Sustainable Environment Research 26 (2016) 255–261

Contents lists available at ScienceDirect

Sustainable Environment Research

journal homepage: www.journals.elsevier.com/sustainable-environment-research/

Original Research Article

An experimental study on the impact of two dimensional materials in waste disposal sites: What are the implications for engineered landfills?

Diana M. Caicedo-Concha [a], [*], John J. Sandoval-Cobo [b], Kai Whiting [c]

[a] *Faculty of Engineering, Universidad Cooperativa de Colombia, Cali 760035300, Colombia*
[b] *Faculty of Engineering, Universidad EAN, Bogota 110221241, Colombia*
[c] *Department of Mechanical Engineering, Universidad de Lisboa, Lisbon 1-1049-001, Portugal*

ARTICLE INFO

Article history:
Received 28 January 2016
Received in revised form
5 April 2016
Accepted 20 June 2016
Available online 20 August 2016

Keywords:
Landfill processes
Preferential flow
Waste structure
Two dimensional materials
Landfill policies

ABSTRACT

It is generally accepted that landfilled municipal solid waste develops a heterogeneous and anisotropic structure during placement, degradation and settlement. Flow and transport processes, in traditional and alternative landfills, are strongly influenced by the type of structure developed. The presence of preferential flow has gained research interest, given its impact on landfill processes. This paper describes an experimental investigation carried out on a specimen of degraded municipal solid waste.

Preferential flow was detected and caused by the specimen layered structure composed of two dimensional particles derived from less easily degradable materials such as plastics, textiles and paper which made up more than 50% of the specimen dry mass. The results suggest that two dimensional particles play a role in promoting preferential flow because they modify flow paths and increase the tortuosity. A high content of less easily degradable two dimensional materials suggests incompatibility with better management practices, seeking a more even distribution of fluids to enhance degradation and faster stabilisation rates within engineered landfills. Consequently, there is a need to re-think the types and quantities of materials that are restricted under current landfill policies.

1. Introduction

In total 1.3 billion tonnes of municipal solid waste (MSW) are produced globally, at an average daily rate of 1.2 kg per capita. By 2025 this amount will increase to 2.3 billion tonnes per year [1].

Although final disposal of MSW is considered the least desirable option it remains the predominant solution worldwide [2]. Approximately, 80% of global urban MSW is placed in waste disposal sites, of which only 20% is contained in engineered and controlled landfill sites [3]. This is despite the fact that pollution originating from active and closed landfill sites and open dumps, is likely to persist for centuries, rather than decades [4]. MSW has a heterogeneous composition. Its properties are influenced by the materials that constitute the waste body. The nature of MSW varies within and among countries, although some general tendencies can be drawn [5,6]. In higher income countries, paper and plastics, account for 31 and 11% of the waste matrix, respectively. Under current MSW practices, the entry of paper, plastics and textiles into controlled waste disposal sites is not likely to experience a significant reduction in the short to medium term because their generation is linked to economic growth [1]. Such waste entries are incompatible with waste management practices focused on recycling and recovery [7,8].

The effect of preferential flow (PF) on modern landfill operation is not yet certain, although the effectiveness of leachate and gas collection systems in engineering landfills and the operation of modern landfills, that seeks to improve biodegradation and stabilisation processes, do rely on the fluid flow characteristics of the waste body [2]. Research evidence suggests that certain materials such as paper, plastics and textiles have the potential to affect fluid flow patterns and therefore influence some characteristics within a waste body. The experiments discussed in this paper add further empirical evidence to support this hypothesis.

---

[*] Corresponding author.
E-mail address: diana.caicedoc@campusucc.edu.co (D.M. Caicedo-Concha).
Peer review under responsibility of Chinese Institute of Environmental Engineering.

http://dx.doi.org/10.1016/j.serj.2016.08.001

To use the United Kingdom as an example, approximately 48 Mt of MSW were generated in 2006. This was reduced to 28 Mt by 2012, due to the implementation of the 1999 Landfill Directive. This European directive was introduced in an attempt to reduce the amount of biodegradable waste sent to landfill. It was successful. The proportion of such waste was 79% in 2006, a percentage which dropped to 46% by 2010 [9]. The disposal of plastics however, has not seen such a reduction. In fact, the amount of plastic sent to UK landfills increased slightly from 3.5 to 3.9 million from 2006 to 2010 [10].

Any increase of non-easily and not rapidly biodegradable materials such as, but not limited to, plastics, textiles and paper may be of concern for controlled waste disposal site operations and management, as two dimensional particles (as defined in Section 2.3) are thought to divert or impede flow paths, alter flow patterns and reinforce the waste structure [11–15]. This likelihood is thought to increase with particle size and higher overall proportions in the waste body. If the materials are horizontally oriented, this will also have an effect. Two dimensional particles are said to reduce permeability in porous medium, whilst increasing its heterogeneity [11,16–18]. The combination of these effects increases tortuosity [19,20], which may influence the transport and distribution of liquids and gases within a waste matrix. Such conditions could favour PF, a mechanism which causes the transport of contaminants to be associated primarily with a small fraction of the total pore space [21].

The transport of water and solutes is essential for the degradation of biodegradable fractions within the waste matrix, as this leads to the stabilisation of landfilled waste. The distribution and eventual flushing of non-biodegradable substances, are also dependent on the movement and distribution of liquid through waste which are, in turn, strongly influenced by the MSW structure. Studies by Dixon and Langer, Hudson, Ivanova and Rees-White at laboratory and field scale [14,22–24] indicate that landfilled MSW develops a strong, layered and anisotropic structure, resulting from its heterogeneity and deposition in progressive layers and compaction. Experimental laboratory work on waste columns has revealed the presence of non-uniform flow and stagnant zones [25–27] whilst tracer test field studies indicate PF in landfills [28–30].

Scaling up results from laboratory to field scale is a challenge for scientists. Some of the difficulties include the number and size of the samples used, and the representation of field conditions in the laboratory. A study by Rosqvist and Destouni [30] compared experimental results from tracer tests at both laboratory and field scales. Their results showed that not only the waste body but also, the local fluctuations of the surrounding environment, can influence the hydraulic characteristics and flow patterns and by extension, favour PF in landfills. To better understand the nature of different phenomena in landfills (e.g., hydraulic properties, flow patterns, waste mechanics and degradation rates), controlled experiments are generally first conducted at laboratory scale and, at later stages are scaled up to pilot or landfill scales, in order to properly account for site specific conditions.

Plastics, textiles and paper are of particular interest when it comes to enhancing engineered landfill performance, via an improved understanding of how such materials can create PF conditions. PF could, for example, lead to a partial leaching of the bulk waste fill, giving a false indication as to the degradation state of a waste disposal site. This may result in an underestimation of pollution potential and the premature and erroneous decision to change a site's status from closure to post-closure [30].

In this paper, the extent of which plastics, textiles and paper, influence MSW structure and PF is investigated using flow visualisation techniques. Changes in the mass fractions during degradation and how they may affect landfill processes are also discussed.

2. Materials and methods

PF mechanisms are widely studied within soil science and related disciplines. Flow visualisation studies have become increasingly popular because they permit the optical recognition of flow paths and make it possible to infer flow regimes from both a qualitative and quantitative perspective [31,32]. Flow visualisation techniques can range from the qualitative observation of structures [33,34] to the use of tracers, particularly dyes such as Brilliant Blue [21,34]. The latter is used in this paper.

2.1. Sample and previous testing

An experimental study was undertaken using a compressed and aged waste sample, collected in 2007 from a MSW landfill site in the UK. Both the waste structure and the flow paths were analysed through visual methods, using Brilliant Blue dye. The study of the structure involved the cutting of the sample into sections to evaluate its content and layout. Special attention was paid to the orientation of those two dimensional materials that have the potential to modify flow patterns.

The waste specimen was previously used in waste settlement studies by Ivanova [23]. A pre-treatment of the waste specimen included the removal of metals and the characterisation of waste constituents. The specimen was used as a control sample placed in a consolidating anaerobic reactor (CAR), where microbial processes were inhibited during the first 345 days, in acidic conditions. The sample was saturated using a prepared mineral media containing 10% of anaerobically digested sewage sludge. Following the 345 days, the sample was kept for a further 574 days in a perspex cylinder of 480 mm diameter, under a 50 kPa compression load, achieving a final dry density of 0.48 t m^{-3} and a total porosity of 31.4%.

2.2. Hydraulic conductivity measurements

The sample's hydraulic characteristics were obtained via hydraulic conductivity measurements. It was re-saturated by pumping water through the base of the CAR cell. Constant head (CH) hydraulic conductivity tests were performed with the methodology typically used for compressed soil and MSW samples [35–37]. The CH tests were run in upward and downward flow conditions to assess any significant differences produced by localized pore water pressures or air bubbles under both flow directions. The test were run under three different hydraulic gradients (i.e., 0.5, 1.5 and 2.5). The inlet and outlet head conditions were set by installing pipes connected to the top platen holes, which in turn discharged through a ‘T’ joint with a breather pipe open to atmosphere as described by Sandoval [38].

2.3. Structural and material characterisation

Following the hydraulic conductivity tests, the core sample was drained and extracted from the cell using a piston and then wrapped in cling film. It was 483 (± 4) mm in diameter, suggesting that the original structure had been reasonably well preserved.

The core's top portion (230 mm height) was cut into six 80 mm wide sections (denoted a, b, c, d, e and f in Fig. 1) so as to enable a detailed structural examination; the bottom core section (120 mm height) was used in dye tracer tests (see Fig. 1b). The remnants from the cutting process, 2000 g of the original sample, were thoroughly mixed together to provide five representative waste sub-samples, in preparation for the particle size distribution (PSD) analysis and subsequent material characterisation. The five samples were sieved using meshes of 20, 12, 7, 5, and < 5 mm, according to the British

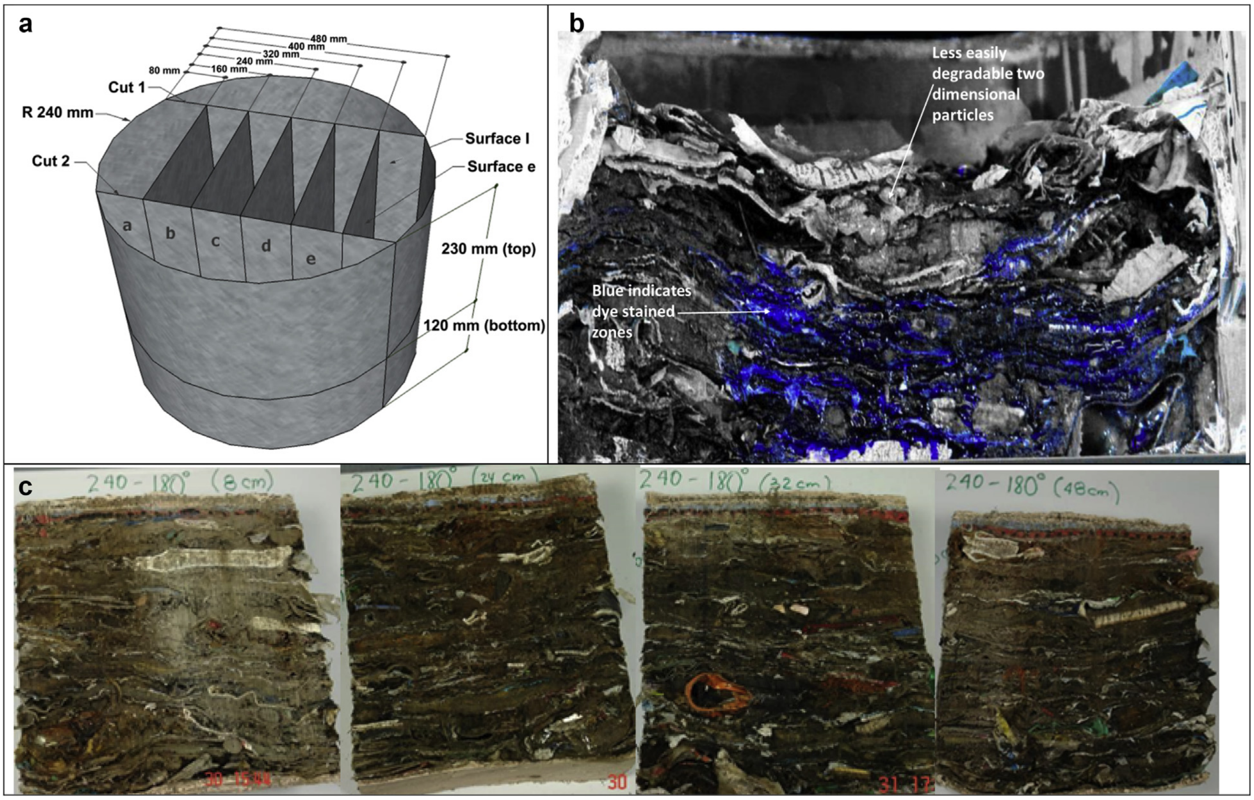

Fig. 1. Schematic representation of the cutting of the initial core MSW used (a. left up side); exposed surface of MSW after irrigation with dye solution where dark blue regions indicate areas that were dye-stained and (b. right up side); selected exposed surfaces photographed from the six 80 mm sections of the experimental setup and uniform irrigation tests (c. down side).

Standard 1377-2 [39]. The waste constituents were categorised into one of the following: paper, flexible plastic, rigid plastic, textile, glass, metal, wood, yard waste, combustible, food, and unidentified. These categories are similar to those suggested by Dixon and Langer [14] and those used by Ivanova [23] for the characterisation of waste constituents for the MSW sample before degradation (see Table 1). Waste constituents were categorised according to their shape in accordance with Kölsch [13]: 0D (grains), 1D (fibres, sticks or strings), 2D (flat particles with two long dimensions and one short, e.g., foils and sheets) or 3D (boxes). Particle shape is an important characteristic that affects flow processes. Plastics, textiles and paper may be classified as two dimensional, should they meet above criteria.

Waste constituents were also categorised according to their potential for degradation as inert components (e.g., glass and metals), less easily degradable materials (e.g., plastics, paper, wood and textiles) and readily degradable organics (e.g., food and yard waste) following a classification similar to that of Meraz et al. [40].

2.4. Flow distribution: single point and uniform irrigation tests

Once extracted from the cell, a block sample (310 × 320 × 120 mm) was produced from the bottom portion of the core, as shown in Fig. 1a. The block sample was attached to a strong mesh (with an aperture size of approx 10 mm). This experimental set up helped to minimise flow disruptions that could rise from fluids going through the side of a tank wall if the specimen were contained (see Fig. 1b).

Five graduated concentric containers were placed beneath the sample and aligned with its centre, allowing for the collection and measurement of the outflow distribution (Fig. 2). Flow paths were studied under single point and uniformly irrigated conditions. Hydraulic conductivity results indicated that hydraulic conductivity for the MSW specimen should be in the order of 3.0–4.2 $\times 10^{-4}$ m s^{-1} (see Section 3.2). Darcy's equation, at the tested hydraulic gradients and core area, states that a minimum flow of 60 mL min^{-1} is necessary to achieve saturation. Any flow rate less than this will create unsaturated flow conditions. For the single point experiments a 50 mL min^{-1} flow rate (4.6 × 10−6 m s^{-1}) was established at the sample's centre using a Watson Marlow 505S peristaltic pump connected to a needle (Fig. 2a). The flow was switched at 5 min intervals from on to off mode. Following steady state conditions, measurements were taken every 10 min, for a total of 40 min. To simulate uniform irrigation conditions, the setting was changed by replacing the needle with a purpose built rainfall simulator device (Fig. 2b). The latter was built using small metallic capillary tubes (internal diameter, ID, of 0.7 mm), inserted into an acrylic sheet and mounted on a Perspex cylinder (ID of 160 mm and height of 74 mm). Water was irrigated at a rate of 50 mL min^{-1} over a central circular area of 160 mm in diameter. Irrigation was maintained until steady state flow conditions were reached. In Table 2 the expected percentage of the total applied flow collected in each container for both experiments is calculated, if a non-tortuous flow pattern is assumed.

2.5. Dye test methodology

Flow visualisation experiments were undertaken. A 1 g L^{-1} Brilliant Blue dye solution (Sigma Aldrich Coomassie Brilliant Blue,

Table 1
Composition by percentage dry mass of MSW sample – Before degradation (*Source: Ivanova* [23]) and – After degradation (*Source*: *Authors*).

Material	Dim.	Degradability category	% Of total mass before degradation		% Of total mass after degradation								
					Mesh size (mm, in terms of percentage, %)								
			Total per material (%)	Total grouped (%)	> 75	75–63	63–37.5	37.5–20	> 20 mm	20–10	< 10	Total per material (%)	Total grouped (%)
Flexible Plastics	2D	Less easily degradable	10.2	**50.5**	0.9	0.9	6.4	4.5	50.8	0.8	0.0	13.4	**56.4**
Rigid Plastics	2D	Less easily degradable	9.9		0.1	2.2	8.7	3.5		0.5	0.0	14.9	
Paper	2D	Less easily degradable	27.3		0.0	0.8	8.2	8.5		3.9	0.0	21.5	
Textiles	2D	Less easily degradable	3.1		< 0.1	0.0	2.9	3.3		0.4	0.0	6.6	
Glass	2D	Inert	2.6	**9.4**	0.0	0.0	0.0	1.2	1.4	5.2	0.0	6.4	**6.6**
Metals	2D	Inert	6.8		0.0	0.0	0.2	0.0		0.0	0.0	0.2	
Wood	3D	Less easily degradable	3.19	**6.2**	0.0	0.0	1.8	1.3	3.9	0.7	0.0	3.8	**4.6**
Combustible	3D	Less easily degradable	2.96		0.0	0.0	0.2	0.7		< 0.1	0.0	0.8	
Food waste	3D	Readily degradable	2.27	**20.7**	0.0	0.0	0.0	000	2.8	0.2	0.0	0.2	**0.2**
Yard waste	3D	Readily degradable	18.40		2.2	0.0	0.3	0.3		0.6	0.0	3.4	**3.4**
Unidentified	0D		13.32	**13.3**	0.0	0.0	0.0	0.0	0.0	0.0	28.8	28.8	**28.8**

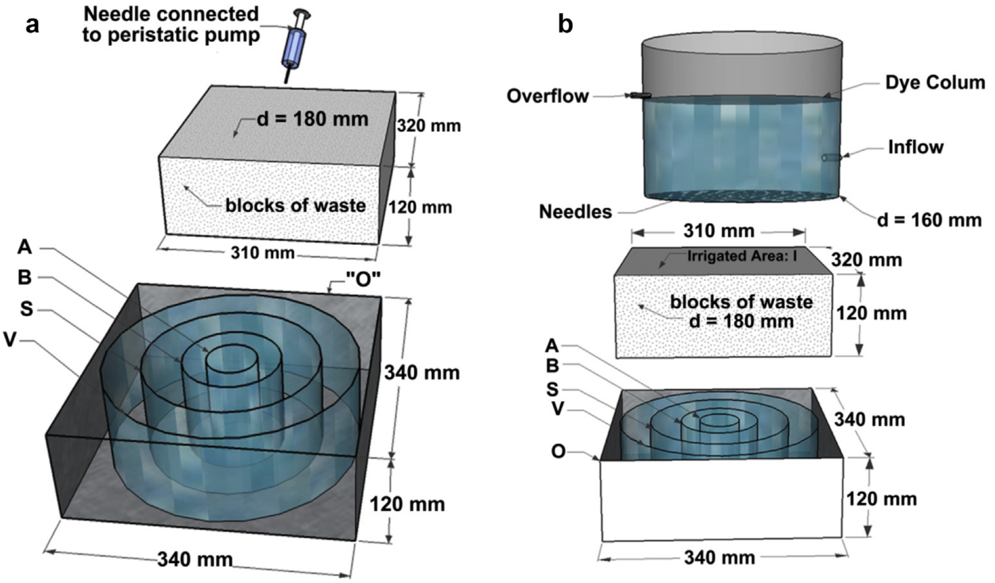

Fig. 2. A schematic representation of the experimental setup used for single point (a. left) and uniform irrigation (b. right) tests.

Table 2
Percentage flow expected (in containers) and summary of outflow results for single point and uniform irrigation tests.

Container	Percentage flow expected			Summary of outflow results					
	Diameter (mm)	Expected collected flow (%)[a]		Area sector (%)		Average outflows (%)			
		Single point test	Uniform irrigation test			Single point test		Uniform irrigation test	
A	63	100	15.5	3.1	3.1	0.0	0.0	0.4	0.4
B	122	0.0	42.6	8.6	75.3	1		18	
S	220	0.0	41.9	26.5		2	14	19	56
V	315	0.0	0.0	40.2		11		19	
O	n.a.	0.0	0.0	21.4	21.4	86	86	43	43

[a] Expected % of total applied flow with assumed non-tortuous flow pattern.

CAS No 3844-45-9) was prepared. This concentration provided a sufficient visual contrast in the waste matrix. Upon achieving steady state conditions, Brilliant Blue was supplied at 43 mL min^{-1}. Both, the total outflow and the concentric distribution were monitored for 60 min. Photographs of the specimen's cross section were taken to visually support the analysis (see Fig. 1 b).

3. Results and discussion

3.1. Structural and material examination

The deconstruction process of the specimen revealed it to be layered and highly structured. Vertical cuttings were achieved with specialised equipment, resulting in good structural preservation. The exposed surfaces obtained from the thin sectioning process are presented in Fig. 1, which shows that 1) the 80 mm sections maintained their structure during the cutting process; 2) although the specimen had undergone, in previous research, 229 d of active anaerobic degradation, all surface revealed identifiable pieces of less easily biodegradable materials such as plastics, textiles and paper; 3) these materials that appeared, on visual inspection, to constitute a significant proportion of the specimen's mass, made up a considerable percentage in the quantitative characterisation, as Table 1 indicates; and 4) for plastics, textiles and paper a horizontal orientation predominated.

Table 1 contrast the results obtained by Ivanova [23], when the sample was fresh (i.e., before degradation), and those collected by the authors in this present paper (i.e., after degradation).

Prior to biodegradation, two-dimensional less easily degradable materials such as paper, plastics and textiles accounted for 50.5% of the total dry mass, a percentage that increased to 56.4%, following biodegradation. The content of plastics and textiles increased from 20.0 to 3.1% to 28.4 and 6.6%, respectively. Although, the content of paper decreased from 27.3 to 21.5% as a result of degradation; this material remained as a predominant fraction within the waste matrix after degradation. Incidentally, paper, plastics and textiles, constituted the greatest fraction of those particles larger than 20 mm in size. This is an important aspect since two dimensional particles have the potential to divert or impede fluid flow in solid waste. According to Caicedo [18], the larger the particle, the stronger the flow diverting or impeding effect.

3.2. Flow distribution: single point and uniform irrigation tests

The average K for tests run in the upward flow conditions was 3.6×10^{-4} m s^{-1} (i.e., 3.0 and 4.0×10^{-4} m s^{-1} minimum and maximum respectively). For tests run in the downward flow conditions the average hydraulic conductivity was 3.7×10^{-4} m s^{-1} (3.2 and 4.2×10^{-4} m s^{-1} minimum and maximum respectively). No significant differences (< 6.3%), under similar hydraulic gradients, were obtained.

3.2.1. Single-point tests

The flow distribution, expressed as a percentage of the total outflow, is presented in Fig. 3a. As the injection point was centred on the waste specimen, most of the outflow should have been collected in sector A, as indicated by the non-tortuous vertical flow bar. However, no fluid was in fact collected in A. The greatest volume flow (71–94%) was collected in O sector.

3.2.2. Uniform irrigation test

Flow distribution, expressed as a percentage of the total outflow, is presented in full in Fig. 3b. In this test, the fluids that irrigated over sector I (diameter 160 mm) were expected to have been collected in sectors A, B and S, assuming non-tortuous flow patterns. The greatest volume flow however, was collected in O (39–46%), V (19–21%) and S (18–21%). This indicates a tortuous flow pattern. Results also show that the Brilliant Blue solution followed a similar flow pattern to that of water.

3.2.3. Tests comparison

Water will always look for the easiest way to flow through a medium. Outflow through the O sector at the periphery, which constituted 21.4% of the total area, was 86 and 43%, for the single point and uniform irrigation tests, respectively, suggesting the presence of horizontal channels that could have led to tortuous flow paths resulting in PF. The above percentage difference may be explained by the fact that with point injection methods it is easier for water to form a pond on a specimen's surface, when compared to uniform irrigation.

The layered structure developed in the specimen during the compression experiments, undertaken by Ivanova [23], was caused by the presence of predominantly horizontally orientated plastics, paper and textiles. The fractional mass content of less easily degradable two dimensional materials (i.e., plastics, paper and textiles) exceeded 50% (by dry mass), prior to biodegradation, a number that increased by 6%, following degradation.

The experiments discussed in this paper provide empirical evidence to facilitate an understanding of waste body characteristics. The results presented support the theory that horizontally orientated plastics, paper and textiles play a role in the modification of flow paths and lead to increased tortuosity, which in turn creates PF conditions. Whilst, the experiments were carried out on a single specimen of aged MSW, and the results cannot be directly extrapolated to landfill site conditions, the outcomes suggest that PF is a likely phenomenon at both laboratory and field scale, especially when the content of less easily degradable two dimensional materials in the waste body is proportionally high. Further research will be necessary in order to ascertain, in more detail, the causes and consequences of PF at field scale. Future investigations could involve field tracer tests to quantify PF [i.e., 28–30] and tracer

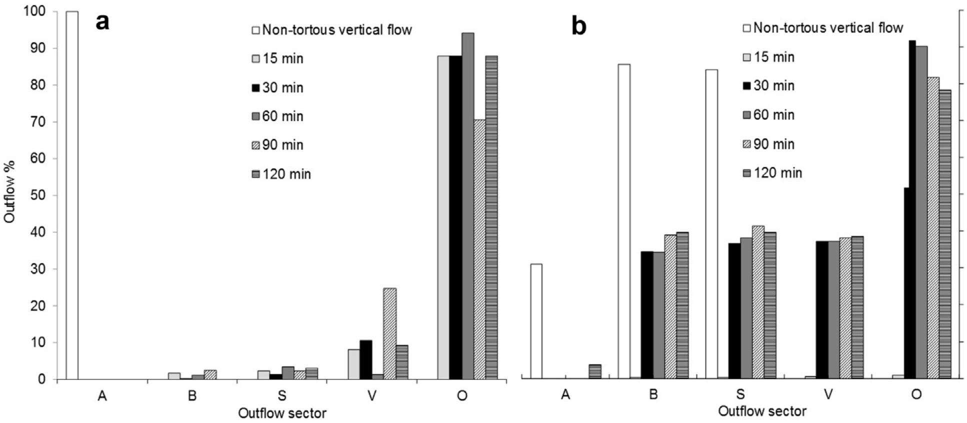

Fig. 3. a (left) Outflow distribution during injection point test. Data for the non-tortuous vertical flow bar assumes linear water flow and negligible spreading; b (right) Outflow distribution during the uniform irrigation test. Data for the first 60 min (represented by solid bars) correspond to water irrigation. The supply was then changed to dye solution (represented by dashed bars).

visualisation techniques to qualitatively describe PF spatial distribution [i.e., 21].

The presence of PF holds implications for waste disposal sites. It is of particular relevance for aged residues that are found in the latter stages of landfill operation (i.e., closure and post-closure). PF may lead to uneven degradation and this can generate non-uniform gas and leachate production, and alter settlement rates, even within the same waste cell. A key issue is that partial leaching of the bulk waste fill, in particular, can give a false impression as to a landfill cell's level of biodegradation. This may create pollution problems, due to a poor estimation as to contaminant transport potential. It may also result in the premature and erroneous decision to switch from closure to post-closure operations and management, which can have severe environmental implications.

This paper identified that a more than 50% content, in mass terms, of two dimensional materials of plastics, textiles and paper favoured PF in a well degraded waste specimen. Following the 1999 European Landfill Directive, one of the consequences of the substantial drop in easily biodegradable waste entering controlled waste disposal sites, is the proportional increase of less easily degradable two dimensional materials in landfilled waste. The impact of such an increase is still unclear. PF patterns do however affect the distribution of fluids, an undesirable condition for the operation of leachate and gas collection systems in engineered landfills and this influences the rate of both degradation and stabilisation processes in modern landfills.

Two-dimensional materials do however have potential reinforcing effects that are important factors in securing structural stability and improving the geotechnical properties of the waste body in landfill sites [15]. An additional consideration is that materials with a high cellulose content, such as paper and cardboard, are responsible for the long term production of methane in landfills, which if managed correctly can provide energy [3]. Therefore, not only the entry of easily biodegradable residuals, but also of less-easily biodegradable two-dimensional materials need to be taken into account when drawing-up landfill waste disposal regulations.

Composition of landfilled waste is likewise an important aspect. More research is needed to demonstrate how best to balance the entry of easily and less easily biodegradable materials, with special regard as to their proportion within the overall waste body. Policies to encourage the recycling of less-easily biodegradable two-dimensional materials such as plastics, textiles and paper should be put forward to progressively limit the entry of such materials to landfills.

Currently only textiles are considered to be a priority resource stream across the UK, for example, under various government waste targets. More research needs to be undertaken at the policy level to ascertain how best to approach this problem.

4. Conclusions

Two novel techniques infrequently used in waste characterisation studies, i.e., thin sectioning and visualisation of flow paths with dye tracers, were successfully applied. Thin sectioning revealed that the MSW specimen's strong and layered structure was influenced by a high content (over 50% by dry mass) of horizontally orientated two dimensional materials including plastics, textiles and paper. The use of Brilliant Blue, as a dye tracer, was shown to be a useful tool for the visual identification of flow paths in MSW. Colour contrast between the waste matrix and the dye was sufficient to achieve visual differentiation.

PF was found to be a predominant flow mechanism during unsaturated flow rate conditions. Outflow through the sectors at the periphery, which constituted 21.4% of the total area, was 86 and 43%, for the point injection and uniform irrigation tests, respectively. This suggests the presence of horizontal channels which in turn could have led to tortuous flow paths, and caused PF. These results may imply that as a consequence of the MSW's layered structure, the horizontal hydraulic gradient is several times larger than the vertical.

This paper has identified the possibility that PF may have an impact on landfill operation and management. And, given that PF is a phenomenon enhanced by the increased percentage of two dimensional particles, such as plastics, textiles and paper, in the overall waste body, practices of reducing the entry of easily biodegradable residuals, without considering the implications of less easily biodegradable two dimensional materials within the waste matrix, seem to be incompatible with the modern techniques associated with engineered landfill sites. Consequently, further research needs to be undertaken at the policy level to ascertain how best to approach this problem.

Acknowledgements

The work described in this paper was carried out as part of EPSRC research grant EP/E041965: Science and strategies for the long-term management and remediation of landfills at the University of Southampton—UK. The experimental results presented in this study are part of the PhD thesis by D. Caicedo, supervised by Professors William Powrie and David Richards from the University of Southampton, and were carried out by first and second authors of this paper. We acknowledge the support of FCT through PhD grant PD/BP/113742 to Kai Whiting. Special thanks to Mr. Geoff Watson for his support during the experiments described in this paper.

References

[1] WB. What a Waste: A global Review of Solid Waste Management. Washington, DC: World Bank; 2012.
[2] Williams P. Waste Treatment and Disposal. Chichester, UK: John Wiley & Sons; 2013.
[3] Themelis NJ, Diaz M, Estevez P, Velasco M. Guidebook for the Application of Waste to Energy Technologies in Latin America and the Caribbean. New York: InterAmerican Development Bank; 2013.
[4] Hall DH, Drury D, Gronow JR, Pollard SJ, Smith R. Estimating pollutant removal requirements for landfills in the UK: III. Policy analysis and operational implications. Environ Technol 2007;28:25–32.
[5] UN-HABITAT. Solid Waste Management in the World's Cities. 2010. London, UK.
[6] EEA. Managing Municipal Solid Waste: A Review of Achievements in 32 European Countries. Copenhagen, Denmark: European Environment Agency; 2013.
[7] Brunner P, Ulrich K. Final sinks as key elements for building a sustainable recycling society. Sustain Environ Res 2014;24:443–8.
[8] Kaila J. How do we manage consumption wastes from a sink point of view? Sustain Environ Res 2014;24:415–22.
[9] EEA. Municipal Waste Management in the United Kingdom. Copenhagen, Denmark: European Environment Agency; 2013.
[10] Eurostat. Statistics Explained. Luxembourg: Municipal Waste Statistics; 2014.
[11] Xie ML, Aldenkortt D, Wagner JF, Rettenberger G. Effect of plastic fragments on hydraulic characteristics of pretreated municipal solid waste. Can Geotech J 2006;43:1333–43.
[12] Ashby MF, Jones DRH. Engineering Materials 2. Oxford, UK: Pergamon Press; 1986.
[13] Kölsch F. Material values for some mechanical properties of domestic waste. In: Fifth international waste management and landfill symposium; 1995 Oct 2–6; Cagliari, Italy.
[14] Dixon N, Langer U. Development of a MSW classification system for the evaluation of mechanical properties. Waste Manage 2006;26:220–32.
[15] Fernando S, Powrie W, Watson G, Richards D. The impact of the reinforcing content on the shear strength of mechanically biologically treated waste. Third International Workshop in Hydro-Physico-Mechanics of Landfills. 2009 Mar 10–13; Braunschweig, Germany.
[16] Velkushanova K, Caicedo D, Richards D, Powrie W. A detailed characterisation of an MBT waste. In: Twelfth International Waste Management and Landfill Symposium; 2009 Oct 5–9; Cagliari, Italy.
[17] Caicedo D, Watson G, Richards D, Powrie W. Exploring the use of micro-focus computed tomography for a better conceptual understanding of structure in

landfilled waste in the context of post-closure management for landfills. Sustain Environ Res 2011;21:259–68.
[18] Caicedo DM. A Study of the Structure in Solid Wastes and Some Implications for Fluid Flow in Landfills [Ph.D. dissertation]. Southampton (UK): Univ. of Southampton; 2013.
[19] Fetter CW. Contaminant Hydrogeology. Upper Saddle River, NJ: Prentice Hall; 1999.
[20] Dullien F. Porous Media: Fluid Transport and Pore Structure. San Diego, CA: Academic Press; 1992.
[21] Flury M, Flühler H, Jury WA, Leuenberger J. Susceptibility of soils to preferential flow of water: a field study. Water Resour Res 1994;30:1945–54.
[22] Hudson AP. Evaluation of the Vertical and Horizontal Hydraulic Conductivities of Household Wastes [Ph.D. dissertation]. Southampton (UK): Univ. of Southampton; 2007.
[23] Ivanova LK. Quantification of Factors Affecting Rate and Magnitude of Secondary Settlement of Landfills [Ph.D. dissertation]. Southampton (UK): Univ. of Southampton; 2007.
[24] Rees-White T. Improving Yields from Vertical Landfill Wells through Better Design, Installation and Maintenance [Ph.D. dissertation]. Southampton (UK): Univ. of Southampton; 2007.
[25] Capelo J, de Castro MAH. Measuring transient water flow in unsaturated municipal solid waste: a new experimental approach. Waste Manage 2007;27:811–9.
[26] Zeiss C, Major W. Moisture flow through municipal solid waste: patterns and characteristics. J Environ Syst 1993;22:211–31.
[27] Korfiatis GP, Demetracopoulos AC, Bourodimos EL, Nawy EG. Moisture transport in a solid waste column. J Environ Eng ASCE 1984;110:780–96.
[28] Johnson CA, Schaap MG, Abbaspour KC. Model comparison of flow through a municipal solid waste incinerator ash landfill. J Hydrol 2001;243:55–72.
[29] Bendz D, Singh VP. Solute transport under steady and transient conditions in biodegraded municipal solid waste. Water Resour Res 1999;35:2333–45.
[30] Rosqvist H, Destouni G. Solute transport through preferential pathways in municipal solid waste. J Contam Hydrol 2000;46:39–60.
[31] Weiler M, Fluhler H. Inferring flow types from dye patterns in macroporous soils. Geoderma 2004;120:137–53.
[32] Lipsius K, Mooney SJ. Using image analysis of tracer staining to examine the infiltration patterns in a water repellent contaminated sandy soil. Geoderma 2006;136:865–75.
[33] Beven K, Germann P. Macropores and water flow in soils. Water Resour Res 1982;18:1311–25.
[34] Mooney SJ, Morris C. Morphological approach to understanding preferential flow using image analysis with dye tracers and X-ray computed tomography. CATENA 2008;73:204–11.
[35] Stoltz G, Gourc JP, Oxarango L. Liquid and gas permeabilities of unsaturated municipal solid waste under compression. J Contam Hydrol 2010;118:27–42.
[36] Beaven R. The Hydrogeological and Geotechnical Properties of Household Waste in Relation to Sustainable Landfilling [Ph.D. dissertation]. London (UK): Univ. of London; 2000.
[37] Daniel D. State-of-the art: laboratory hydraulic conductivity tests for saturated soils. In: Daniel DE, Trautwein SJ, editors. Hydraulic Conductivity and Waste Contaminant Transport in Soil. West Conshohocken, PA: ASTM; 1993.
[38] Sandoval J. Characterisation of Saturated and Unsaturated Flow of Liquids in Municipal Solid Waste [MPhil. Dissertation]. Southampton (UK): Univ. of Southampton; 2012.
[39] BSI. BS 1377–2:1990. Methods of Test for Soils for Civil Engineering Purposes. Classification Tests. London, UK: British Standards Institution; 1990.
[40] Meraz RL, Vidales AM, Dominguez A. A fractal-like kinetics equation to calculate landfill methane production. Fuel 2004;83:73–80.