ARTICLE IN PRESS
CLAY-04098; No of Pages 12
Applied Clay Science xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Applied Clay Science
journal homepage: www.elsevier.com/locate/clay

Research paper

Centrifuge model study on the performance of fiber reinforced clay-based landfill covers subjected to flexural distress

P.V. Divya [a], B.V.S. Viswanadham [a,*], J.P. Gourc [b]

[a] Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India
[b] LTHE, University of Joseph-Fourier, Grenoble F-38041, France

ARTICLE INFO

Article history:
Received 17 April 2016
Received in revised form 23 November 2016
Accepted 7 December 2016
Available online xxxx

Keywords:
Clay-based landfill covers
Centrifuge models
Differential settlement
Cracking
Fibers
Landfills
Digital image cross-correlation
Flexural distress

ABSTRACT

The influence of discrete and randomly distributed polyester (PET) fibers in improving the crack resistance and water-tightness of clay barriers was studied by conducting a series of centrifuge model tests at 40 gravities using a large beam centrifuge available at Indian Institute of Technology Bombay. Model clay barriers with and without fibers were subjected to flexural distress by inducing differential settlements using a settlement simulator. Two types of clay barriers were prepared by using two different types of soil, namely bentonite amended silty soil (Soil A) and kaolin clay-sand mixture (Soil B). Digital image cross-correlation (DIC) technique was used for analyzing the images captured by a digital photo camera and a charged couple device (CCD) camera, mounted along with the model. Unreinforced soil barriers (URSB) were found to lose their water-tightness and integrity at relatively lower distortion levels compared to identical fiber reinforced soil barriers (FRSB). Also, the performance of URSB and FRSB was found to be superior for Soil A compared to Soil B. The capability of PET fibers on preservation of existing unreinforced soil barriers was also demonstrated. The strain at crack initiation, ε_c, for FRSB is 2.90 and 2.36 times higher than identical URSB for Soil A and Soil B, respectively. Similarly, the strain at the onset of water breakthrough, ε_b, for FRSB is 2.14 and 2.79 times higher than identical URSB for Soil A and Soil B, respectively. There is a significant influence of fiber inclusion in retarding the crack initiation and water breakthrough at the onset of flexural distress for both the soil types. Thus, FRSB can withstand more distortion and strain while maintaining the integrity of the clay barrier. This observed behaviour of restraining cracks and improved performance of FRSB is primarily due to the reinforcement effect achieved due to soil-fiber interactions.

1. Introduction

Waste generation and proper disposal of waste in an environmentally sound manner are continually growing problems at global, regional and local levels. Improper disposal of waste can lead to the pollution of all vital components of the living environment. Environmental pollution due discharged waste water is also widely reported (Valipour and Singh, 2015; Valipour, 2015; Yannopoulos et al., 2015). Landfills continue to be the most predominant method of waste disposal worldwide. It is found to be the economical way of disposing MSW compared to other waste management techniques such as incineration and composting (Reddy et al., 2009). In India, Solid Waste Management rules (SWM rules, 2015) recommend landfilling the solid wastes that are neither recyclable nor recoverable. It needs to be done with the provision of impermeable barriers, leachate collection and treatment systems. LLRW requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities (IAEA, 2009). Clay formations in their natural state exhibit very favorable conditions for the disposal of short lived low and intermediate level radioactive waste stored in containers (Viswanadham and Rajesh, 2009). Possibilities of occurrence of flexural distress induced by the differential settlements in landfill covers are inevitable due to the decomposition of underlying waste in MSW landfills (Sivakumar Babu et al., 2010) and due to the possible space among the waste storage containers or tilting of waste storage containers in LLRW disposal facilities (Gourc et al., 2010).

Landfill covers provide a protective layer to isolate the underlying waste from the environment, and thus, the cover system is an important component of a waste containment system. One of the most important components in landfill covers is the impermeable barrier layer which prevents migration of leachate or gas to the surrounding soil. Barriers are made of natural or modified soil (compacted soil barriers) and/or synthetic materials, such as geomembranes, geosynthetic clay liners, etc. Compacted soil barriers can be adopted economically if the soil having a coefficient of permeability $<1 \times 10^{-9}$ m/s is available within the close proximity of landfill sites (Heerten and Koerner, 2008; Gourc et al., 2010). Clay is generally weak in tension. If the tensile strains are large enough, the clay barrier layer may crack and lose its water-

* Corresponding author.
E-mail addresses: divya.pv.nair@gmail.com (P.V. Divya), viswam@civil.iitb.ac.in (B.V.S. Viswanadham), jean-pierre.gourc@ujf-grenoble-alpes.fr (J.P. Gourc).

http://dx.doi.org/10.1016/j.clay.2016.12.010
0169-1317/© 2016 Published by Elsevier B.V.

tightness. The tensile strain at failure of compacted clay is typically between 0.1% and 4% (LaGatta et al., 1997). Clay barriers of landfill covers should be able to withstand the flexural distress/cracks induced by the differential settlements and maintain their water-tightness.

Several researchers studied the differential settlement behaviour of impermeable barriers by full-scale testing, reduced-scale testing and by employing various numerical modelling schemes (Lee and Shen, 1969; Jessberger and Stone, 1991; Scherbeck and Jessberger, 1993; Gabr and Hunter, 1994; Liang et al., 1994; LaGatta et al., 1997; Edelmann et al., 1999; Viswanadham and Mahesh, 2002; Rajesh and Viswanadham, 2009, 2015; Gourc et al., 2010; Divya et al., 2012a). Differential settlements can be characterized in terms of distortion levels (LaGatta et al., 1997; Qian et al., 2002). Distortion level, a/l is defined as the ratio of settlement a to the influence length l within which differential settlements of landfill covers take place (length over which settlement value cease to zero). Qian et al. (2002) considered differential settlements of landfill covers as large craters to localized depressions. Large craters having distortion level of 0.167 resulted in maximum strain of about 1.8% in landfill covers. In comparison, a typical local depression having distortion level of 0.27 resulted in a maximum strain of about 4.5%. Compacted soil barriers lose their integrity at very low distortion levels due to low tensile strength and low tensile strain at failure of the soil. Few researchers attempted to improve the performance of landfill covers with the provision of geogrid reinforcements (Zornberg and Kavazanjian, 2001; Zornberg et al., 2001; Viswanadham and Jessberger, 2005; Viswanadham and Muthukumaran, 2007; Rajesh and Viswanadham, 2011, 2015) and geomembranes (Giroud et al., 1992; Rowe and Sangam, 2002; Rowe et al., 2004, 2009; Rowe, 2005; Take et al., 2007; Brachman and Gudina, 2008a,b; Bouazza et al., 2008; Rowe, 2011; Divya et al., 2012a, b). In recent times, geosynthetic clay liners are used in developed countries due to their limited thickness, ease of installation and low hydraulic conductivity (LaGatta et al., 1997; Koerner, 2001; Bouazza, 2002; Bouazza et al., 2002, 2008; Rowe, 2011). But, due to the uncertainties involved in the use of geosynthetics; many of the countries like India and France are still using the locally available low permeable soil or amended soil alone or with a HDPE geomembrane (CPCB, 2008; Gourc et al., 2010). Despite of all the precautions taken while manufacturing, transportation, handling, storage and installation; defects in geomembranes such as wrinkles and holes, and imperfections in the seams are widely reported (Rowe, 2005; Take et al., 2007; Zhu et al., 2009). Discrete and randomly distributed fibers are recently gaining increased attention to improve tensile strength of the soil (Maher and Ho, 1994; Ziegler et al., 1998; Viswanadham et al., 2010b; Consoli et al., 2011; Divya et al., 2014; Li et al., 2014; Tang et al., 2016). Discrete fibers are manufactured in several lengths and are available in different types such as monofilament, fibrillated, tape, and mesh type. One of the main advantages of Discrete and Randomly Distributed Fibers (DRDF) is the strength isotropy and the absence of potential planes of weakness that can develop parallel to oriented direction of reinforcements (Maher and Gray, 1990). Though, some researchers reported the influence of discrete fibers in improving the tensile strength of soil barriers (Viswanadham et al., 2010b, 2011; Plé and Lê, 2012; Divya et al., 2014); there seems to be scarcity of work in this area especially for different types of soil barriers. Studies dealing with the preservation of existing unreinforced clay based barriers of covers (or capping systems) were also found to be very limited. In the case of an already existing unreinforced barrier, the removal of entire barrier may become tedious and sometimes impossible due to the danger of exposing the underlying waste especially where exposure of hazardous wastes can cause environmental hazards such as in the case of low level radioactive waste disposal facilities (Gourc et al., 2010).

The main objective of the present study is to understand the influence of discrete and randomly distributed polyester (PET) fibers on improving the crack resistance and water-tightness of clay barriers by conducting a series of centrifuge model tests. An attempt was made to compare the performance of two different types of soil barriers at the onset of flexural distress with and without fibers. Another objective is to understand the capability of PET fibers on preservation of existing unreinforced soil barriers from cracks induced by differential settlements.

Differential settlements, Cracking and mobilization of fiber-soil interactions are highly influenced by the prototype stress conditions (such as in embankments, slopes, and landfill covers). In small-scale model tests under normal gravity, the same stress levels cannot be achieved in model and prototype. Full scale tests are not always possible and are costly and laborious. In centrifuge model tests, stress similarity is achieved by accelerating a model of scale 1/N to N times the earth's gravity and thereby increasing the unit weight of the soil. Hence, centrifuge modelling technique was adopted in the present study to understand the performance of unreinforced and fiber reinforced barriers at the onset of differential settlements considering the advantage of producing identical stress-strain behaviour of the soil in the model and prototype. The interaction of fibers and soil particles in a fiber-soil composite depends on soil compositions, fiber shape, fiber surface roughness and effective contact area, etc. (Tang et al., 2010). Tang et al. (2007, 2010) reported the use of Scanning Electron Microscopy (SEM) analyses to understand the micromechanical interaction and interface morphologies of fiber reinforced clay soil. It is a powerful tool to provide detailed visual information on fiber distribution and particle arrangements. SEM analysis was used in the present study to discuss the micromechanical interaction between fibers and soil particles.

2. Materials and methods

2.1. Materials

Two different types of soil barrier materials were selected to model clay barriers; classified as CL and CH according to unified soil classification system (USCS). Selection of model barrier materials were done in such a way that they represent the properties of fine-grained soils used in clay barriers of landfill covers reported by Benson et al. (1999). According to the database given by Benson et al. (1999), average liquid limit of the clay barrier material varied from 21 to 101, the fines content varied from 48% to 99%, and nearly all the barrier soils were classified as either CL or CH. For an effective barrier, the required hydraulic conductivity has to be less than or equal to 1×10^{-9} m/s and compaction is ensured to the wet side of optimum. One of the barrier material used in the present study was bentonite amended silty soil. Basic index tests that will help in identification and classification of soil including determination of consistency limits, specific gravity and particle size analysis and permeability tests were carried out on all the formulated soil blends. Out of the various combinations tried, bentonite amended silty soil with 15% bentonite content was found to match with the properties of fine grained soils used in clay barriers and is referred herein as Soil A. Soil A is classified as CH as per USCS.

Another model barrier soil used in the present study is kaolin clay-sand mixture. Out of the various blends of kaolin and sand tried, a blend of kaolin and sand in the ratio of 4:1 (i.e. 80:20) by dry weight was selected as an ideal soil barrier material and is referred here as Soil B. Soil B is classified as CL according to USCS. The relevant properties of Soil A and Soil B are given in Table 1.

Polyester fibers (PET) with a special triangular cross-section having an equivalent diameter of 40 μm having breaking load of 0.326 N at an elongation strain of 19.25% (0.145 N at 5% strain and 0.246 N at 10% strain) were used as discrete fiber reinforcement inclusions. Fig. 1 shows the fibers used in the present study. Scaling considerations for modelling fiber reinforced soil in a centrifuge are reported by Viswanadham et al. (2011) and Divya et al. (2016). When fibers undergo stress within a soil-fiber composite, the force equilibrium is achieved by equating the tensile force acting perpendicular to the cross-section of the fiber and the friction force between soil-fiber interfaces along the fiber length over the fiber surface. From the deduced scaling

Please cite this article as: Divya, P.V., et al., Centrifuge model study on the performance of fiber reinforced clay-based landfill covers subjected to flexural distress, Appl. Clay Sci. (2016), http://dx.doi.org/10.1016/j.clay.2016.12.010