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Long-term moisture measurements in large-scale bioreactor cells using TDR and neutron probes

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ABSTRACT

This paper investigates the measurement of moisture content in municipal solid waste using two different indirect techniques: neutron scattering and time-domain reflectometry (TDR). Therefore, six laboratory-scale landfill bioreactors were instrumented with both neutron and TDR probes; in addition to that a gravimetric moisture balance was established for each cell. Different leachate recirculation modes were applied to perform different wetting conditions. In a first step, both probes were calibrated based on the water balance from three cells presenting homogeneous water distributions and sufficient temporal moisture variations. The calibration functions were then used for temporal and spatial moisture monitoring of all six cells. The results show that both methods are sensitive to moisture variations and provide interesting information on the complexity of vertical flows within the municipal solid waste. Nevertheless, it appears that neutron scattering offers better accuracy at the laboratory scale.

1. Introduction

1.1. Background

Research on municipal solid waste (MSW) landfilling aims mainly at controlling the different parameters that influence the degradation of waste. The traditional approach of landfills with uncontrolled biodegradation at natural water content which has long prevailed is now more and more replaced by new practices enabling an improved control of biodegradation. It is generally acknowledged that the main drivers for waste biodegradation are its organic content, its moisture content, in addition to the temperature and pH conditions (e.g. [1–6]).

Landfill bioreactors are based on the principle of accelerated in situ waste biodegradation by reaching a biochemical optimal moisture content which lies above the moisture content at waste placement (at least in Western countries [7]). Typically, conventional landfills reach gravimetric moisture contents of 30–40% (wet weight basis); a level that lies below the optimal range of 40–70% for biodegradation [4,7]. Landfill bioreactor engineering thus mainly focuses on the way to increase the moisture of the waste material. Moisture is generally added in the form of leachate, which is injected or recirculated in the landfill cells, and bioreactors hence offer an alternative and cheap leachate treatment option [1,8,9]. A continuous monitoring of MSW moisture seems essential to operate the landfill and this is only possible when real-time and non-destructive moisture content measurements are made. MSW moisture measurements are also needed to better predict the remaining biodegradation potential of existing landfills and for the study of multiphase flows [10] or landfill settlements [11].

Despite the fact that the thermogravimetric (oven drying) method is the standard calibration method, this technique is not appropriate for continuous moisture monitoring on site-scale applications because it is both local and destructive [12]. Therefore, indirect methods have been developed for agricultural and engineering applications in order to offer non-destructive, fast and repeatable measurements. These methods can be divided based on their principle of operation into electromagnetism, electrical or thermal conductivity, tensiometry and neutron scattering [10].

One original feature of the present paper is to use in parallel two indirect methods, neutron scattering and time-domain reflectometry (TDR). The aim of this paper is to validate and to clarify the limits of neutron scattering and TDR for long-term moisture

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measurements in large-scale laboratory bioreactor cells. After a brief introduction to the techniques and to the challenges of moisture measurement in MSW, the materials and methods are presented, followed by the results and a comparison of the techniques. The results should be useful to improve MSW moisture monitoring and landfill operation.

1.2. Types of moisture measurement

The standard method to determine the gravimetric moisture content w of a solid sample is the thermogravimetric method which consists in oven-drying small volumes of the material [12]. The gravimetric moisture content w of the sample is defined by:

$$w = \frac{M_w}{M_s} \quad (1)$$

where M_w is the mass of water and M_s is the total solid mass.

The mass of water is determined from the evaporated mass at a given oven temperature ranging from 60 to 105 °C depending on the authors. This direct method is both time-consuming and destructive for the sample. Indirect methods provide information on a physical parameter – e.g. dielectric constant, temperature, resistivity, electrical conductivity or neutron count ratio – that can be later correlated to the moisture content of the medium. Most of the indirect moisture measurements are correlated with the volumetric moisture content of waste θ defined by:

$$\theta = \frac{V_w}{V_t} = w\frac{\rho_d}{\rho_l} \quad (2)$$

where V_w is the volume of water (m^3), V_t is the sampled volume (m^3), ρ_d is the dry density of the sample (kg/m^3) and ρ_l is the density of the leachate (kg/m^3), assumed to be the one of water.

The methods chosen hereafter consider the volumetric moisture content θ which will be referred to using the acronym "VMC".

Despite recent research efforts on indirect moisture measurement methods, until now there is no commonly accepted way of measuring the VMC of MSW [13]. MSW being a heterogeneous aggregate of materials, indirect VMC measurements are challenging since this matrix has different compositions, particle sizes, densities, porosities and moisture contents for each component. In addition to that, moisture is generally present in the form of leachate which varies in strength and composition, thus potentially altering the signal especially for EM techniques [14]. Two publications proposed an extensive review of different moisture measurement techniques for MSW within landfills [15,16]. Ideally, moisture measurement techniques should include characteristics such as reliability, ease of measurement, non-destructiveness, repeatability, accuracy and large sampling volume [10]. Most of the techniques are sensitive to several parameters and require accurate calibration.

Electro-magnetic and electrical methods were first applied to soils [17,18] but numerous authors demonstrated their applicability to MSW [7,11,13,16,19–21]. However fewer studies have been conducted on neutron scattering in MSW. To our knowledge, only few publications referred to neutron scattering as a method to determine the VMC of waste materials with satisfying results [10,22]. In this paper, both methods will be compared.

1.3. Indirect moisture measurement techniques in MSW

1.3.1. Principle of neutron scattering

Neutron probes emit fast neutrons from a radioactive source into the material. These high energy neutrons emitted from the source are either slowed down (or thermalized) through repeated collisions with the nuclei of atoms in the material (scattering) or absorbed by those nuclei [10]. Most atoms, except those with a very low molecular weight, scatter neutrons with little energy loss because their mass is much greater than the neutron's one. However, if the neutron hits a hydrogen atom its energy is reduced on average to about half because neutrons and hydrogen nucleus have the same mass [23]. Since hydrogen atoms are essential components of water molecules, the resultant cloud density of slowed neutrons detected by a counter, is assumed to be correlated to the material's VMC [10]. This is valid if the significant source of hydrogen atoms results only from water molecules in the medium. A suitable calibration curve is finally required to determine the material's VMC from the measurements of thermalized neutrons.

The count ratio C_R is more typically used than the direct neutron count to establish the calibration curve. It is expressed as the ratio of the count x in the measured material to a standard count x_s, measured in a sample of pure water:

$$C_R = \frac{x}{x_s} \quad (3)$$

Using a calibration based on the count ratio rather than the direct counts allows the same calibration equation, even if the source strength decays [23]. It also guarantees that any change in the counting time does not invalidate the calibration curve [10]. The theory suggests a linear relationship between the count ratio and the VMC [23,24]:

$$\theta_N = a_N C_R + b_N \quad (4)$$

where the subscript N refers to the neutron technique and a_N and b_N are the calibration constants.

1.3.2. Principle of TDR

TDR is an electro-magnetic (EM) technique that measures the travel time of a fast rise-time pulse travelling along the TDR probe waveguide placed into a material. The signal produced by the TDR generator is sent via a coaxial cable through the probe's head inside the porous medium and reflected both when entering the probe's rod and at its end. The resulting waveform is collected and the travel time T of the EM wave can be calculated. The bulk electrical permittivity K (also called dielectric constant) is then calculated using Eq. (5). Finally, the VMC can be inferred using semitheoretical models or empirical formulas [18,21].

$$K = \left[\frac{cT}{2L}\right]^2 \quad (5)$$

where c is the speed of light ($3 \times 10^8\ m\,s^{-1}$), T is the travel time of the EM wave, and L is the length of the probe.

The semitheoretical approach has been developed for soils and relies on the addition of travel time for each phase of the material: solid particles, liquid solution and air within the soil [18,25]. This approach leads to Eq. (6) [18,19,25]:

$$\theta_T = a_T\sqrt{K} + b_T \quad (6)$$

where the subscript T refers to the TDR technique and a_T and b_T are the calibration constants.

The empirical approach consists in fitting parameters of mathematical expressions to calibrate the relationship between the VMC and the permittivity. Eq. (7) was proposed for a wide range of soils [17,18]:

$$\theta_T = -0.053 + 0.0292K - 0.00055K^2 + 0.0000043K^3 \quad (7)$$

A similar polynomial was suggested for MSW basing the results on various experiments at the laboratory scale [21]. A more detailed description of the TDR theory can be found in other publications [13,21].

Table 1
Advantages and disadvantages of thermogravimetric, neutron and TDR measurements [10,12,15,16,21,23]. The major findings of this research are also included as referred to in Section 4.

	Advantages	Disadvantages	Major findings of this research
Thermogravimetric method	Accurate absolute measure	Small sampling volume	Questionable sampling size, especially for heterogeneous VMC distribution
	Very simple calculation	Destructive and time-consuming method	Impossibility to track evolutions
Neutron scattering	Vertical profiles of VMC may be obtained with one probe	Only relative values of VMC	Robust method, insensitive to ageing effects or failures
	Large measurement volume	Measurements may be material-sensitive	Good means to track spatial and temporal evolutions
	Linear relationship between C_R and θ	Risks and costs due to the use of radioactive material	
Time-domain reflectometry	Relatively inexpensive method	Absolute measurement of VMC is difficult	Automated long-term, reliable method to measure moisture
	Automation possible	Small measurement volume	Local and not average measurement
	Relatively insensible to material and liquid effects when coated probes are used	Disturbance of the material when the sensor is installed	

1.3.3. Application of the methods to MSW and resulting limitations

According to some publications, neutron scattering is appropriate to monitor VMC changes in MSW but fails to determine the absolute VMC notably because of the bound hydrogen effect [10,16]. In fact, the wood and plastics present in the waste account for neutron scattering that is not caused by the presence of water molecules. This effect may alter the offset of Eq. (4) but no influence on the relative VMC measurements was reported [10]. Hence, neutron scattering can be used to measure moisture changes with acceptable errors if the presence of neutron capture elements is not important.

On the other hand, EM techniques are less expensive but sensitive to leachate quality [13,16,21] which can be successfully counterbalanced by using coated probes [13]. However, it was shown that absolute VMC measurements in MSW with TDR are not entirely reliable [21]. Here, only relative VMC measurements will be made in accordance with the approach chosen for the neutron measurements.

As in soils, both techniques have a limited measurement volume in MSW, namely a sphere of influence of approximately 15 cm in radius (approximately 14 L in volume) for the neutron probes and a cylinder of approximately 4–5 cm in radius and 50 cm in length (approximately 3 L in volume) for the TDR probes used in this paper (unpublished results). As the probes are intended to measure the VMC of shredded materials, it is believed that the measurement volume of the probes is sufficient for this study. However, the measurement volume may be limited for site-scale applications with coarser particles.

While both methods have some limitations, the methods are rather complementary as they do not share these limitations. Table 1 proposes a summary of advantages and disadvantages of the techniques used in this paper.

2. Experimental

2.1. The bioreactor cells

Six bioreactor cells of 1 m diameter and 1.2 m^3 in total volume referred to A1, A2, A3, B1, B2 and B3 were built at the LGCIE Institute in Lyon (France). These cells were filled with a MSW from a French landfill. In fact before filling the waste into the cells, it was shredded and sieved at 15 cm (coarsely shredded waste) for the 3 'A' cells and 7 cm (finely shredded waste) for the 3 'B' cells. The main waste components were yard and kitchen waste (31%), papers (21%), plastics (14%), cardboard (6%), glass (6%) and metals (5%). More details about the waste characteristics can be found in another publication [26].

In each cell, a 10 cm-thick gravel layer for leachate drainage was set at both the top and bottom of the cell. The initial height of waste in cell (i) is referred to as z_i (Table 2); evidently this value decreases with time due to settlement. A 45 mm-diameter central aluminium tube was used for moisture measurements by the neutron probe and for the measurement of vertical displacement of a magnetic plate on the top of the waste sample using a specific probe, moved downward in the tube. Three TDR probes were placed at different heights and in different horizontal directions. The cells were maintained at a constant room temperature of $35 \pm 2\,^{\circ}C$. The settle-

Table 2
Characteristics of the six bioreactor pilots at the LGCIE [26].

Reactor	A1	B1	A2	B2	A3	B3
Characteristics	Saturated-drained, coarse shredding	Saturated-drained, fine shredding	High injection rate, coarse shredding	High injection rate, fine shredding	Moderate injection rate, coarse shredding	Moderate injection rate, fine shredding
Volume (m^3)	0.82	0.82	0.77	0.80	0.81	0.83
Initial dry mass (t DM)	0.30	0.36	0.30	0.36	0.30	0.36
Initial dry density, ρ_d ($t\,m^{-3}$)	0.37	0.45	0.40	0.45	0.37	0.44
Initial waste height, z_i (cm)	110	109	102	106	107	110
Initial moisture added (L)	391	328	0	0	0	0
Injection rate (L/(t DM day))	0	8.0	8.0	8.0	2.0	2.0
Start of injection	–	Day 199	Day 87	Day 87	Day 157	Day 157
θ_G at start of injection	–	36%	15%	23%	14%	22%
End of injection	–	Day 241	Day 190	Day 206	Day 364	Day 311
θ_G at end of injection	–	45%	32%	45%	27%	30%

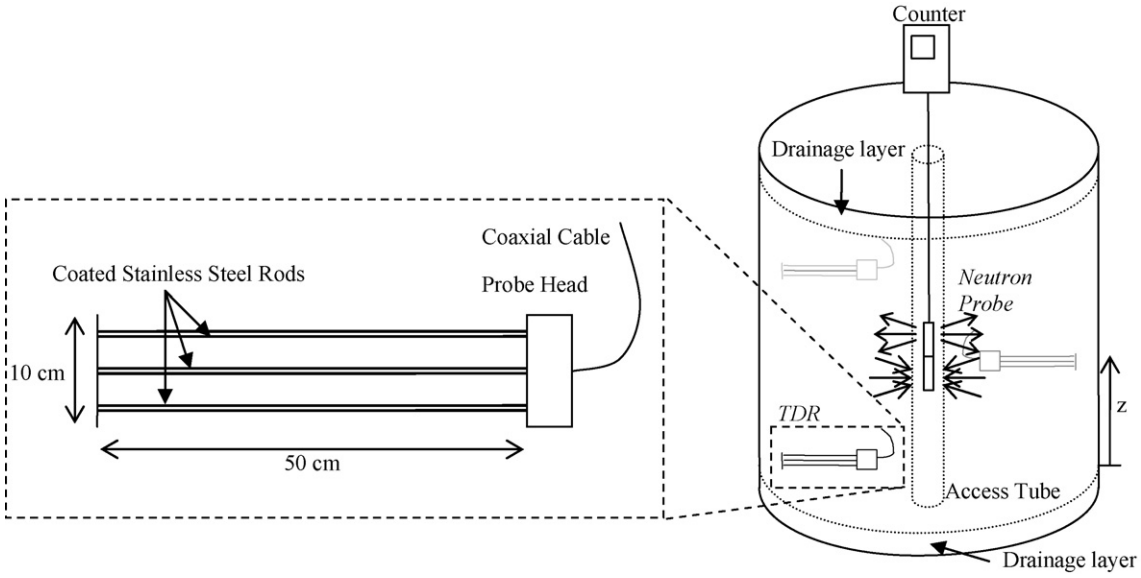

Fig. 1. Schematic diagrams of the TDR and neutron probes (not to scale) and their position in the bioreactor tanks.

ment measurements are not detailed in this paper, but the vertical displacement of the TDR probes is accounted for (Section 2.2.2). More information can be found in another paper dedicated to the settlement measurements and modelling [27].

Two different operating procedures for leachate addition were tested (Table 2) [26]:

- The cells A1 and B1 were saturated with leachate collected from the landfill where the waste was collected. Leachate was injected into both cells from the bottom under constant head and it was verified that the leachate level inside the cell reached the top of the column. After 12 h, leachate was drained out by opening a bottom valve. Cells A1 and B1 kept respectively 148 L and 145 L of leachate. Given that cell B1 had not reached field capacity, a late injection phase at a rate of 8 L/(t DM day) (litres per tonne dry matter per day) was performed from Day 199.
- A leachate circulation was performed from the beginning for the remaining four cells. 8 and 2 L/(t DM day) were injected downwards once a week during 1 h for the pilots A2–B2 and A3–B3 respectively (Table 2) after an initial period without injection events.

Table 2 provides detailed information on the successive injection phases. The global VMC θ_G given by Table 2 corresponds to the ratio between the cumulated volume of leachate, obtained by subtracting the leachate outflow to the leachate inflow, and the global volume of waste measured experimentally (Eq. (2)). The experimental setup was monitored for 13 months.

2.2. The setup for moisture measurement

2.2.1. The moisture measurement devices

Three-rod type TDR probes have been designed at the LTHE in Grenoble for the experiments carried out at the LGCIE in Lyon. Fig. 1 shows a schematic diagram of the 50 cm-long probes. The TDR probes are placed in staggered rows at three different levels z: 20, 50 and 80 cm from the bottom of the waste. Each one is connected through a coaxial cable to an automatic data acquisition system, TDR100 from Campbell Scientific (Logan, UT, USA) which generates and acquires the signal. A coaxial multiplexer, SDMX50, also from Campbell Scientific, is used to make several measurements at once. Measurements were taken at regular time intervals prior to the injection events. Readings were also taken from cells A1 and B1 at the same time interval.

A neutron probe from Campbell Pacific Nuclear (CPN, InstroTek, Raleigh, NC), was used, model 503 DR Hydroprobe. The radioactive source consists in an Americium-Beryllium source of fast neutrons. Fig. 1 shows a schematic diagram of the measuring setup. The probe is inserted manually in the central aluminium tube of the cell, and measurements are taken at a vertical spacing of 10 cm.

Neutron measurements are made at the same time interval as the TDR measurements, i.e. just before the injection events.

2.2.2. Neutron and TDR calibrations

The global VMC θ_G for each cell and local probe measurements are provided. Consequently, only a correlation between the global VMC and an average probe measurement can be considered; the average of all measurements on the entire cell height for each probe is the most representative value. Looking for this kind of correlation, it is more relevant to restrict the calibration to the cells with the more homogenous probe responses along the vertical axis, indicating limited spatial moisture distribution heterogeneity. It is supposed that at each time step an average of all measurements on the entire cell height for both probes is the most representative. For the neutron probe, a neutron leakage could occur if the measurement volume comprises gravel from the drainage layers at the boundaries of the waste sample (Fig. 1) therefore the measurements at $z = 0$ and $z = 90$ cm are not included in the average. Hence, only the eight medium neutron count ratios are averaged for each global VMC (Fig. 2a). The TDR probes' measurement volumes are completely included in the waste volume, and the average of the three measurements is considered (Fig. 2b). It is worth noting that the vertical settlement of waste is also accounted for, reflected by the position of the TDR probes as well as by the modification in θ_G (as the volume V_t is decreasing, Eq. (2)).

Fig. 2 illustrates some results obtained over a short-time period (200 first days), using the cell B2. The dashed lines delimitate the central domain where the neutron measurements are averaged (Fig. 2a). Convenient scales are used for every type of measurement, C_R, $\sqrt{K}$ and θ_G for a better readability (Fig. 2b).

Knowing the initial global VMC of the material and tracking moisture variations, it is possible to calibrate the probes using the relative measurements.

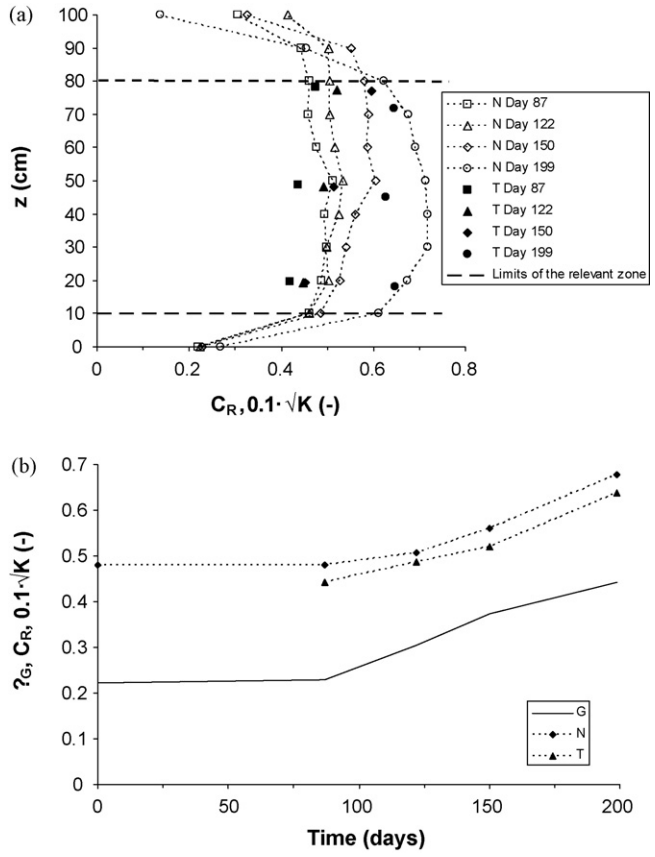

Fig. 2. (a) Temporal profiles of count ratios and square roots of the permittivity versus height in B2, (b) global VMC θ_G (G), neutron count ratio average (N) and square root of the average permittivity (T) versus time in B2 (reactor with high injection rates).

Table 3
Calibration results for the A2, A3 and B2 cells.

Reactor	Neutron calibration		TDR calibration	
	a_N	r^2	a_T	r^2
A2	1.291	0.88	0.082	0.83
A3	1.265	0.98	0.075	0.96
B2	1.492	0.88	0.126	0.90

In accordance with the limitations of Section 1.3, a linear relationship between $\Delta\theta$ and ΔC_R is supposed. As increments are considered, the offset of the relationship is 0 ($\Delta\theta_{N,T} = (\theta_{N,T})^{\text{Day } D} - (\theta_{N,T})^{\text{Day } 0}$). When the variations of VMC are low, the variations of the measurement outputs are also low and the linearity may not be always obvious; therefore a calibration using cells with significant VMC variations must be considered. In fact, the cells with the highest temporal VMC variations and a homogeneous spatial VMC distribution were hence selected for calibration, namely A2, A3 and B2. Table 3 shows the calibration results.

Following calibration functions are used, according to Eqs. (4) and (6):

$$\Delta\theta_N = a_N \ \Delta C_R \tag{8}$$

$$\Delta\theta_T = a_T \, \Delta\sqrt{K} \tag{9}$$

The slopes of the two calibration functions are an average of slopes from the cells A2, A3 and B2:

$$\Delta\theta_N = 1.350 \ \Delta C_R \tag{10}$$

$$\Delta\theta_T = 0.094 \, \Delta\sqrt{K} \tag{11}$$

The value for a_T shown in Table 3 for the shredded material (cell B2) falls into the same range as the slopes of 0.12–0.15 found by using another testing method on the same waste material [21].

3. Results

3.1. Temporal moisture evolution

Eqs. (10) and (11) are used, in agreement with the calibration results, to compare global VMC and average signal values:

$$\theta_N = \theta_N^0 + 1.350 \ \Delta C_R \tag{12}$$

$$\theta_T = \theta_T^0 + 0.094 \ \Delta\sqrt{K} \tag{13}$$

The assumption is that θ_N^0 and θ_T^0 are taken as the initial θ_G for the first measurement with the respective method for each bioreactor, as the initial global VMC θ_G^0 is easy to assess.

$$\theta_N^0 = \theta_T^0 = \theta_G^0 = \theta^0 \tag{14}$$

Average global θ_G and measured θ_N and θ_T are in good agreement for A2, B2 and A3. This seems logical, as these pilots were considered for the calibration relationships. To validate the calibration functions, these latter must be tested on cells with other injection rates.

Cells B1 and B3 show an overall good agreement between θ_G and θ_N, θ_T. The late injection phase after Day 199 is in particular clearly visible for cell B1. Cell A1 shows a good agreement only during the saturation phase (up to Day 31). This may be due to the repetition of measurements with low θ_G variations (the only variations of θ_G are due to waste settlement) which is not appropriate for a linear calibration. From the third measurement, the variation both in θ_G and in the response of the probes is negligible. An erroneous VMC estimation at the third measurement date results in a systematic discrepancy for all following measurements, explaining the poor moisture monitoring performance on this cell.

In the cell B3, θ_G increases by 10% in 389 days, but θ_N does not follow the trend (Fig. 3). Two suggestions can be made: either the slope of the calibration function is not high enough (poor sensitivity), or the neutron probe did not observe the water front. This will be investigated more thoroughly in the next section.

The influence of shredding is not clearly highlighted by these results, although there is a difference in sensitivity between the two different series of test ('A' and 'B'). A given θ_G variation

Table 4
Statistical analysis of the VMC estimation performance.

Cell	Neutron RMSE ($m^3\ m^{-3}$)	TDR RMSE ($m^3\ m^{-3}$)	Neutron maximum discrepancy ($m^3\ m^{-3}$)	TDR maximum discrepancy ($m^3\ m^{-3}$)
A1	0.063	0.104	0.100	0.177
B1	0.028	0.071	0.055	0.112
A2	0.018	0.030	0.037	0.079
B2	0.030	0.052	0.053	0.073
A3	0.015	0.022	0.042	0.045
B3	0.041	0.014	0.062	0.022

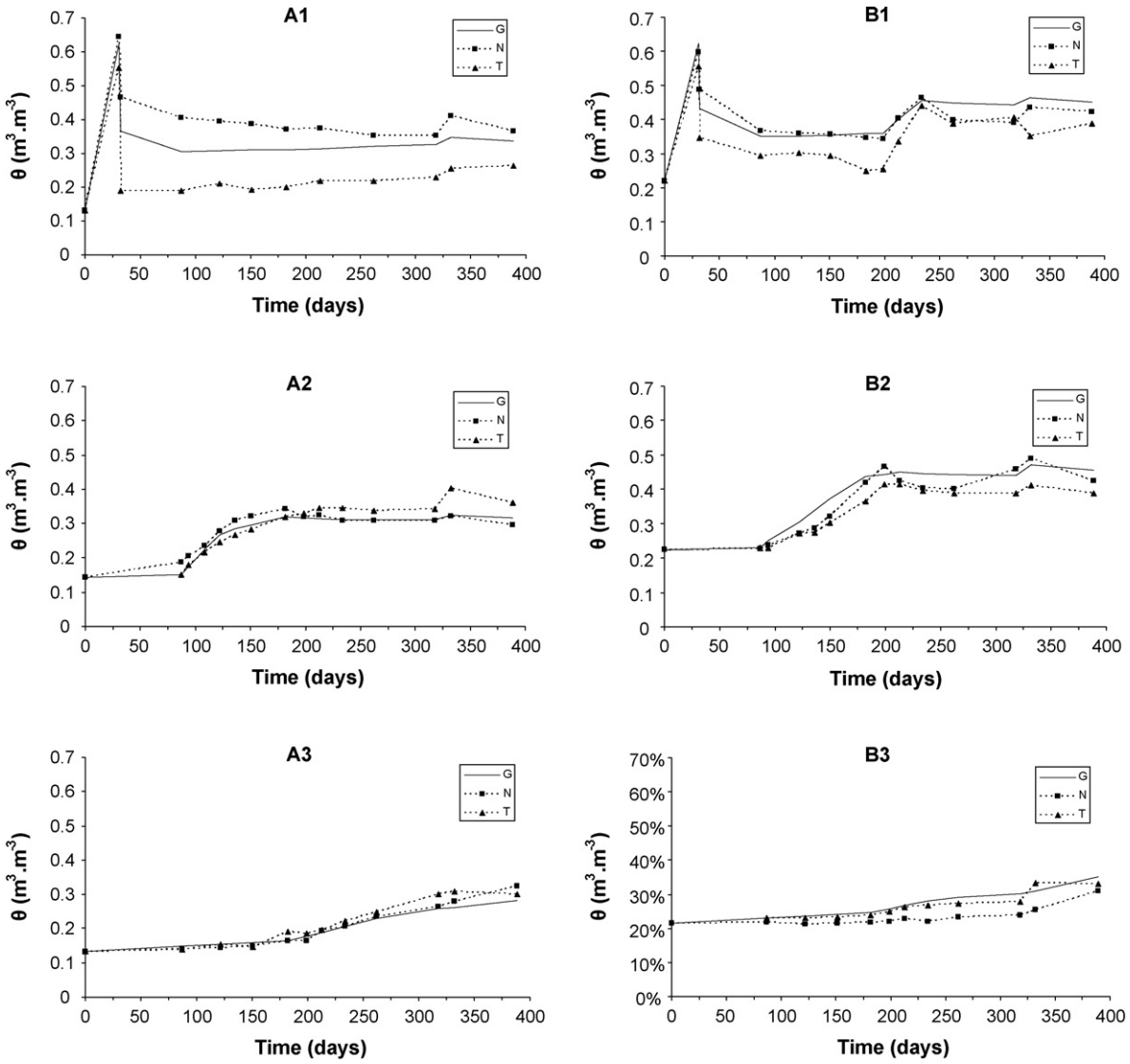

Fig. 3. Temporal VMC evolution monitored by both methods in the six bioreactor cells (*G* corresponds to θ_G, *N* corresponds to θ_N and *T* corresponds to θ_T).

results in a greater signal variation for the cells filled with 'A' waste (coarsely shredded) than for the 'B' waste (finely shredded) (Fig. 3). But this result should be interpreted with care because the measurement volumes of the probes are limited. It was chosen here to use one unique calibration curve for each technique as the MSW composition of both series of cells was identical, but this result indicates that for different types of waste it seems essential to establish a separate calibration curve.

To better assess the prediction accuracy, Table 4 gives the error calculation for the VMC estimates in the 6 cells. The root mean squared error (RMSE) is always below 0.11 $m^3\ m^{-3}$ for both methods, showing that the trends are well correlated. The RMSE associated to the cells used for calibration are low. For the TDR, B3 has the lowest RMSE although it is not used for calibration. It must be noticed that the highest TDR RMSE values are associated with the saturated-drained cells A1 and B1. Neutron scattering generally provides better VMC estimates except in cell B3 which was not used for calibration. The maximum discrepancies are presented to get a concrete idea of the largest errors in VMC estimation. As pointed out before, the largest discrepancies are observed for the saturated-drained cells A1 and B1.

3.2. Spatial moisture evolution

Figs. 4 and 5 respectively show the spatial VMC evolution over time in two cells with finely shredded MSW, B1 and B2, obtained by using Eqs. (12), (13) and (14) to convert raw measurements in VMC (θ_N and θ_T). These two cells highlight interesting behaviours and provide some clues to understand complex flows within MSW. It must be noticed that, in accordance with Section 2.2.2, some measurements at the top and the bottom were removed, being irrelevant due to partial neutron leakage into the gravel drainage layer.

On Fig. 5, the profiles obtained by neutron scattering follow the water balance: the moisture of the waste increases due to regular leachate injections. Moreover, downward injections and drainages by the bottom of the cell result in higher VMC at the cell's top. The results shown in Fig. 4 from the initially saturated cell B1 highlight the opposite behaviour: moisture is accumulating at the bottom of the cell during saturation (Day 31). In cell B2 (Fig. 5), TDR and neutron VMC estimations only coincide at the bottom at Day 199. This indicates probably that the waste was not wetted at the bottom during the first 150 days, or at least not wetted in the measurement volumes of the probes at these times.

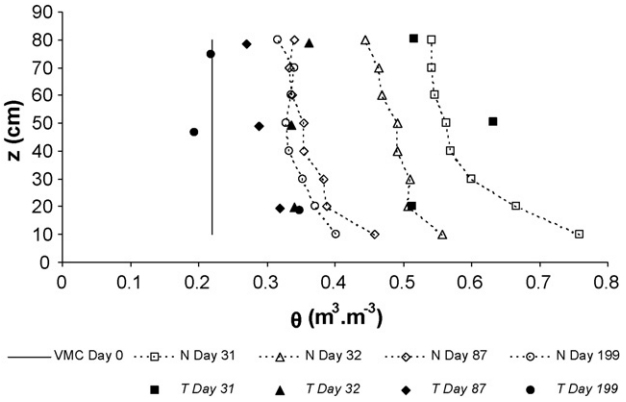

Fig. 4. Temporal VMC profiles versus height from neutron (*N*) and TDR (*T*) measurements in B1 (saturated-drained reactor).

For both cells, the upper and central measurements made using TDR and neutron scattering generally do not coincide. On Fig. 5, the two methods give quite different VMC values after Day 150, especially at the top of the cell. In fact, before Day 150, leachate addition resulted in higher VMC as the porous matrix is efficiently wetted. After Day 150, most of the leachate percolates through the cell without increasing the VMC. This could be interpreted as the enhancement of preferential flows. Indeed, preferential pathways were also observed by other authors in large-scale cells [22,28], which may potentially have an effect on the waste stabilization process [5]. It is a matter of fact that measurements by both techniques are sensitive to the location of the probe: in case of heterogeneous percolation, central measurements (neutron probe) may differ much from lateral measurements (TDR probes) (Fig. 1). Consequently, the observed discrepancy between the two methods can be attributed to an actual spatial discrepancy of the VMC and not to a calibration problem.

It may be supposed that flows are more homogeneous in the saturated-drained cell B1, because of the initial saturation which is a more homogeneous way to wet the material than downward percolation. This explains why spatial variations of VMC versus time are in better accordance in cell B1.

4. Discussion

This paper presented long-time measurements of VMC using TDR and neutron scattering in large-scale cells subject to unsteady leachate flows. Both types of probes were able to monitor moisture over the entire experience time without any technical failure,

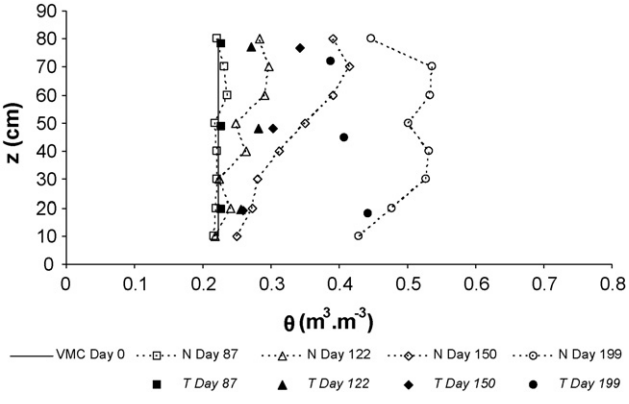

Fig. 5. Temporal VMC profiles versus height from neutron (N) and TDR (*T*) measurements in B2 (reactor with high injection rates).

physical resistance problem, or ageing effect. Both methods have proven to be relevant for the temporal moisture monitoring (Section 3.1). However, the monitoring of spatial VMC variations is more difficult when using TDR (Section 3.2). With only three vertical measurements and smaller measurement volumes, TDR appears in fact to be less relevant in predicting spatial VMC distribution. This limitation could be counterbalanced by installing more TDR probes in the setup. When using the neutron probe, even if one measurement initially derives much from the average, due to the number of spatial measurements, the other measurements generally give a good estimate of local VMC. The limitation of this method comes from the initial VMC distribution of the waste. Indeed, if the waste presents initial heterogeneous distribution of the VMC, all following profiles should be modified. It implies that an accurate global calibration can only be made if water is initially well-distributed along the vertical axis, i.e. waste must have local VMC values close to the global one. Neutron scattering is probably more adequate for water monitoring in large-scale bioreactors: despite initial local heterogeneities, the leachate injection events and the water distribution are clearly visible. Moreover, this method can detect significant variations of VMC. Hence, it appears that with this calibration method, neutron scattering is more convenient.

Remarkably, when compared to the classical gravimetric method to determine moisture content, both indirect methods have shown the ability to track moisture evolution in space and time, which is obviously not possible with the direct method, as it is destructive. Table 1 includes some of the findings of this paper as far as the advantages and disadvantages of the methods are concerned.

This research points out that a multi-technique approach is relevant especially because of the complex nature of flows in MSW and the relatively small measurement volumes for both probes. In other respects, this kind of monitoring could contribute to a better calibration of a numerical modelling of leachate flow through the waste body.

5. Conclusion

The coupled use of two methods for moisture monitoring in laboratory-scale bioreactors with MSW yielded the following results:

(1) Despite the impossibility to assess local water balances, it was possible to calibrate both TDR and neutron probes from the overall water balance.
(2) In addition, one unique calibration curve for each method valid for all six bioreactors could be fitted. The calibration is related to VMC increments, since it is considered that absolute values of VMC cannot be obtained directly from the two measurement methods. Nevertheless, some discrepancies between probe measurements and global water content were observed, depending on the type of injection and shredding.
(3) Calibration functions were used to determine spatial VMC profiles. Their accuracy depends on the initial vertical moisture distribution in the bioreactor and also on the moisture distribution in the measurement volumes of the probes, as leachate flows in the waste are complex.
(4) Neutron scattering seems to be more convenient as it offers a better accuracy at the bioreactor-scale and additional spatial information. Also, its measurement volume is much larger than that of the TDR which can be a significant advantage in the presence of coarse particles.

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References

[1] M.S. Bilgili, A. Demir, B. Özkaya, Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes, J. Hazard. Mater. 143 (2007) 177–183.
[2] J. McDougall, A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste, Comput. Geotech. 34 (2007) 229–246.
[3] S. Pommier, D. Chenu, M. Quintard, X. Lefebvre, Modelling of moisture-dependent aerobic degradation of solid waste, Waste Manage. 28 (2008) 1188–1200.
[4] D.R. Reinhart, T.G. Townsend, Landfill Bioreactor Design and Operation, Lewis, Boca Raton, FL, 1997.
[5] R. Valencia, W. van der Zon, H. Woelders, H.J. Lubberding, H.J. Gijzen, The effect of hydraulic conditions on waste stabilisation in bioreactor landfill simulators, Bioresour. Technol. 100 (2009) 1754–1761.
[6] X. Zhao, R. Musleh, S. Maher, M.V. Khire, T.C. Voice, S.A. Hashsham, Start-up performance of a full-scale bioreactor landfill cell under cold-climate conditions, Waste Manage. 28 (2008) 2623–2634.
[7] R. Guérin, M.L. Munoz, C. Aran, C. Laperelle, M. Hidra, E. Drouart, S. Grellier, Leachate recirculation: moisture content assessment by means of a geophysical technique, Waste Manage. 24 (2004) 785–794.
[8] D. Jun, Z. Yongsheng, R.K. Henry, H. Mei, Impacts of aeration and active sludge addition on leachate recirculation bioreactor, J. Hazard. Mater. 147 (2007) 240–248.
[9] S. Renou, J.G. Givaudan, S. Poulain, F. Dirassouyan, P. Moulin, Landfill leachate treatment: review and opportunity, J. Hazard. Mater. 150 (2008) 468–493.
[10] S.T.S. Yuen, T.A. McMahon, J.R. Styles, Monitoring in situ moisture content of municipal solid waste landfills, J. Environ. Eng. 126 (2000) 1088–1095.
[11] C.E. Pierce, A. Adeyefa, Z. Xu, Laboratory investigation of TDR system to monitor MSW landfill settlement, Waste Contain. Remediat. (2005), ASCE-GI Specialty Conference, Geofrontiers 05, Geotechnical Special Publication No. 142, Austin (TX), USA.
[12] J.P. Walker, G.R. Willgoose, J.D. Kalma, In situ measurement of soil moisture: a comparison of techniques, J. Hydrol. 293 (2004) 85–99.
[13] R.S. Li, C. Zeiss, In situ moisture content measurement in MSW landfills with TDR, Environ. Eng. Sci. 18 (2001) 53–66.
[14] S. Grellier, H. Robain, G. Bellier, N. Shkiri, Influence of temperature on the electrical conductivity of leachate from municipal solid waste, J. Hazard. Mater. B137 (2006) 612–617.
[15] N.A. Gawande, D.R. Reinhart, P.A. Thomas, P.T. McCreanor, T.G. Townsend, Municipal solid waste in situ moisture content measurement using an electrical resistance sensor, Waste Manage. 23 (2003) 667–674.
[16] P.T. Imhoff, D.R. Reinhart, M. Englund, R. Guérin, N. Gawande, B. Han, S. Jonnalagadda, T.G. Townsend, R. Yazdani, Review of state of the art methods for measuring water in landfills, Waste Manage. 27 (2007) 729–745.
[17] G.C. Topp, J.L. Davis, A.P. Annan, Electromagnetic determination of soil water content: measurements in coaxial transmission lines, Water Resour. Res. 16 (1980) 574–582.
[18] A.A. Ponizovsky, S.M. Chudinova, Y.A. Pachepsky, Performance of TDR calibration models as affected by soil texture, J. Hydrol. 218 (1999) 35–43.
[19] K. Masbruch, T.P.A. Ferré, A time domain transmission method for determining the dependance of the dielectric permittivity on volumetric water content: an application to municipal landfills, Vadose Zone J. 2 (2003) 186–192.
[20] M. Van Praagh, M. Persson, K.M. Persson, Assessment of hydrological parameters in pre-treated waste by time-domain reflectometry, in: Proc. Sardinia 2007, 11th Int. Landfill Symp., 2007.
[21] M.J. Staub, J.-P. Laurent, J.-P. Gourc, C. Morra, Applicability of time-domain reflectometry moisture content measurements in Municipal solid waste, Vadose Zone J. 9 (2009) 160–171.
[22] J. Capelo, M.A.H. de Castro, Measuring transient water flow in unsaturated municipal solid waste—a new experimental approach, Waste Manage. 27 (2007) 811–819.
[23] J.H. Dane, G.C. Topp, Methods of Soil Analysis. Part 4. Physical Methods, 2002, pp. 501–521.
[24] W. Gemmell, B. McGregor, G.F. Moss, Estimation of moisture content by neutron scattering: theory, calculation and experiment, Int. J. Appl. Radiat. Isotopes 17 (1966) 615–620.
[25] Y. Gong, Q. Cao, Z. Sun, The effects of soil bulk density, clay content and temperature on soil water content measurement using time-domain reflectometry, Hydrol. Processes 17 (2003) 3601–3614.
[26] H. Benbelkacem, R. Bayard, A. Abdelhay, Y. Zhang, R. Gourdon, Effect of leachate injection modes on municipal solid waste degradation in anaerobic bioreactor, Bioresour. Technol. 101 (2010) 5206–5212.
[27] J.-P. Gourc, M.J. Staub, M. Conte, Decoupling MSW settlement into mechanical and biochemical processes—modelling and validation on large-scale setups. Waste Manage., in press.
[28] H. Rosqvist, G. Destouni, Solute transport through preferential pathways in municipal solid waste, J. Contam. Hydrol. 46 (2000) 39–60.