Engineering Geology 196 (2015) 1–11

Contents lists available at ScienceDirect

Engineering Geology

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

Experimental investigation of thermal and mechanical properties of lignin treated silt

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ARTICLE INFO

Article history:
Received 31 January 2015
Received in revised form 29 June 2015
Accepted 2 July 2015
Available online 6 July 2015

Keywords:
Thermal resistivity
Unconfined compressive strength
Resilient modulus
Lignin

ABSTRACT

This paper presents details of a study that deals with measurement of thermal resistivity, determination of mechanical properties, and microstructural characteristics of a lignin treated silt. Changes in thermal and mechanical properties of the lignin treated silt were studied over a curing period of 60 days. Investigations were carried out with respect to the effect of the lignin content, moisture content, and curing time on the soil properties including compaction characteristics, thermal resistivity, unconfined compressive strength, and resilient modulus. In addition, the pore-size distribution and the microstructures of lignin treated silt with different packing moisture contents were analyzed. Relationships between the thermal resistivity and properties that capture compaction and mechanical characteristics of lignin treated silt were established. The study reveals that curing time and the amount of lignin content have a considerable influence on the thermal resistivity, mechanical properties, and microstructure of lignin treated silt. The initial thermal resistivity of lignin treated soil increases with an increase in lignin content and the difference in thermal resistivity disappears after 60 days of curing. The increase in lignin content leads to the increase in the unconfined compressive strength and resilient modulus of lignin treated soil. The optimum content of lignin for silt in Jiangsu Province is approximately 12%. With an increase in the lignin content, both the unit pore volume and mean diameter of an intra-aggregate pore, and that of an inter-aggregate pore decrease, whereas the magnitude of the volume inter-aggregate pore increases considerably. The fundamental behavior of treated silt changes when the lignin content exceeds 8%. The impurities contained in lignin would affect the fundamental behavior of treated silt. Linear relationship is established between the initial thermal resistivity and unit weight.

1. Introduction

Earth structures such as rail and road subgrade, foundations and embankment dams associated with poor engineering property soils are in danger of stability and settlement. Silts that are difficult to compact and with low strength are widely distributed in many parts of China, particularly in the regional Jiangsu Province and southeastern China. Silt beneath foundations can easily cause many engineering problems, such as differential settlement, unacceptable lateral movement, and loss of bearing capability, if effective ground improvement is not implemented. Therefore, it is necessary and important to improve their engineering properties in an appropriate and cost effective method.

Chemical stabilizing agents (such as cement, lime, fly ash, gypsum, and other calcium-based materials) have been used extensively for improvement of the soils with poor engineering properties by earlier researchers (Bell, 1996; Lo and Wardani, 2002; Hebib and Farrell, 2003; Sariosseiri and Muhunthan, 2009; Cuisinier et al., 2011; Rahardjo et al., 2013). The engineering behavior of treated soils has been improved dramatically by using these agents. However, the traditional stabilizers are not always readily acceptable in engineering construction because of environmental threat. The treated soils always pose a threat to the environment by changing the soil pH (Rollings and Burkes, 1999; Sunil et al., 2006; Indraratna et al., 2012). The growth of vegetables and the quality of groundwater are also affected. The longevity of steel structures and concrete elements underground will be reduced in the alkaline environment (Mitchell and Soga, 1976; Perry, 1977; Sherwood, 1993). Moreover, traditionally treated soils also exhibit an excessive brittle performance especially under traffic loading or impact loading (Fernandez and Santamarina, 2001; Okyay and Dias, 2010). To overcome these problems, a new alternative soil stabilizer that improves soils environmentally friendly and maintains sufficiently ductile treated soils must be found. Lignin, a kind of origin polymer compound which is a by-product of paper and timber industry has been recognized in recent years as a promising soil stabilizer for cohesive and non-cohesive soils (Puppala and Hanchanloet, 1999; Karol, 2003; Tingle and Santoni, 2003; Santoni et al., 2005; Indraratna et al.,

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http://dx.doi.org/10.1016/j.enggeo.2015.07.003
0013-7952/

2009; Ceylan et al., 2010). It consists of both hydrophilic groups including sulfonate, phenylic hydroxyl, alcoholic hydroxyl and hydrophobic groups including the carbon chain (Chen, 2004; Jiang, 2008). The global paper and timber industry generates massive lignin-based by-product after exacting valuable fiber and wood pulp from plant biomass. The management and disposal of this by-product pose major challenges in efforts to protect the environment and reuse the natural resources. According to the government statistics, about 140 million tons of cellulose was isolated from plant biomass and about 50 million tons of lignin-based by-products were got at the same time in the paper manufacturing industry one year in China (Wei and Song, 2001; Yao et al., 2009). Over the past decades, more than 95% of the lignin-based by-products were directly discharged into rivers in the form of black liquid or burned after enrichment. This treatment method not only polluted the ecological environment but also caused serious waste of natural resources.

To improve the disposal efficiency, lignin as a soil stabilizer has been studied and implemented. The effectiveness of lignin-based stabilizer to treat geomaterials has been studied by examining compaction and compressibility characteristics, swelling, moisture susceptibility, unconfined compressive strength, shear strength, and erosion resistivity (Gow et al., 1961; Santoni et al., 2002; Indraratna et al., 2008; Kim et al., 2011; Ceylan et al., 2012; Chen et al., 2014). Even though numerous studies have been carried out to explore the role of lignin as a soil stabilizer, most works have highlighted effects on the mechanical performance in particular. In contrast, the effect of lignin on thermal property change has not been reported in the literature and the relationship of the thermal conductivity with the strength gain for lignin treated soil is not fully understood. In addition, knowledge of both the thermal and mechanical properties of foundation soils with binders added is important for thermomechanical analyses of underground structures, such as oil and gas pipelines, electric transmission lines, energy piles, and nuclear waste repositories (Lee and Shang, 2014).

In view of the above, this study is concerned with the beneficial use of lignin-based industrial by-product to treat silt as a stabilizer. A series of laboratory tests were conducted on thermal characteristics, mechanical properties and microstructural characteristics of lignin treated silt. The effects of lignin content, and moisture content on compaction characteristics, thermal resistivity, unconfined compressive strength, q_u, and resilient modulus were studied. Changes in thermal resistivity, q_u, and resilient modulus of the specimens were monitored during the curing period. The microstructural characteristics of the treated silt, as lignin content increases, were investigated by resorting to scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP). Based on these results, the relationship between thermal resistivity and unit weight was established. Moreover, the correlations between thermal resistivity and q_u, and resilient modulus during the curing period were investigated. It is believed that such investigations would be quite useful to understand the short-term development of thermal and mechanical properties of lignin treated soils.

Table 1
Physicochemical properties of silt tested.

Property	Characteristic
Specific gravity, G_s	2.71
Grain size distribution (%)[a]	
Clay (<0.005 mm)	10.8
Silt (0.005–0.075 mm)	80.1
Sand (0.075–2 mm)	9.1
Liquid limit (%)	32.4
Plasticity limit (%)	23.6
Plasticity index	8.8
Optimum moisture content (%)	16.1
Maximum dry unit weight (γ_{dmax}), (kg/m^3)	1720
pH	8.74

[a] Measured using a laser particle size analyzer Mastersize 2000.

2. Materials

In this study, silt, lignin, and water were the host materials used to make the compacted mixtures of silt and lignin. The physicochemical properties and oxide composition of silt are summarized in Tables 1 and 2, respectively. The microstructure and chemical composition of lignin were determined by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis. The chemical elements contained in lignin are shown in Fig. 1.

2.1. Silt

Natural silt was collected from a highway construction site in northern Jiangsu, China. According to the Technical Specification for Construction of Highway Subgrade in China, silt can be used in construction specified or should be removed. The maximum dry density and optimum moisture content obtained from the standard Proctor compaction method were 1720 kg/m^3 and 16.1%, respectively. Furthermore, the liquid limit and plastic index of the soil were found to be 32.4% and 8.8, respectively. The tested soil is primarily comprised of silt-sized particles (80.1%) with some clay-sized (10.8%), and sand-sized (9.1%) particles. Based on the Unified Soil Classification System (ASTM (2011) D2487), the tested soil is classified as a low plasticity silt (ML). Meanwhile, the major oxides in the soil include silica (63.20%), alumina (12.53%) and calcium oxide (6.41%), which account for a total amount of 82.14% by weight. The magnesium oxide is relatively low at 2.39%.

2.2. Lignin

The lignin used in this investigation is a processed waste by-product from paper manufacturing industry in Henan province, China. It contains approximately 80% lignin, 10% cellulose, and a small amount of impurities. It can be observed that lignin was composed of carbon (C), oxygen (O), sodium (Na), and sulfur (S) (see Fig. 1). Lignin is a kind of polymer compound that contains a number of hydrophilic groups including sulfonate, phenylic hydroxyl, as well as alcoholic hydroxyl, and hydrophobic groups including the carbon chain (Vinod et al., 2010). Lignin used in this study is a yellow-brown powder with a smell of fragrance that was soluble in deionized water having a pH value of 12.23 (10 g lignin dissolved in 10 mL distilled water). This stabilizer is inflammable and does not contain heavy metal constituents. Compared with other traditional and nontraditional stabilizers, lignin is cheaper, environmentally friendly, nonbiodegradable, and nonhazardous for soil stabilization. This stabilizer does not corrode metals and is not classified as hazardous according to the National Occupational Health and Safety Commission (NOHSC) criteria (Indraratna et al., 2008).

Table 2
Oxide chemistry of silt tested.

Oxide chemistry[a]	Characteristic (%)
Silicon oxide (SiO_2)	63.20
Aluminum oxide (Al_2O_3)	12.53
Calcium oxide (CaO)	6.41
Ferric oxide (Fe_2O_3)	3.12
Potassium oxide (K_2O)	2.46
Magnesium oxide (MgO)	2.39
Sodium oxide (Na_2O)	2.30
Sulfate oxide (SO_3)	0.18
Phosphorus oxide (P_2O_5)	0.16
Others	7.25
Loss on ignition[b]	5.81

[a] Mineral composition was analyzed by X-ray flourescence method using ARL9800XP + XRF spectrometry.
[b] Value of loss on ignition is referenced to 950 °C.