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Micro X-ray visualisation of the interaction of geosynthetic clay liner components after partial hydration

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ABSTRACT

High-resolution X-ray tomography was used to observe a partially hydrated geosynthetic clay liner (GCL) specimen to gain a better understanding of the interaction of its compnents (i.e., geotextiles, fibres and bentonite) on partial hydration when deployed as part of a composite liner system. Detailed in-situ studies of hydration processes in GCLs has proven difficult despite more than two decades of effort. X-ray tomographs were collected at spatial resolutions of 12 and 7 μm to identify the different components within a GCL, as well as to examine in finer detail their interaction within the GCL after initial partial hydration. Tomograph projections provided an excellent aspect of the interaction of these components and some concepts, such as the presence of shearing features within the bentonite component, may require re-consideration based on evidence from X-ray tomography.

1. Introduction

Geosynthetic clay liners (GCLs) are made of a thin (4–7 mm) layer of bentonite contained between two layers of geotextile commonly held together by needle-punching (Bouazza, 2002). A primary function of GCLs is to prevent, minimise or slow the flow of leachates and any soluble contaminants from potential pollution sources such as waste containment facilities (Hornsey et al., 2010; Rowe, 2014; Touze-Foltz et al., 2016). The low hydraulic conductivity of bentonite (the active component of GCLs) has resulted in GCLs becoming one of the preferred components in engineered liner systems (Gates et al., 2009). However, the as-manufactured gravimetric water content (GWC) of the bentonite component is too low (≈10%) for the GCL to minimize leachate flow or gas migration (Vangpaisal and Bouazza, 2004, Lee and Shackelford, 2005; Bouazza and Rahman, 2007; Katsumi et al., 2008; Bradshaw et al., 2013; Bouazza and Gates, 2014; Liu et al., 2015; Rouf et al., 2016a, 2016b, 2017). As a result, passive hydration from the subgrade is expected both to occur immediately upon installation and to be completed before the GCL comes into contact with any leachate from within the containment system. In practice, however, a considerable degree of uncertainty exists concerning the hydration process of GCLs (Rayhani et al., 2011; Anderson et al., 2012; Chevrier et al., 2012; Rouf et al., 2016c; Bouazza et al., 2017a).

Recent applications of X-ray imaging have primarily been focussed on deformations and desiccation cracking of GCLs (Mukunoki et al., 2014; Mukunoki and Take, 2015) and self-healing in polymer-treated bentonites undergoing wet-dry cycling in seawater (De Camillis et al., 2017). The focus of this paper is to make direct observations, through high-resolution X-ray microscopy (XRM), on the interaction of the different components (bentonite, geotextiles and fibres) within a GCL, after it has undergone partial hydration to gain some insight on how pores, geotextile fibres and textural aspects of bentonite influenced internal hydration. The information from such studies can complement exhumation studies (Meer and Benson, 2007; Benson et al., 2007; Benson and Meer, 2009; Scalia and Benson, 2011; Buckley et al., 2012; Rowe et al., 2017) as well as inform models of hydration (e.g., Bouazza et al., 2017a) and thermal conductivity of GCLs (Singh and Bouazza, 2013; Bouazza et al., 2017b).

1.1. Background: X-Ray computed tomography

X-ray computed tomography (XCT) is an X-ray transmission radiographic imaging technique allowing for non-destructive three-dimensional (3D) digital reconstruction of images of a specimen (Cnudde and Boone, 2013). Traditional XCT uses geometric magnification to attain images with micron-scale resolution, depending largely on sample size. Recent advances in optical magnification of X-rays using scintillation screens, as well as in computational processing and the use of graphics

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cards, now allow for higher spatial resolution using XRM which is less limited by sample size. For the instrument used in this study, the optimal spatial resolution achievable can be as high as 0.7 microns (μm). However, to achieve these sub-μm resolutions, small sample sizes are still needed to optimize the optical magnification capabilities of the instrument. Such resolution capacities are referred to as micro-XCT or micro-XRM.

X-ray imaging is based on mapping in 3D the differences in the attenuation of X-rays transmitted through a sample (Ketchum and Carlson, 2001). Materials with a higher density, or those containing a greater proportion of elements with high atomic number (Z), will attenuate X-rays more effectively than lower density and low-Z elements, thus limiting the intensity of the X-rays that pass through the sample. The attenuation coefficient of a sample therefore is directly proportional to the composition (Z). Important ways by which X-rays are attenuated are the photoelectric absorption, Compton scattering or Rayleigh scattering by the sample. These processes occur in tandem and from the point of view of the XRM user, cannot generally be separately discerned. In the present context, because the samples were cylindrical, they presented a relatively uniform absorption cross-section to the X-rays during rotation. For such a sample, scanned in multiple rotations about a central axis, the distribution of the attenuation coefficient can be shown to be related to the sample density. Density contrast corresponds to the boundaries between phases, and therefore the resulting high-resolution images can depict sample texture.

2. Materials and methods

2.1. Instrumentation

The instrument (Zeiss Xradia XRM520Versa®) used in the current study was equipped with a tunable X-ray source (micro-focus operating range of 40–150 kV, 1–10 W) that projected a cone-shaped X-ray beam. The sample holder assembly was mounted on a 4-axis sample stage. An optical magnification lens (4×), with a scintillation screen attached to the front of the objective, was used. The transmitted the X-ray-to-visible light went to a 2k by 2k high-resolution 16-bit CCD digital camera detector.

2.2. Sample jig

A sample jig was manufactured from high-density polyethylene (HDPE) in part to minimise beam hardening effects associated with the GCL sample, but also to control sample volume and hydration (Fig. 1). The jig wall thickness was 2 mm. The adjustable sample space had a fixed diameter of 22 mm and a variable height of 3–13 mm. The jig was adjusted by loosening the septum cap and screwing down the top to a prescribed distance to achieve the final desired thickness for the GCL to hydrate into. For the purposes of this study, the sample height was held constant at 13 mm, thus the total volume available for the GCL as it hydrated ($\approx$4942 mm^3) was held constant for the duration of the study.

2.3. GCL

A commercially available needle-punched GCL (Elcoseal® X1000) manufactured by Geofabrics Australasia Pty. Ltd. was used in this study. Powder sodium bentonite formed the core of the GCL. The GCL had a nonwoven polypropylene geotextile cover layer and a woven polypropylene geotextile carrier. The external surface of the woven carrier geotextile was thermally treated to provide a physical bond between the two geotextiles. The basic physical characteristics of the GCL are given in Table 1. The mass per unit area of the bentonite (M_{bent}) was calculated from the difference between the mass per unit area of the GCL (M_{GCL}) and the mass per unit area of the geotextiles (M_{GTX}). M_{GCL} and M_{GTX} were obtained on GCL virgin specimens at their as received water content. The chemical, mineralogical and index properties of the bentonite component extracted from the GCL, as measured in the laboratory, are given in Tables 2 and 3. Measurements of cation exchange capacity (CEC) were made by the $BaCl_2$ compulsive exchange method with Ba analysis by X-ray fluorescence (a routine in-house method by

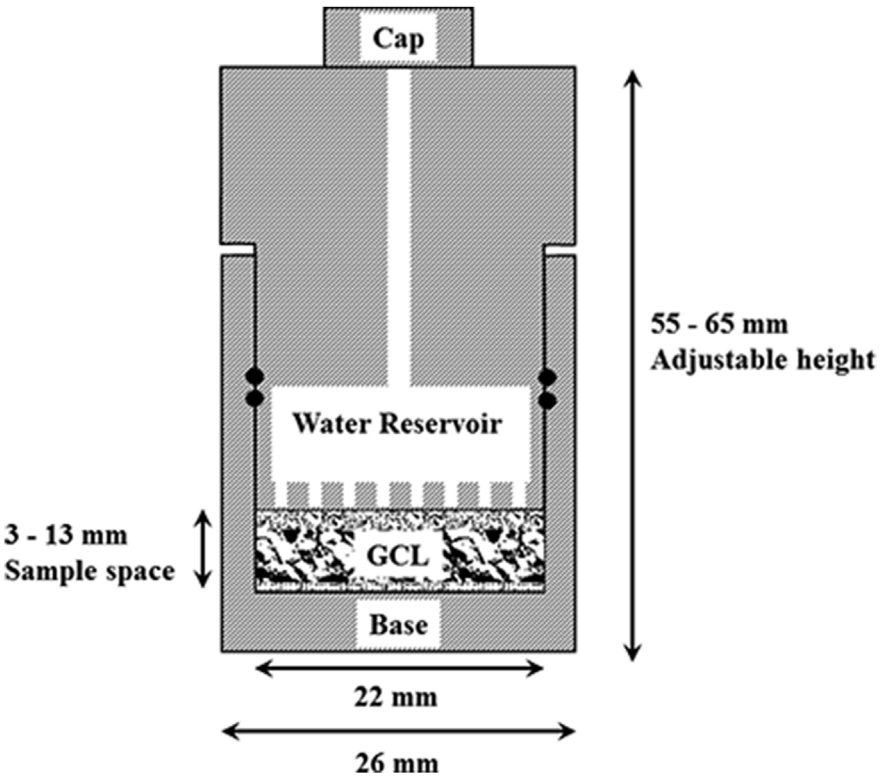

Fig. 1. Sample jig used for XRM examination of a partially hydrated GCL.