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Biochemical, hydrological and mechanical behaviors of high food waste content MSW landfill: Liquid-gas interactions observed from a large-scale experiment

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A B S T R A C T

The high food waste content (HFWC) MSW at a landfill has the characteristics of rapid hydrolysis process, large leachate production rate and fast gas generation. The liquid-gas interactions at HFWC-MSW landfills are prominent and complex, and still remain significant challenges. This paper focuses on the liquid-gas interactions of HFWC-MSW observed from a large-scale bioreactor landfill experiment (5 m × 5 m × 7.5 m). Based on the connected and quantitative analyses on the experimental observations, the following findings were obtained: (1) The high leachate level observed at Chinese landfills was attributed to the combined contribution from the great quantity of self-released leachate, waste compression and gas entrapped underwater. The contribution from gas entrapped underwater was estimated to be 21–28% of the total leachate level. (2) The gas entrapped underwater resulted in a reduction of hydraulic conductivity, decreasing by one order with an increase in gas content from 13% to 21%. (3) The "breakthrough value" in the gas accumulation zone was up to 11 kPa greater than the pore liquid pressure. The increase of the breakthrough value was associated with the decrease of void porosity induced by surcharge loading. (4) The self-released leachate from HFWC-MSW was estimated to contribute to over 30% of the leachate production at landfills in Southern China. The drainage of leachate with a high organic loading in the rapid hydrolysis stage would lead to a loss of landfill gas (LFG) potential of 13%. Based on the above findings, an improved method considering the quantity of self-released leachate was proposed for the prediction of leachate production at HFWC-MSW landfills. In addition, a three-dimensional drainage system was proposed to drawdown the high leachate level and hence to improve the slope stability of a landfill, reduce the hydraulic head on a bottom liner and increase the collection efficiency for LFG.

1. Introduction

Municipal solid waste (MSW) landfill is one of the most common used methods for waste disposal in many developed and developing countries (Laner et al., 2012; Agamuthu, 2013). The MSW in developing countries has the uppermost component of food waste, being 40–85% of the total amount (wet mass basis). It is common that the food waste mostly composed of intra-particle water and easily hydrolysis materials (sugar, protein, fat, etc.). On this account, the landfilled high food waste content (HFWC) MSW presents the behaviors of rapid hydrolysis process, large leachate production rate and fast gas generation (Zhan et al., 2017). Furthermore, a high leachate level was often observed at HFWC-MSW landfills (Dho et al., 2002; Zhan et al., 2015). Below the leachate level, the generated gas tends to accumulate within the saturated zones in a landfill. The entrapped landfill gas could have a significant impact on hydrological properties of MSW (Hudson et al., 2001; Powrie et al., 2008). Therefore, a sound understanding of liquid-gas interactions is required for the management of leachate and gas at MSW landfills.

Recent years, the liquid-gas interactions in the waste pile have been paid attention to and/or investigated by a few researchers.

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Hudson et al. (2001) investigated the hydrogeological properties of a gassing household waste contained in a large size compression cell (2 m in diameter), and found that a large volume of gas accumulated under the leachate level and increasing pore water pressure resulted in a compression of the accumulated gas. Further investigation reported by Powrie et al. (2005, 2008) indicated that the accumulated gas in the waste can significantly reduce the hydraulic conductivity, especially at lower pore water pressures. Beaven et al. (2007) found a reduction in fluid density due to entrained gas in the horizontal well and a negative linear relationship between leachate flow rate and atmospheric pressure in a MSW landfill in United Kingdom, which were probably the results of gas/leachate interaction. Merry et al. (2006) derived a theoretical model for estimating the excess pore pressure at the bottom of saturated waste, and found that the formation of landfill gas may result in a greater pore pressures than what would be predicted by fluid statics.

All the above studies are very valuable, however, it still presents significant challenges to understand the complex liquid-gas interactions at wet landfills of MSW. On one hand, the gas and moisture are not uniformly distributed in the landfill (Li and Zeiss, 2001; Zacharof and Butler, 2004). As a result, the localized phenomena are often observed at the MSW landfill sites. For example, the leachate mound perched by low permeable materials (Zhan et al., 2015), and the gas accumulated in the regions being rich in organic matter (Beaven et al., 2007; Rosqvist et al., 2011). On the other hand, the properties of MSW such as unit weight, porosity, and hydraulic conductivity are found to vary with depth due to the change in overburden stress and degree of degradation (Zekkos et al., 2006; Jain et al., 2006; Reddy et al., 2011). It is difficult to capture the above behaviors in an element test or a small-size model test. Large-scale experiment or field monitoring is believed to be an effective way to investigate the scale-dependent liquid-gas interactions at the MSW landfills. As far as the authors are aware, limited data have been obtained from the field site.

In the present work, a large-scale (5.0 m × 5.0 m × 7.5 m) bioreactor experiment was conducted to investigate the biochemical, hydrological and mechanical behaviors of HFWC-MSW. The measurements of leachate quantity, leachate level, leachate biochemistry, gas composition, waste temperature, earth pressure and waste settlement were reported in Zhan et al. (2017). This paper focuses on the liquid-gas interactions observed from the experiment and the corresponding quantitative analyses. The liquid-gas interactions include: the effect of self-released leachate, entrapped gas and waste compression on the leachate level, the effect of entrapped gas on hydraulic conductivity, the accumulation and dissipation of pore-gas pressure in the entrapped gas zone, and the loss of organic carbons with effluent leachate. Based on the analytical findings, an improved method was proposed for the prediction of leachate production at HFWC-MSW landfills. In addition, a three-dimensional drainage system was proposed to drawdown the high leachate level.

2. Materials and methods

2.1. Experimental setup

The experiment was carried out in a large-size geotechnical model test system constructed in Zhejiang University, China. The experimental cell was 5 m in length, 5 m in width and 7.5 m in height, as shown in Fig. 1. It consists of insulating and impermeable layer at the side wall and bottom, and leachate drainage layer, waste pile, leachate recirculation and LFG collection layer, surcharge loading layer. It was filled with unprocessed MSW directly from a transfer station in Hangzhou, China. The fraction of food waste contained in the fresh MSW was as high as 59.4% (wet mass basis), leading to a high initial moisture content of 70.2% (wet mass basis). The quantity of 91.3 t wastes was filled into the experimental cell, resulting in an initial waste thickness of 5.3 m and a unit weight of 8.0 kN/m^3. A detailed description of each layer was given in Zhan et al. (2017). After operating for 930 days, an airbag loading system with a domain of 0–200 kPa was designed and installed above the surcharge loading layer, as shown in Fig. 1. The loading system consists of pressurized airbag, loading plate, reaction beam and constant pressure control cell. The value of applied vertical stress was recorded by the two earth pressure cells on the top of the waste pile.

The experimental cell was instrumented to monitor the temperature, earth pressure, settlement, moisture content, leachate level and pore gas pressure at various depths in the waste pile. As shown in Fig. 1, the transducers were installed in seven layers, which donated as L_0–L_6. The initial elevations of L_0–L_6 were −0.3, 0.0, 0.9, 1.9, 3.0, 4.4 and 5.3 m, respectively, when defining the bottom of waste layer as the datum point. The two pairs of earth pressure cells installed in layer L_1 and L_4 were to measure the total vertical and horizontal stresses within the waste pile, while the other two cells in layer L_6 were to measure the total vertical stress on the waste surface. Three settlement plates were installed in layer L_2, L_4 and L_6, respectively, to evaluate the compression behaviors of the waste. Two pore-water pressure transducers installed in layer L_2 were to measure the head of leachate mound in waste pile, while the other two in layer L_0 and one in layer L_6 to measure the hydraulic head in the drainage layer and recirculation layer, respectively. The leachate level in waste was also recorded from the standpipe inserted at the side of the cell. The thermistor was incorporated in each of the above transducers to measure the waste temperature. In addition, sixteen time domain reflectometry (TDR) probes were installed in layer L_2, L_3, L_4 and L_5, four probes were in rectangle distribution in each layer, to monitor the moisture content. Besides, the pore gas pressure in the waste pile was measured by U-tube method. The U-tubes filled with water were connected to the 1# and 2# leachate sampling holes (Fig. 1) after no leachate drainage but landfill gas ejection was observed from the holes. The pore gas pressure was quantified by the water level difference in the U-tubes. Leachate flowed out from the cell was collected in a storage tank to monitor effluent volumes and to obtain samples for chemical analysis, including pH, chemical oxygen demand (COD) and volatile fatty acid (VFA). The measurements undertaken on the LFG collection layer include gas pressure, gas flux and gas composition. A detailed description of the monitoring system was given in Zhan et al. (2017).

2.2. Experimental operations

The following experimental operations were undertaken in the cell in the first two years: a surcharge loading to simulate the landfill process, three cycles of leachate drawdown and refilling tests to measure the hydraulic conductivity, etc. A detailed description of the experimental operations was given in Zhan et al. (2017). Since the day 262, no leachate was drained from the two leachate sampling holes which installed 0.5 m above the bottom of the waste pile. However, a plenty of gas ejected out from these two holes. The gas pressures were then measured by U-tube method from the day 277. After that, the surcharge loading was raised by the mean of gravel layer on day 370. The value recorded by the vertical earth pressure on the waste surface was increased from 32.2 kPa to 45.2 kPa. Further surcharge loading was applied to 87.4 kPa by the airbag loading system on days 930–951. It was performed to investigate the hydrological responses under an additional stress.