanotechnology and nanomaterials has drawn the attention of various researchers from the civil, geotechnical, and geoenvironmental engineering disciplines [51–55]. From a geotechnical and geoenvironmental engineering perspective, nanoclays have the potential for use as environmentally friendly additives in a variety of soil improvement and waste containment applications [56,57].

Nanoclays are nanoparticles of layered mineral silicates, which can be categorized into several classes, such as montmorillonite, bentonite, kaolinite, hectorite, halloysite, etc. depending upon their chemical composition and nanoparticle morphology [58,59]. The production of nanoclays generally involves the extraction of desired nanomaterials from natural clays using various techniques, including energetic stirring followed by centrifugation and freeze-drying, centrifugation and cross-flow filtration, or ultracentrifugation [60]. Just like for traditional clay minerals, a layer is the basic structural unit of nanoclays, with individual layers being composed of tetrahedral and/or octahedral sheets, and with the arrangement of sheets playing a vital role in defining and distinguishing the nanoclay minerals [59].

A few researchers have also studied the effects of various nanomaterials, such as nanoaluminum, nanocopper and nanoclay, on the swelling and shrinkage behavior of fine grained soils [61–63]. Their results showed that the addition of nanoclay has negligible effects on the optimum water content and maximum dry unit weight of the stabilized soil. In addition, the plasticity index and shrinkage limit of the treated soil were observed to increase with the addition of nanoclay. Scanning electron microscopy (SEM) results have shown that the soil fabric changes with nanoclay addition, even with relatively small additive amounts. This fabric change was associated with the nanoclay particles filling the interparticle void space. In addition, the nanoclay particles were observed to increase the surface area available for interaction between the clay particles and the surrounding environment [64].

Taipodia et al. [65] have performed stabilization of sandy and clayey soils using nanoparticles such as $CaCl_2$, CaO and KNO_3. The results from this study showed that the shear strength increases and the permeability decreases when the nanoparticles were added. Nanoclay stabilization has also been observed to foster the development of plastic (ductile) stress–strain behavior [66–68]. Experimental investigation of the stabilizing effects of nanoparticles such as nanosilicate, nanoaluminum, nanocopper and nanoclay has indicated a reduction of collapse behavior after the addition of the nanomaterial. Other researchers have reported that the addition of nanoclay improved the erosion resistance of sandy loam soils [48,69]. Zomorodian et al. [70] investigated the strength behavior of a kerosene contaminated sandy lean clay using nanoclay and nanosilica, and reported an increase in uniaxial strength and stiffness as a result of stabilization.

3. Laboratory studies

3.1. Project site and material characteristics

The soil that was tested in the current study was collected from the foundation of a project that had exhibited collapse behavior. The foundation soil for this project supported an irrigation channel (Fig. 1) that ran from Gonbad dam through the province of Golestan (coordinates: lat. 38.15-36-30 N; long. 54.00-56.00 E). Fig. 1a shows non-uniform subsidence that indicated the presence of collapsible soil. Fig. 1b shows damage that occurred to the concrete lining of the channel due to wetting-induced subsidence. Fig. 1c shows additional failure features that were observed around the study area, which included collapse and subsidence, dispersion, and sliding.

Loess in Golestan Province has a thickness varying from 30 to 150 m and covers more than 17% of the province area [71]. These soils are generally friable, pale yellowish brown or buff in color, slightly coherent, very light and dry, typically nonstratified and often calcareous [72]. At the study location, both disturbed and undisturbed samples were extracted from ten exploratory boreholes that ran to a depth of ten meters each. The natural moisture