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Cracking, water permeability and deformation of compacted clay liners improved by straw fiber

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ABSTRACT

The cracking resistance performance, impermeability, strength and deformation characteristics of improved clay were systematically evaluated by cracking test, water permeability test, unconfined compression test and shear test, respectively. The cracking test suggested a high resistance of the improved clay by straw fiber against cracking. With the increase of fiber content (FC), the cracking intensity factor (CIF) i.e. the ratio of the crack area to the total area, decreased at low fiber contents and then turned to increase at higher fiber contents. However, the effect of fiber additive on the surface shrinkage was not significant. The improved clay with FC = 0.3% was found to have the highest resistance to cracking. After 25 days of desiccation, CIF and surface shrinkage of compacted clay were determined to be 0.015 and 12.1% respectively. However, CIF of the improved clay with FC = 0.3% was only 0.0013 and surface shrinkage was 10.31%. Cracking was propagated by wetting–drying cycles. After four wetting–drying cycles, the CIF of the compacted clay was 0.032 and the CIF of the improved clay with FC = 0.3% was 0.0081. The result of water permeability test for cracked clay indicated that a traditional landfill cover system merely consisting of compacted clay would not be sufficient to serve as an effective barrier against rainwater permeation into the landfill. At a rainfall intensity of 10 mm/d, the rainwater penetrated to a 15 cm depth of the clay liners. The improved clay with FC = 0.3% had the least permeability. The rainwater had not penetrated to the 15 cm depth of clay liners even if the rainfall intensity reached 50 mm/d. The results of unconfined compression tests and shear tests indicated that with the increase of FC, the unconfined compressive strength and shear strength increased firstly and then decreased. At FC = 0.3%, the unconfined compressive strength peaked at 459.15 kPa, and c, φ peaked at 80.9 kPa and 21.06°, respectively. The improved clay with straw fiber additive could be used in landfill cover system to enhance the anti-seepage ability and strength of landfill liners.

1. Introduction

In order to reduce the leachates from municipal solid waste (MSW) and protect the ecological environment safety, the landfill cover system is required to be constructed when the storage limit is achieved. The compacted clay cover structure is recommended by “Technical code for municipal solid waste sanitary landfill” (CJJ17-2004), and the hydraulic conductivity of compacted clay must be less than 1×10^{-7} cm/s. However, desiccation cracking of the landfill cover system with compacted clay can occur under the action of both external and internal circumstances (Tang et al., 2010; Li and Zhang, 2011). Once the landfill cover system cracks, it would provide a convenient flow path for the rainwater and thus increase the amount of leachate from MSW in landfill. Albrecht and Benson showed that desiccation cracking caused the hydraulic conductivity of clay liner to increase by about three orders of magnitude (Albrecht and Benson, 2001).

A number of research efforts have been made to overcome the problems of desiccation cracking in landfill cover system. A few have considered soil additives (lime, sand, and cement) to increase the soil strength and resistance to cracking (Leung and Vipulanandan, 1995; Omidi et al., 1996a, b; Cetin et al., 2006). However, the effect of addictives to constrain cracking was not significant and the required low permeability in landfill cover system was not achieved. In recent years, due to good toughness and ductility in fiber material, it was widely used in compacted clay and concrete to improve the shear strength and resistance to cracking. In recent decades, the engineering characteristics of soil containing fibers have been studied with triaxial tests, unconfined compression tests, direct shear tests, CBR tests and permeability tests. Polypropylene fiber is a common synthetic material that is widely used to reinforce soil and concrete (Maher and Ho, 1994; Nataraj and McManis, 1997; Cetin et al., 2006; Ozkul and Baykal, 2007; Tang et al., 2007; Harianto et al., 2008). In addition, other materials were used as the additives improving the strength and resistance to cracking of compacted clay. The effects of length and content of sisal fibers on the clay strength were studied by Prabakar and Sridhar (Prabakar and Sridhar, 2002). Physical property and reinforcement effects of coconut

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Table 1
Chemical composition of clay (%).

SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
58.42	25.23	0.24	0.51	0.12	5.32	2.67

Table 3
Chemical composition of straw (%).

Ash	HNO_3–C_2H_5OH cellulose	Hemicellulose	Lignin	Fat waxy	Loss
13.52	35.65	26.83	10.44	5.21	8.35

fibers were studied experimentally by Khosrow et al.(Khosrow et al., 1999). Silica fume and red mud were proposed as the modifiers for compacted clay to improve the strength and resistance to cracking (Kalkan and Akbulut, 2004; Kalkan, 2006, 2009).

In China, most of the straw is burned in rural area as a traditional fuel, which has led to a waste of resource and environmental pollution. The straw fiber can be extracted from straw and used as a soil additive to form a straw fiber-clay mixture, which can avoid ecological environment pollution induced by burning straw and improve resistance of landfill cover system to cracking. Thermogravimetric analysis and thermomechanical analysis were applied by Zabihzadeh to study the thermal stability and thermal expansion of mixture of wheat straw powder, polypropylene and high density polyethylene (Zabihzadeh, 2010). Pradhan et al. have observed physicochemical properties of biological treated soybean-straw fiber (Pradhan et al., 2009). Wheat straw was used by Bolcu and Stanescu to reinforce epoxy resin. Bolcu and Stanescu determined the elastic modules and tensile strength of the mixture through laboratory tests (Bolcu and Stanescu, 2010). Xue et al. successfully extracted straw fiber from straw wastes for application in road construction and characterized its surface microstructure and mechanical property (Xue et al., 2009).

In this paper, straw fiber was used as reinforcement additive to improve the compacted clay strength and resistance to cracking. To evaluate the feasibility of fiber-clay mixture as the material of landfill cover system, cracking test was applied for the improved clay in the conditions of dehydration and multiple wetting–drying cycles to determine the resistance of fiber-clay mixture to cracking. The permeability of cracked clay in the condition of rainfall was studied by water seepage tests. The permeability of straw fiber-improved clay was tested with the PN3230M environmental soil flexible wall permeameter under dry–wet cycles. Strength and deformation characteristics of fiber-clay mixture were analyzed by unconfined compression tests and direct shear tests.

2. Materials and test methods

2.1. Materials

The clay used in this study was taken from an excavation site in Changqing Garden in Wuhan. The soil samples were collected on the site at 5–7 m deep underground. The chemical composition and fundamental physical indexes are listed in Tables 1 and 2, respectively.

The straw fiber was extracted by alkaline soaking. The impurities, such as leaf, ear, and joint, were removed from straw. The raw straw with length of 3–5 cm was cleaned, dried and then packed. The dosage of NaOH to raw straw was 10%. The straw sample was cooked under the temperature of 150–160 °C and at the maximum pressure of 380–530 kPa for 3–4 h. The high temperature digester was used in the preparation. The straw fiber was extracted through cooking, filtration, washing, and drying. The chemical composition of straw is presented in Table 3 and the fundamental physical properties of straw fiber are listed in Table 4. The microstructure of straw fiber is shown in Fig. 1. The straw fiber surface appears rough and uneven with visible grooves, as shown in Fig. 1.

2.2. Test methods

Different straw fiber contents (0%, 0.05%,0.1%, 0.2%, 0.3%, 0.4%, 0.5%) were used for the preparation of compacted clay at a given target dry density (1.65 g/cm^3) and initial moisture content (0.19). These soil samples were further subjected to cracking test under the impacts of continuous dehydration and wetting–drying cycles. The cracking test was conducted in an oven at a stable temperature of 40 °C. Electronic balance was used to determine the change of moisture content in compacted clay. A digital microscopic image system was applied to monitor the development of cracks in compacted clay (Figure 2). The clay samples were dried for 5 days followed by the first wetting–drying cycle, and then one cycle was conducted every 5 days. Four wetting–drying cycles were conducted in 25 days.

Water seepage test was conducted for the cracked clay under the action of four wetting–drying cycles. As shown in Fig. 3, the inner diameter of container is 50 cm and the thickness of compacted clay is 20 cm. For the soil samples, the compactness, moisture content and straw fiber content were at 1.65 g/cm^3, 0.19 and 0.3%, respectively. Heating source and rainfall simulator could simulate the sun radiation and rainfall to form the wetting–drying cycles while lasting for 25 days. The 3 cm thick rubber blanket was laid on the inner-wall of container to prevent water from flowing along the container wall, which guaranteed that seepage performance of cracked clay could be evaluated correctly. The moisture sensors were installed on the site at 5 cm, 10 cm and 20 cm depth from surface of soil layer, monitoring the changes of moisture contents of soil layer at different depth with elapsed time. The percolation behavior of the cracked clay was evaluated with rainfall intensities of 10 mm/d and 50 mm/d, respectively. The 1 hour-long rainfall was conducted by a rainfall simulator.

The PN3230M environmental soil flexible wall permeameter, made by American GEOEQUIP, was used to test the permeability of the straw fiber-improved clay under dry–wet cycles. The permeameter can prevent the sidewall leakage that might be caused by the specimen's volume change during the dry–wet cycles. The specimens used in this test have an initial dry density of 1.65 g/cm^3 and an initial moisture content of 19%. The straw fiber volume ratios used to improve clays were 0, 0.3%, 0.5%. The specimen was initially sized at a diameter of 50 mm and a height of 50 mm for permeability test. All samples were made by pressing a specific quantity soil into the cutting ring of the above-mentioned size. The samples were placed in a Vacuum Saturator can for 48 h before permeability test, and then placed in a dryer for 72 h at 50 °C after permeability. The aforementioned steps were repeated for 4 dry–wet cycles.

Different straw fiber contents (0%, 0.05%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%) were used in the preparation of compacted sample at a given target dry

Table 2
Basic physical indexes of clay.

ρ_{dmax}/g/cm^3	W_{opt}	W_L	W_p	I_p	Particle size distribution/%			
					>0.05 mm	0.05–0.005 mm	0.005–0.002 mm	<0.002 mm
1.65	0.19	48.5	26.2	22.3	12	32	45	11