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Investigating the effect of compression on solute transport through degrading municipal solid waste

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A B S T R A C T

The effect of applied compression on the nature of liquid flow and hence the movement of contaminants within municipal solid waste was examined by means of thirteen tracer tests conducted on five separate waste samples. The conservative nature of bromide, lithium and deuterium tracers was evaluated and linked to the presence of degradation in the sample. Lithium and deuterium tracers were non-conservative in the presence of degradation, whereas the bromide remained effectively conservative under all conditions. Solute diffusion times into and out of less mobile blocks of waste were compared for each test under the assumption of dominantly dual-porosity flow. Despite the fact that hydraulic conductivity changed strongly with applied stress, the block diffusion times were found to be much less sensitive to compression. A simple conceptual model, whereby flow is dominated by sub-parallel low permeability obstructions which define predominantly horizontally aligned less mobile zones, is able to explain this result. Compression tends to narrow the gap between the obstructions, but not significantly alter the horizontal length scale. Irrespective of knowledge of the true flow pattern, these results show that simple models of solute flushing from landfill which do not include depth dependent changes in solute transport parameters are justified.

1. Introduction

The movement of potential contaminants arising from within Municipal Solid Waste (MSW) landfills is of relevance to managers, regulators and broader society. The contaminants (in the form of solutes and particles) are transported by the advective flow of water and by diffusion. Contaminants are flushed out by rainwater entering the landfill, or due to the introduction of additional fluids to the waste. There are a number of reasons why understanding flushing is important. Firstly, the contaminant loading (quality) and volume of the leachate arising from the site over time affects the engineering of leachate storage and treatment facilities. Secondly, depending on circumstances, the generated flux and concentration of mobile contaminants in the leachate and the remaining mobilisable mass within the waste are important in determining potential pollution risks posed by the waste. The evaluation of the present and projected nature of this 'source term' (together with site-specific factors, including the engineered barriers and nature of the surrounding environment) will be important in ensuring that adequate levels of environmental protection are maintained. Since timescales of the order of many decades or even centuries may be appropriate (Harris et al., 1994), uncertainties surrounding flushing processes are likely to relate to significant uncertainties in future financial and societal costs. Understanding waste flushing requires knowledge of the nature of the key transport processes through wastes and how these change under different conditions. The effect on flow and solute movement due to the generation of gas and settlement in degrading organic waste over time has been examined by Woodman et al. (2013b). Aside this relatively uncontrolled natural process, certain site conditions can be controlled by engineers. For example, waste can be pre-treated by shredding and screening to give a maximum particle size.

There is an existing body of literature on how the hydraulic behaviour of municipal solid waste is affected by compression (e.g. Powrie and Beaven, 1999; Hudson et al., 1999, 2001, 2004; Stoltz et al., 2010; Olivier and Gourc, 2007). As well as variation due to different methods of compaction, waste in a landfill can be substantially compressed by the weight of overlying layers, which may reach several tens of metres deep. Compression flattens deformable objects and closes up pore-space. The result is a higher bulk density, reduced water-filled and drainable porosities, and lower permeability (Powrie and Beaven, 1999; Beaven, 2000). Hydraulic conductivity has been shown to vary over five orders

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Nomenclature

a	immobile block characteristic dimension (ratio of block volume to area) (L)	Q	flow rate ($L^3\,T^{-1}$)
A	cross sectional area of waste (L^2)	t_{cb}	characteristic time of diffusion in immobile zone (T)
C_b	initial tracer concentration within the system ('background') ($M\,L^{-3}$)	θ	volumetric water content (–)
D_a	apparent diffusion coefficient ($L^2\,T^{-1}$)	θ_m	volumetric water content of mobile zone (–)
K	hydraulic conductivity ($L\,T^{-1}$)	θ_{im}	volumetric water content of immobile zone (–)
L	length of sample (L)	θ_s	saturated volumetric water content (–)
		θ_d	drainable (volumetric) water content (–)

of magnitude when total applied stress is varied from 50 to 600 kPa (e.g. Powrie and Beaven, 1999). These changes have potentially profound implications for water flow through landfill and, therefore, upon site operation and management. Therefore, compression has a significant impact on advection rates, volumes of liquid and gas which can be stored within the waste and the volume which will be retained at 'field capacity'.

The rate of advection exerts a strong control over solute movement; slower flow implies slower movement of solute in the portion of the waste with flowing leachate. The pattern of the flow may also change with compression. Given the heterogeneous nature of MSW, there is evidence (e.g. Bengtsson et al., 1994; Ehrig, 1983) that rather than being uniformly distributed, flow is concentrated into preferential pathways with less mobile zones existing between these pathways. The nature and inter-connectivity of preferential flow paths may change under compression with a tendency for pathways to either converge or disperse. By implication, less mobile zones of the waste would change shape and/or size in response to any changes in preferred pathways. Since the removal of contaminant from less mobile zones is likely to be dominated by diffusive fluxes, changes to the timescale of mass transfer from these regions is potentially important. The effect of compression on this slower diffusively rate-limited release has not been systematically reported in the literature. Given that compression affects bulk flow rates and porosity, large changes might be anticipated on the pattern of the flow and hence solute movement. This is important, as the time taken for sufficient contaminant dilution to occur is a key factor in determining the period of time after which an operator may handover responsibility for the 'completed' site (other factors are also important, including degradation, waste and leachate composition and temperature). The duration of the dilution period is dependent both on the time of advection through the more mobile portions of the pore space and on the time of diffusion through the less mobile portions. This paper aims to quantify the effect of compression on this latter, less well-described aspect of solute transport, based on evidence gained from a programme of tracer experiments. More specific research questions are, (i) does compression change the inferred block diffusion time and (ii) do other key variables affect this relationship (i.e. scale of measurement, waste type)?

2. Materials and methods

This study draws from and adds to the results from a series of previously reported closed-loop tracer tests on wastes compressed at different applied loads (see Table 1). In Test 0 and Tests 8–13 the simulated results have been reported separately (Woodman et al., 2013a, 2013b) and are combined with new simulations for Tests 1–7 to provide a more comprehensive analysis of the effect of compression than would be achieved for a single sample. The effect of compression of each sample is examined and compared to the other samples (thus scoping for whether waste type and sample size are important compared to the primary compression variable).

2.1. Experimental setup

The experiments shared a basic configuration. Each cell had a mixed reservoir of leachate which flowed through the waste and was pumped back to the reservoir after exiting via the cell outlet. The closed-loop configuration is an alternative to conventional 'in-line' tracer test (where the fluid leaving the column is not fed back to the inlet). The closed-loop column can be kept in a (dynamic) physical and chemical equilibrium, with the exception of the changing tracer concentration (Woodman et al., 2009). This is more difficult to achieve in an 'in-line' test, where fresh water and tracer are injected at the inlet, potentially altering the conditions of the waste-leachate system (for example affecting pH over time).

The reservoir in tests 3–7 were mixed manually using a stirrer following tracer addition and thereafter by means of a pump recirculating liquid from the bottom to the top of the tank. Tests 1–2 and 8–13 relied for mixing on the turbulence generated by the cascading inflow of recirculated liquid to the top of the reservoir. The exception of all the tests was Test 0 in which the outlet fluid was run to drain, in the manner of an ordinary column tracer experiment.

In all tests the waste was enclosed top and bottom by layers of gravel to provide well-distributed flow into and out of the waste. Fig. 1 provides schematics of the apparatus. Each cell was in hydraulic equilibrium before the tracer tests commenced. The tracer tests were started by instantaneously adding and mixing a tracer into the leachate reservoir and thereafter sampled in the reservoir (sample point 'R') and/or at the outlet to the waste cell (sample point 'O'). The samples provided a number of breakthrough curves (BTCs), which were analysed firstly in terms of mass-balance and secondly by modelling. The tests were all run for approximately a month (in the range 26–45 days).

2.2. Tracers

Three different tracers were applied in these tests: deuterium (added as deuterium oxide, D_2O), lithium (Li) and bromide (Br). LiBr was added in all the tests except for test 0 where LiCl was added as a tracer at the same as indigenous bromide was flushed out. The tracers, their measurement techniques and errors are detailed in Table 2.

Lithium has been used several times as a tracer for transport within MSW (Blakey et al., 1998; Öman and Rosqvist, 1999; Rosqvist and Bendz, 1999; Beaven et al., 2003). Its common use in MSW is explained by its relatively low cost and frequently low background concentration (Harris, 1979; Blakey et al., 1998). Lithium has been shown to have a low affinity for sorption to waste under laboratory conditions (Stegemann et al., 2006). Leaching tests from a range of MSW-derived wastes indicate that leached concentrations of lithium show a dependency on pH, possibly indicating the influence of mineral phases on solubility, but maximum