

Influence of temperature on the electrical conductivity of leachate from municipal solid waste

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Abstract

A bioreactor landfill is designed to manage municipal solid waste, through accelerated waste biodegradation, and stabilisation of the process by means of the controlled addition of liquid, i.e. leachate recirculation. The measurement of electrical resistivity by Electrical Resistivity Tomography (ERT) allows to monitor water content present in the bioreactors. Variations in electrical resistivity are linked to variations in moisture content and temperature. In order to overcome this ambiguity, two laboratory experiments were carried out to establish a relationship between temperature and electrical conductivity: the first set of measurements was made for leachate alone, whereas the second set was made with two different granular media saturated with leachate. Both experiments confirm a well known increase in conductivity of about 2% °C⁻¹. However, higher suspended matter concentrations lead to a lower dependence of electrical conductivity on temperature. Furthermore, for various porous media saturated with an identical leachate, the higher the specific surface of the granular matrix, the lower the effective bulk electrical conductivity. These observations show that a correct understanding of the electrical properties of liquids requires the nature and (in particular) the size of the electrical charge carriers to be taken into account.

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1. Introduction—theory

Municipal solid waste (MSW) contains various elements (degradable waste, glass, paper, plastic, cardboard, metal, etc.) which, taken individually, are in general not very hazardous for the environment. However, the leaching of MSW produces a very highly concentrated leachate of ions and suspended matter.

Waste management techniques using landfills are now trying to accelerate the waste biodegradation process and to decrease waste stabilisation times. In addition, such processes should limit potential threats to the environment. This type of management approach is applied to bioreactors.

A bioreactor relies on a process in which waste biodegradation and stabilisation are accelerated through the controlled addition of liquids, i.e. using leachate recirculation through vertical boreholes or horizontal trenches. The increase in moisture content enhances the growth of bacteria responsible for solid waste decomposition [1]. Furthermore, as the biogas production is enhanced during landfill operations the economical viability of this alternative energy resource can be improved. Several research programs were conducted or are being developed, with the aim to monitor bioreactor landfill sites [2]. As an example, one of the current concerns of these programs is the need to control the quantity and diffusion of injected leachate, in order to obtain homogeneous and optimal moisture content throughout the whole waste mass of the bioreactor cell.

Leachate recirculation can be monitored by various geophysical methods. One of these, referred to as “Electrical Resistivity Tomography” (ERT), has proved to be effective in monitoring variations in electrical resistivity ρ within a bioreactor during leachate re-circulation [3–5]. Variations in electrical resistivity are linked to variations in moisture content

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θ : the higher the moisture content, the lower the electrical resistivity.

Electrical resistivity also depends on other parameters, such as temperature T , clay content CC , ionic content σ_w (S/m), resistivity of the solid phase ρ_s (Ω m), particle size distribution [6], permeability k (m/s), porosity Φ (%), and pressure p (Pa) [7]. These influences can be summarised by a general equation:

$$\rho = f(T, \theta, \sigma_w, CC, \dots) \quad (1)$$

It is well known that an increase in temperature leads to a decrease in electrical resistivity. In the case of bioreactor management, injected leachate may have a much lower temperature than the waste deposit mass, the latter being influenced by exothermic biodegradation reactions. As a consequence, the expected decrease in resistivity due to an increase in moisture content can be masked by the opposite effect resulting from the lower temperature of the additional moisture.

In the study reported here, two approaches were used to study these effects: firstly, waste temperature variations were monitored using sensors placed inside the bioreactor; secondly, laboratory experiments were undertaken to establish the relationships between resistivity and temperature of the leachate liquids. The relationship between leachate conductivity σ_w (S/m) and temperature T can be written as:

$$\frac{1}{\rho_w} = \sigma_w = g(T) \quad (2)$$

This imposes a constraint on the general expression for resistivity given in (1). Archie's law is an experimental relationship linking the formation factor F , i.e. the ratio between bulk effective resistivity ρ_b and liquid resistivity ρ_w , to the influences of porosity and saturation:

$$F = \frac{\rho_b}{\rho_w} = a \cdot \phi^{-m} \cdot S^{-n} \quad (3)$$

where F is the so called "formation factor", ρ_b the bulk effective resistivity (Ω m), ρ_w the resistivity of the liquid filling the pores (Ω m), a an empirically derived constant ranging between 0.5 and 2.5 which depends on lithology ($a < 1$ for rocks with intergranular porosity and $a > 1$ for rocks with fractured porosity), ϕ is the porosity (volume fraction of the pores, %), S the fraction of pore space filled by the liquid (saturation, %), m , also known as the cementation factor, an empirically derived exponent ranging between 1.3 and 2.5, and n is an empirically derived exponent, which is also known as the tortuosity or connectivity factor ($n \approx 2$ for almost all formations with saturation ranging between 0.2 and 1).

For a saturated medium, Archie's law simplifies to:

$$\frac{\rho_b}{\rho_w} = a \cdot \phi^{-m} \quad (4)$$

This law was established for oil reservoirs, corresponding mainly to shales, sandstones, or unconsolidated sands. Archie's law is thus appropriate to the laboratory experiments presented here, where the solid matrix corresponds to calibrated sand grains or glass balls. It should however be noted that the use of expression (3) to calculate the waste saturation, in cases where

there is a strong presence of clay minerals and/or metallic conductors, still has to be validated and/or adapted.

2. Methodology

2.1. Protocol

In the following, two different leachates [8] are analysed. The samples were taken from two French bioreactors, located in the Jura (L1) and Vendée (L2) regions, respectively. Table 1 presents the main geochemical characteristics of the two leachates: the concentrations of suspended matter and major ions are much higher in L1 than in L2. The calculation using Schlumberger indexes shows that the equivalent NaCl concentration for L1 is 2.6 higher than that for L2.

The following two experiments were carried out:

- Experiment I: electrical conductivity was measured as a function of temperature for the leachates L1 and L2 alone (liquid phase).
- Experiment II: electrical conductivity was measured as a function of temperature for two granular media saturated with leachate L2: 160 μ m sand grains (Fontainebleau sand) and 1 mm glass balls.

A special incubator and resistivity-meter were used to control the temperature and resistivity of the samples. A 250 ml sample of leachate is analysed in a cell equipped with four electrodes C1, C2, P1, and P2. The difference in electrical potential (ΔV) between P1 and P2 is measured during the injection of a controlled current (I) between electrodes C1 and C2.

The sample temperature was then progressively increased from 30 °C to 80 °C (corresponding to the expected range of temperatures in bioreactor waste) over a period of 45 h. The sample temperature was then maintained at 80 °C for a period of 5 h, before being cooled down to 30 °C (Fig. 1). The cool-down to room temperature took 12 h. This protocol was repeated twice for the leachates alone and once for sands saturated with L2.

In order to accurately monitor the temperature variations, a (metallic) sensor was placed inside a second identical cell filled with 250 ml of water, which was then immersed in the sample. This approach ensured that the electrical measurements were undisturbed and prevented leachate degradation of the sensor.

The protocol and measurements were controlled by a computer, and the temperature T , voltage drop ΔV (V), and current I (A) recorded every minute. The electrical resistance R (Ω) is

Table 1
Main characteristics of the two studied leachates

	Leachate L1 (mg/l)	Leachate L2 (mg/l)
SS	230	180
[Ca]	57	44
[K]	1220	310
[Mg]	100	80
[Na]	1000	430
[Cl]	1700	620
[NaCl] equivalent	4065	1561

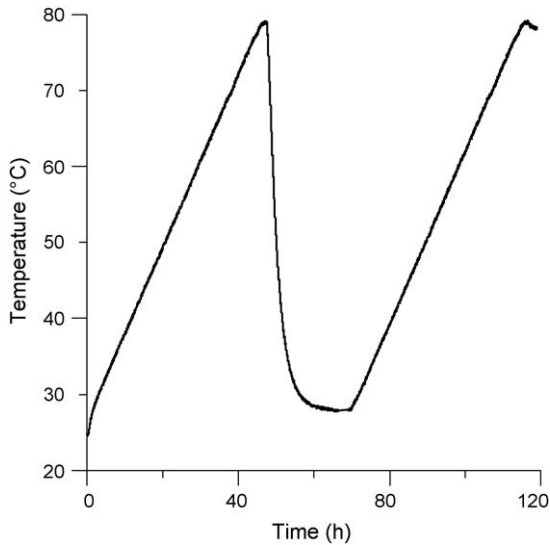


Fig. 1. Temperature excursions during the experiments. Temperatures are given in degree Celsius and time in hours.

calculated as:

$$R = \frac{\Delta V}{I} \quad (5)$$

This protocol allows the electrical behaviour of the leachate to be studied as a function of temperature, during the different phases of leachate recirculation: a rise in temperature when leachate is injected into the waste, and a drop in temperature when leachate is held in a storage pond, separate from the waste, before being recirculated.

Notes: The repeatability of the measurements was checked during a 50 h test of L1 at 30 °C. The dispersion in the values of electrical conductivity and temperature was found to be, respectively, 0.18% and 0.32%. These values are quite low, in comparison with the uncertainty of field resistivity-meters, which is usually about 2%.

As both leachates contain large quantities of suspended matter (about 200 mg/l) which with time could settle to the bottom of the cell, a Teflon-coated agitator was used to ensure adequate mixing of the leachate in the cell during conductivity measurements. The agitator was turned slowly enough to avoid distortion of the leachate surface, but fast enough to maintain a homogeneous medium. The measured electrical resistivity of a homogeneous liquid was found to vary by 0.12% when made with or without an agitator. As these variations are similar to the overall measurement uncertainties they can be considered to be non significant. It can thus be concluded that the use of an agitator, to ensure a homogeneous distribution of suspended matter in the leachate, does not interfere with the electrical measurements. The L1 conductivity measured in the presence of the agitator is 1.89% higher than that measured without the agitator. This difference, a decade higher than the level of measurement uncertainties, is of significance. It shows that the layering of leachate, resulting from sedimentation of the suspended matter at the bottom of the cell, has an influence on electrical conductivity measurements.

2.2. Determination of the geometric coefficient

Electrical conductivity is a physical quantity such that a geometric coefficient K (m) is needed to derive it from the measured conductance. This coefficient depends only on the position of the electrodes used to measure the resistance (or its inverse, the conductance), and on the shape of the measured sample. The relationship between the measured properties and the conductivity is:

$$\frac{1}{\sigma} = K \frac{\Delta V}{I} \quad (6)$$

where σ is the electrical conductivity of the medium (S/m), K the geometric coefficient (m), I the injected current (A), and ΔV is the measured difference in electric potential (V).

Weidelt and Weller [9] established the following equation to calculate K for a cylindrical conductor of finite length L :

$$\frac{a}{K} = f(\beta - \alpha) - 2f(\beta) + f(\beta + \alpha) \quad (7)$$

where a is the radius of the cylindrical sample (m), α the angle between each dipole, and β is the angle between the centres of each dipole, and

$$f(\varepsilon) = \frac{a}{\pi \cdot L} \cdot \log \frac{1}{\sin(\varepsilon/2)} \quad (8)$$

where a is the radius of the cylindrical sample (m), L the length of the cylinder sample (m), and ε is the corresponding angle.

In the present case (Fig. 2), $a = 0.0375$ m, $L = 0.0566$ m, $\alpha = 90^\circ$, and $\beta = 180^\circ$, leading to $K = 0.2500$ m.

K can also be determined experimentally, using solutions of various concentrations. In the study reported here, KCl solutions are used: a normal solution N (74.55 g/L), diluted solutions N/10 and N/100. The resistances R of these three solutions were measured in the cell at room temperature (Table 2).

The conductivity σ_w of each sample was measured with a conductivity-meter (Knick Konduktometer 703) at the same temperature.

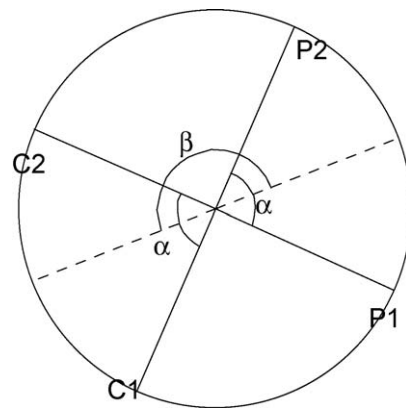


Fig. 2. Scheme of the dipole array for Weidelt method. C1 and C2 represent the current electrodes, and P1 and P2 the potential electrodes. α is the angle between the dipoles, and β the angle between the centers of each dipole.

Table 2
Experimental values for the geometric coefficient K

KCl solution	Resistance, R (Ω)	Conductivity, σ ($\mu\text{S}/\text{cm}$)	K (m)
N	0.366	107.4	0.254
N/10	3.09	12.7	0.255
N/100	27.87	1.375	0.261

From expression (6), the geometric coefficient can be calculated as:

$$K = \frac{1}{R \cdot \sigma_w} \quad (9)$$

The arithmetic mean of the experimental geometric coefficient (Table 2) ($K=0.257$ m) lies within 0.28% of the theoretical value.

3. Results and discussion

The results of experiment I are presented in Fig. 3, where the fitted straight lines have a linear form:

$$\sigma_e = a \cdot T + b \quad (10)$$

The corresponding coefficients a and b are given in Table 3. The coefficient of determination r^2 is also presented. This is

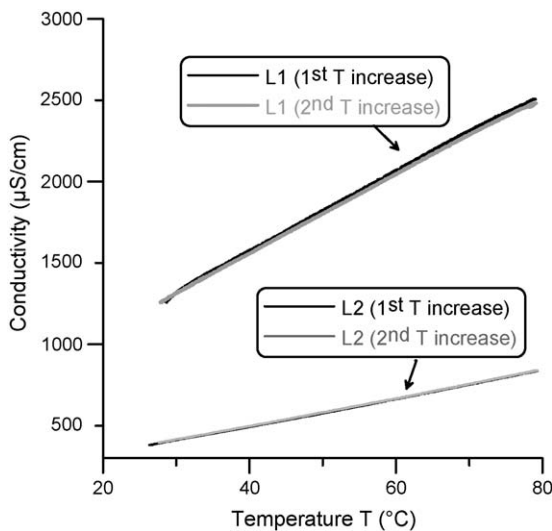


Fig. 3. Conductivity vs. temperature T for L1 and L2. Two experiments have been carried out for each leachate (L1 and L2), that means two temperature increases. Conductivities are given in $\mu\text{S}/\text{cm}$ and temperature in degree Celsius.

Table 3
Linear fit coefficients for σ_e expressed as a function of T , for L1 and L2

	a	b	r^2	$a/(aT_s + b)$
L1	24.3	604.6	0.9997	2.00
	24.0	600.8	0.9996	2.00
L2	8.7	145.8	0.9995	2.39
	8.7	150.8	0.9996	2.36

calculated from:

$$r^2 = 1 - \frac{\sum (\sigma_e - \sigma_m)^2}{\sum (\sigma_m - \bar{\sigma}_m)^2} \quad (11)$$

where σ_e is the estimated electrical conductivity (S/m), σ_m the measured electrical conductivity (S/m), and $\bar{\sigma}_m$ is the arithmetical mean of the measured electrical conductivities (S/m).

It can be seen that very similar values are found, in the case of both leachates, for the coefficients a and b . The experiment is reproducible and reversible. In other words, the electrical properties of the leachates are not influenced by heating/cooling cycles. The difference in conductivity between the two leachates at a given temperature is consistent with the differences in ionic concentration. L1 has a higher ionic concentration than L2, and a correspondingly higher electrical conductivity.

The increase of conductivity ($\Delta\sigma$) with respect to a standard reference temperature T_s is given by

$$\Delta\sigma = \frac{g(T_s + T) - g(T_s)}{g(T_s) \cdot (T - T_s)} = \frac{a}{a \cdot T_s + b} \quad (12)$$

Electrical conductivities are usually corrected with respect to a standard temperature of 25 °C [10]. Using Eq. (12), the expected increases in σ are, respectively, 2.0% °C⁻¹ and 2.4% °C⁻¹, for L1 and for L2 (Table 3). Such increases are similar to the classical 2% increase per degree Celsius given by log Tables or Schlumberger Tables [11].

The disparity in electrical conductivity between the two leachates is a consequence of differences in their composition. The equivalent NaCl and suspended solids (SS) concentrations in L1 are, respectively, 2.6× and 1.3× higher than in L2. As L1 exhibits a slower response to temperature increase than L2, it is likely that the quantity of charge carriers adsorbed onto the SS surface is much higher in L1 than in L2. Indeed, an increase in temperature may have less influence on the movement of charged suspended solid particles than on the movement of ions in the same solution.

The results of experiment II are presented in Fig. 4.

The fitted curves have a linear form (10) whose coefficients are presented in Table 4.

From expression (12) the expected increase in electrical conductivity is 2.4% °C⁻¹, for both saturated solid matrixes. It appears that this relationship is the same as that calculated for L2 alone. In conclusion, these solid matrixes do not have any significant influence on the electrical conductivity. This shows that normalisation of electrical conductivity as a function of temperature is a valid approach for any type of saturated, inert solid matrix.

The porosities of the two matrixes are, respectively, 39.9% and 40.4%, for fine sand (160 μm grains) and glass balls (1 mm in diameter). Despite negligible differences in porosity, a clear

Table 4
Coefficients of adjusted curves for fine sand and glass balls saturated with L2

	a	b	r^2	$a/(aT_s + b)$
Fine sand	2.22	35.29	0.9989	2.44
Glass balls	2.55	42.00	0.9953	2.41

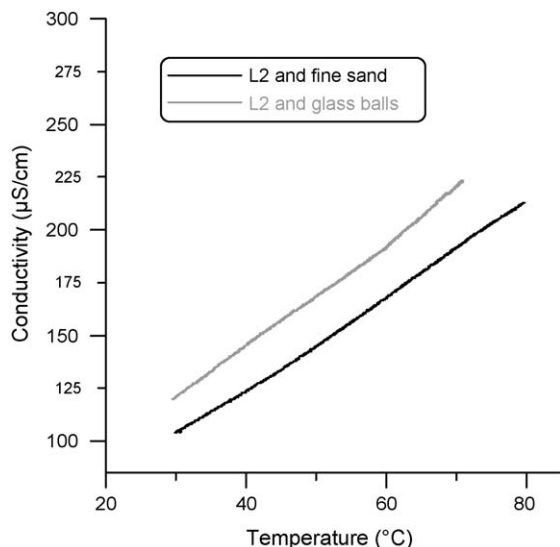


Fig. 4. Conductivity of two two-phase media (L2 and sand; L2 and glass balls) as a function of temperature. One experiment has been carried out for each sample. Conductivities are given in $\mu\text{S}/\text{cm}$ and temperature in degree Celsius.

difference is found between the effective bulk conductivities of the two saturated matrixes. For example, at 40°C the electrical conductivities are $124 \mu\text{S}/\text{cm}$ and $144 \mu\text{S}/\text{cm}$, respectively, for fine sand and glass balls. With the grains approximated to spheres of equal density (2.65) and solid matrix masses of, respectively, 398 g and 411 g for the fine sand and glass balls, their corresponding equivalent surface areas can be calculated as approximately 5.6 m^2 and 0.93 m^2 . It thus appears that the highest measured conductivity corresponds to the solid matrix with the smallest surface area. The differences in observed conductivities can thus be explained by interactions between the charge carriers and the surface area of the solid matrix.

Moreover, from Eq. (4) it follows that:

$$m = \frac{\log(\sigma_b) - \log(\sigma_w) + \log(a)}{\log(\Phi)} \quad (13)$$

For fine sand at $T = 40^\circ\text{C}$, $\sigma_b = 124 \mu\text{S}/\text{cm}$, $\sigma_w = 496 \mu\text{S}/\text{cm}$, and $\Phi = 39.9\%$. The value of “ a ” being estimated at 0.8 (medium with an intergranular porosity), expression (13) leads to a value of $m = 1.75$. This is consistent with values found in the literature [12–14]. At $T = 40^\circ\text{C}$ for the glass balls, $\sigma_b = 144 \mu\text{S}/\text{cm}$, $\sigma_w = 496 \mu\text{S}/\text{cm}$, and $\Phi = 40.4\%$, leading to value of $m = 1.61$ from expression (13). The parameter “ m ”, known as the “cementation factor”, appears to be significantly higher for fine sand than for glass balls. For the matrixes concerned by the present study, differences in the cementation factor may correspond to the fixation of suspended matter and/or ions onto solid surfaces. In other words, some electrical charge carriers are trapped by the solid surfaces. The measured difference in effective bulk conductivity is thus consistent with the difference in solid surface area between the two samples.

Furthermore, the diameter of the pores between the fine sand grains is much smaller than that between the glass balls, such that the movement of charged suspended matter in the presence of an electric field is more limited in a sample containing fine

sand than in a sample filled with glass balls. The latter results clarify the influence suspended matter may have in the electrical properties of leachates.

4. Conclusions and outlook

Both experiments show a classical conductivity increase of about $2\% \text{ }^\circ\text{C}^{-1}$. The influence of suspended matter on electrical conductivity is also pointed out. The higher the suspended matter concentration, the lower the dependence of electrical conductivity on temperature. Furthermore, for porous media saturated with the same leachate, the higher the specific surface of the granular matrix, the lower the effective bulk electrical conductivity. This shows that a full understanding of the electrical properties of liquids must take into consideration the interaction of electrical charge carriers with the surface properties of the solid phase.

As Archie’s law and the Schlumberger Tables were empirically established for media with low-charged liquids, it was not obvious that leachate-saturated media could also be described by these relationships.

The experiments described here are not exhaustive, as only two leachate samples have been studied. The results are nevertheless very promising because they correspond to general laws.

Although the influence of temperature on leachate conductivity has now been determined for the studied media, in order to use ERT on MSW to measure its water content, the influence of other parameters (water content, particle size distribution, permeability, pressure, etc.) on electrical properties also needs to be studied.

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