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Experimental Investigation of the Migration of Organic Pollution in the Underlying Soils of Household Waste Dumpsites: A Case Study in Abomey Calavi, Benin

Sofiath Onifade
Laboratoire des Sciences et Techniques de l'Eau (LSTE)
Université d'Abomey-Calavi (UAC), Benin

Metogbe Belfrid Djihouessi
Laboratoire des Sciences et Techniques de l'Eau (LSTE)
Université d'Abomey-Calavi (UAC), Benin

Martin Pépin Aina
Corresponding Author, Laboratoire des Sciences et Techniques de l'Eau (LSTE)
Université d'Abomey-Calavi (UAC), Benin
E-mail: marnickson@yahoo.fr
Tél: 00229 96613936

François de Paule Codo
Laboratoire des Sciences et Techniques de l'Eau (LSTE)
Université d'Abomey-Calavi (UAC), Benin

Hervé E. Labité
Laboratoire des Sciences et Techniques de l'Eau (LSTE)
Université d'Abomey-Calavi (UAC), Benin

Abstract

The aim of this study was to develop a database for numerical simulations of the migration of the biodegradable organic pollution in soils. An experimental investigation of leachate migration in soils was implemented and experimental device designed for the study took into account the conditions prevailing in household waste dumpsites and those likely to influence the nature of the soil. The permeability of the soil used in the device was 2.36 10-6 m/s and the injected leachate had a high composition in biodegradable organic constituents (as its COD and BOD5 were 13128.19 mg O2/l, and 5822 mg O2/l, with biodegradability rate of 6.17 10-7 s-1, respectively). Leachate infiltration tests revealed that the pollutants retention by soils was a time function that decreased continuously and irreversibly once the maximum retention capacity of the soil was reached. The study showed also that the thickness of the soil layer had no influence on the hydrodynamic behaviour of the pollutants. The analysis of the concentrations in the infiltrated leachates showed that the reduction of organic pollution by the studied soil was not enough to ensure the protection of groundwater.

Keywords: Biodegradable pollutant, soil, soil column test, dispersion.

1. Introduction

In most developing countries, uncontrolled dumps are the most selected removal methods of solid waste by policy makers as an alternative to landfill which is considered too expensive (Aina et *al*. 2012; Mangizvo 2010; Gbinlo 2010). This method is characterized by the absence of engineering controls (such as soil studies before siting, amenities for the management of gas emissions and drainage facilities for the protection of soil) (Bisimwa et *al*. 2012; Zerbock 2003). Also, the non coverage of wastes can allow rainwater to seep through these dumps, thereby producing large quantities of leachate, which can migrate through the soil towards the groundwater reserves due to the absence of drainage facilities (Tahiri et *al*. 2014; Mangizvo 2010).

The thickness of the soil layer between its surface and the roof of the water table is generally regarded as a natural barrier for containment of the emitted leachate pollution. It is recommended that this thickness has to be greater than 5 m when the permeability coefficient (k) of the soil is higher than $10^{-6}\mathrm{m/s}$ and at least 1 m, where k is less than $10^{-9}\mathrm{m\,/\,s}$ (JO: Waste Containment Design, 1997). However, these recommendations are based only on the water infiltration rate carrying pollutants in saturated or non-saturated soils. They do not take into account the different reactions or phenomena that may occur in the containment area, such as the sorption of ions, pollutants migration delay, cation exchange, or even the biodegradation or complexation of organic matter with heavy metals (Aina et *al*. 2008).

This paper presented an experimental study of the migration of leachate from municipal waste dumpsites in a soil column in order to develop a database, which can be used in the management of waste dumpsite, for numerical simulations of the effect of the biodegradability on the migration of leachates in soil.

2. Materials and Methods

Injections of leachate were performed on columns of soil of different heights. The electrical conductivity, COD, BOD_5 and TNK at the inlet and the outlet of the columns were measured and used to analyse the purification capacity of the soil.

2.1 Study Site

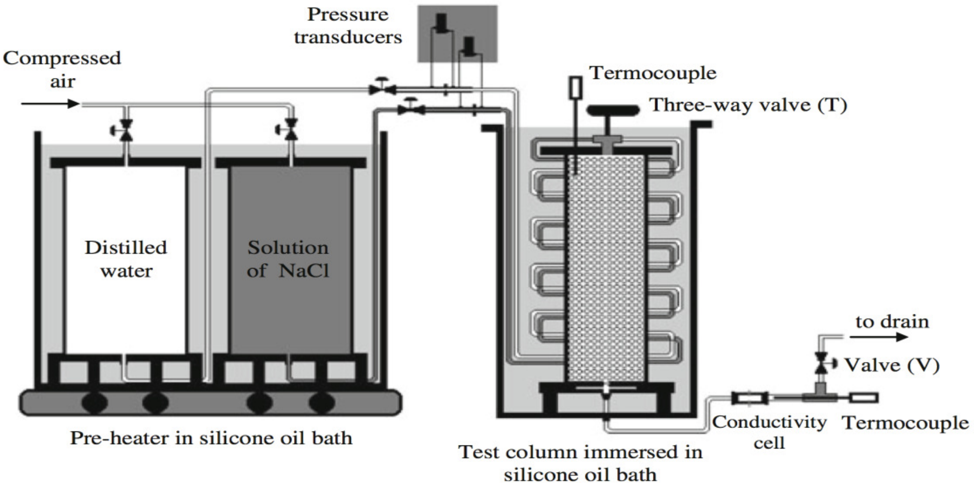
The study was conducted on soil and leachate from the experimental locker landfill of the "Centre Technologique et Pratique pour l'Eau Potable et l'Assainissement" (CTPEA) of the University of Abomey Calavi (UAC/Benin). The locker landfill is located in a tropical climate subequatorial savanna, characterized by an average annual rainfall of 1200 mm distributed over seven months of rain based on the climatic classification of Köppen-Geiger (Peel *et al*. 2007).

2.2 Description of the Experimental Device

The experimental device for this study, shown schematically in **Figure 1**, was based on the experimental protocol of Coutelieris and Delgado (2012) for measuring axial dispersion. Typically, dispersion of pollution along the direction of flow in the porous medium is studied by following the distortion of some concentration wave, as it progresses along the porous medium. For each test, an initially characterized leachate was injected to the upper top of a soil column. Concentrations of the pollutants and electrical conductivity of the percolate were measured and recorded at the outlet of the columns.

At the beginning of each test, the three-way valve (T) was manipulated to inject distilled water through the soil bed until saturation, and no salt was no longer detected by the measurement of electrical conductivity at the outlet (V). Obtaining a constant flow at (V) guarantees a permanent flow in the soil column and provides a verification test for the reproducibility of the experiment. After that, the valve (T) was again manipulated and then, the leachate was injected through the test column at a constant rate. During the tests, the infiltrated volume, the electrical conductivity and the concentrations of BOD_5 and TNK were measured.

Figure 1: Experimental device (elements shown are not to scale)



Source: Coutelieris and Delgado (2012)

2.3 Column Preparation

The identification of the area for sampling the soil columns was done according to ISO 15175: 2004. Therefore, the dumpsite of CTPEA was selected and located at the entrance of Abomey Calavi town.The sampled sol was then characterized by the following tests: particle size analysis (ISO 11277: 2009), apparent density (ISO 11272: 1998), porosity (ASTM D4404-10) and hydraulic conductivity (ISO 17312: 2005).

Monolithic columns were used in these experiments (Lewis and Sjöstrom, 2010). They were obtained on site, by driving into the ground a PVC tube PN di 75 mm (Begin et *al.*, 2003). Two different lengths (*L*) of columns (i.e., columns A and B with a length values of 300 and 600 mm) were collected. The diameter *D* was taken such as the radial dispersion ratio D/L was small enough and neglected with respect to the axial dispersion (Bruinzeel et *al.*, 1962). In this study, 10 carrots of each column type (i.e., A_1 to A_{10} and B_1 to B_{10}) were collected. Above ground level in columns, a rematch of 3 cm was given for a regular arrangement of two layers of glass beads in order to homogenize the flow of injected. Tests injections were repeated twice on each column.

2.4 Characterization of Leachate

The amount of the injected leachate during the study was determined based on the monthly water balance around the experimental locker landfill of CTPEA in accordance with Aina et *al*. (2012). Thus, considering the inlet surface of the soil columns, one month leachate production during the rainy season corresponds to an injection of 450 ml of leachate on 90000 s. As the study is focused on soluble pollutants, leachate collected was filtered through a mesh of 1.2 µm. The characterization of the leachate was made according to ISO / TS 13530: 2009; including pH (ISO 10523: 2008), electrical conductivity (ISO 7888: 1985), the Chemical Oxygen Demand (ASTM D1252 - 06) and total Kjeldahl nitrogen (ASTM D3590-11). The biodegradation rate was determined by simulation tests as presented in OECD (1995) and Nyholm et *al* (1996).

2.5 Delay Coefficient R

Delay coefficient (R) represents the delay accused by a pollutant molecule with respect to the water molecule introduced at the same time at the inlet of a soil column. It is defined by the ratio between the residence time of the pollutant (t_s) and the residence time of the water molecule (Fevrier and Moszxowicz 2001). In the case of a permanent and uniform flow, R is determined by:

$$R = \frac{t_s}{L\theta} \cdot v_z; \quad (2.1)$$

Where:
L is the length of the column;
θ is water content in the column
v_z is the Darcy velocity in column input (Leij and Dane 1992; Das and Kluitenberg, 1996).

2.6 Data Analysis

Experimentation focused on monitoring pollution parameters at the soil columns outlet. Thus, by knowing the initial pollution parameters, variation of attenuation capacity of the soil was computed.

24 and 27 tests were performed on column A and B. pH and EC values were collected at each time period of 4000 s while at each 7000 s, BOD_5 and TNK values were recorded. The database thus formed was analysed (descriptive statistics) and used to plot the breakthrough curves of monitored pollutants.

3. Results and Discussion

3.1 Characterization Tests

3.1.1 Soil Characteristics

The studied soil is a loamy soil. The values of its porosity and permeability were shown in **Table 1**. These values combined with the hydraulic gradient were used to calculate Darcy velocity and interstitial velocity.

The results showed that the soil had low permeability. However, this permeability value was above the required standard for non-controlled landfills in Benin (1.0•E-09). Therefore, a pre-treatment of the dumpsite topsoil is deemed necessary to reduce its permeability and protect the underlying water table.

Table 1: Hydraulic characteristics of soil

Porosity	Permeability. k (*m/s*)	HydraulicGrad. i	Darcy Velocity (*m/s*)	Interstitial Velocity (*m/s*)
27.5%	2.36E-06	8.8	2.08E-06	7.55E-06

3.1.2 Leachate Characteristics

The descriptive statistics of the characterization of the leachate filtered to 1.2 µmwere given in **Table 2**. The results revealed a high organic load relatively biodegradable at a low pH (3.84 <pH <4.09) and therefore proved the young age of the leachage under studied (less than 5 years).The BOD_5/COD ratio value of 0.44 confirmed the young age of the leachage and its provenance from municipal household waste. The pH value reflected the presence of carboxylic acids and bicarbonate ions. The high COD is due to the result of anaerobic degradation processes inside the wastes and reflects the non stabilization of the organic constituents. This leachate is subject to a sharp deterioration. The low value of TNK indicated a low presence of nitrogenous organic matter.

The half-life time determined by the study of the kinetics biodégradion on dissolved organic carbon of the leachate was 13 days. So the constant of degradation of organic carbon of the leachate was 6.17 E-7 s^{-1}.

Table 2: Physical and Chemical Characteristics of the leachate

Parameters	**Unit**	**Max**	**Min**	**Mean**	**SD**	**Precision**
pH		4.09	3.84	3.93	0.14	± 0.01
Elec. Cond.	($\mu S/cm$)	3812	3361	3554	232	±1
COD	($mg\ O^2/l$)	14086	12017	13218	1074	± 20
BOD_5	($mg\ O^2/l$)	6301	5326	5822	488	± 20
TNK	(mg/l)	21	16	18	3	

3.2 Experimental Investigation of Migration on Soil Column

After verification tests of the 20 columns of soil A and B, 17 exhibited stabilization to the flow. At the inlet of each column, a volume of 450 ml of leachate was injected. The results presented in this section were the average values for each column type for all tests performed.

3.2.1 pH Evolution

Before the injection of the leachate at $t = 0$ s, soil columns were saturated with distilled water. Thus, the pH reading to the output (V) indicated a value of 7.00. As shown in **Figure 2**, the pH began to decrease from the injection of the leachate to reach its minimum value of 6.41 after 9628 s; then the pH value raised up to 7.01 after 89502 s. It should be noted the presence of a bearing around the value of pH = 6.74 between 33000 s and 51000 s.

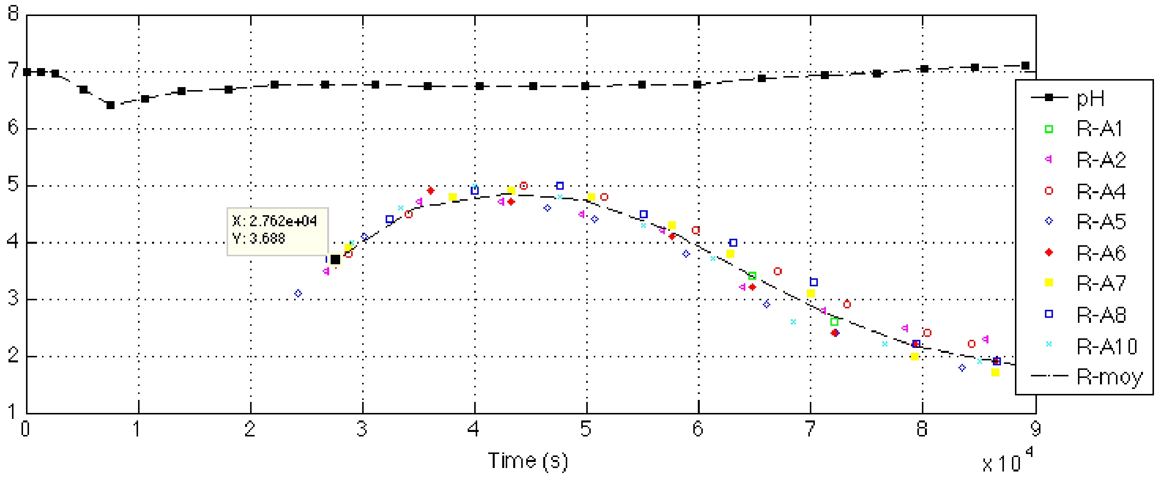
The pH values at the outlet of the columns showed a significant increase in the pH compared to the initial leachate. Indeed, initial leachate being acid with pH = 3.93, and the percolate being neutral with pH = 7.01. These results lead to suspect a strong activity of cationic exchange between the solid matrix of the soil and the pollutants during the migration processes.

3.2.2 Delay Coefficient

The residence time of pollutants in the soil column was determined with the method of moments, applied to the elution curve of the electrical conductivity.

The delay of pollutants molecules, relative to water molecules, during the migration of leachate in the soil columns, was illustrated in **Figure 2**. The first pollutant molecules have spent on average 27000 s to cross columns A, with an average delay of 3.68. A continuous injection of pollutant molecules showed a variation of the coefficient of delay as a function of injection time. The variation of $\boldsymbol{R}$ is expressed by a 3rd degree polynomial function, $y = 6E\text{-}14\ x^3 - 1E\text{-}08\ x^2 + 7E\text{-}04\ x - 8.12$; defined for time greater than $L\theta/v_z$ and schematically by the R-moycurve (**Figure 2**).

Figure 2: pH and the delay coefficient R curves as a function of the injection time for the columns 30 cm



The delay coefficients were greater than 1 and this indicated the presence of physical and/or chemical reactions between pollutants and the solid matrix during the migration. According to Sposito (1989), matter accumulation at solid liquid interface during mass transport in porous media involves the sorption mechanisms. Sorption includes adsorption and ion exchange, which involves the transfer and resulting equilibrium distribution of one or more solutes between a fluid phase and a solid surface (Coutelieris and Delgado 2012).

Initially, an increased of *R* value from 3.68 to 4.71 between 27000 s and 34000 s has been observed. This may be explained by the fact that the water molecules migrate faster than the pollutants molecules. This suggests a retention or accumulation of the pollutants in the soil. Secondly, there was a bearing around the R value (of 4.83) between 34000 s and 52000 s, reflecting stabilization in the speed of migration of pollutants molecules in relation to water molecules. A balance in trade between the soil matrix and leachate flowing there through can explain this. Note the bearing in *R* evolution was also observed for pH evolution at the same time. Finally, a progressive decrease of the phase *R* was observed beyond 52 000 s and this indicated a fast migration of pollutants compared to the water molecules. If *R* descended below 1, after some time,a release of pollutants accumulated in the soil could be observed.

It is apparent that there was a relationship between the pH and the delay coefficient variation. The bridge between these two parameters may be explained by the cationic exchange capacity. Mathematically, a salting out of pollutants accumulated in the confinement layer of waste dumpsites would be inevitable beyond a certain time.

3.2.3. Evolution of the Electrical Conductivity (EC)

The breakthrough curves of EC for columns A and B, for a same Darcy velocity ($q = 0.125\ \mathrm{cm/min}$) was illustrated in **Figure 3a**. The general pattern of these two breakthrough curves was the same and characterized by a quick exit from pollution. Indeed, the measured residence time (i.e., 2.42) of the pollutants was less than the one calculated (i.e., 3.688). **Figure 3a** also showed a shift to the right of columns B breakthrough curves. The shift between the two curves may be explained by the difference in length of the columns. The time taken for the percolation to cross columns A was significantly higher than half of the time taken to cross columns B. Direct comparison of the two breakthrough curves was expressed in non-dimensional data in **Fig 3b**. This figure showed that the evolution of EC had the same hydrodynamic behaviour for the two lengths of tested columns.

Figure 3a: EC breakthrough curves on the columns A (30 cm) and B (60 cm). q=0.125cm/min

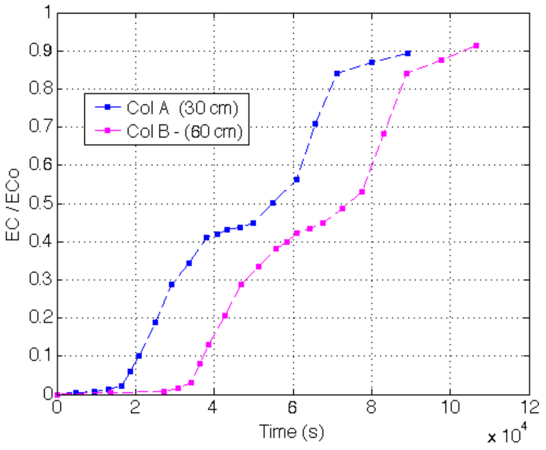
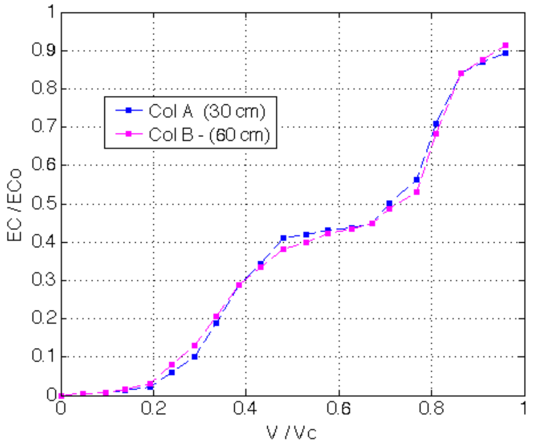


Figure 3b: Comparison of EC breakthrough curves for columns A and B. q=0.125 cm/min



Comparing the experimental results with those available in the literature (Fallico et *al* 2012; Alimi-Ichola and Gaidi 2006), it appeared that these experimental curves presented a bearing in the evolution of the EC to about 40% the initial EC before resuming the normal pace. This change in slope is not usual in the experiments of dispersion. This may be due by presence of macropores in the soil columns.

3.2.4 Biodegradable Organic Matter in the Soil Columns

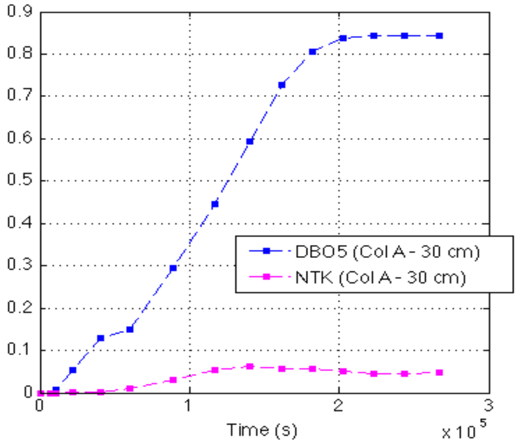
For this phase, 1800 ml of leachate were injected for each test, equivalent to the volume of leachate generated during the long rainy season from April to July in Benin.

Figure 4 showed the breakthrough curves of the BOD_5 and TNK. The monitoring of concentrations at the outlet of columns A, revealed a final abatement of 15.7% of the BOD_5 and 99.65% of TNK. These results support to some extent the attenuation function usually attributed to the underlying soils of waste dumpsites. However, the abatement was not satisfactory and the purifying capacity of the soil decreased gradually in time.

The analysis of the curve of BOD_5 revealed a bearing at the beginning of percolation. Similar phenomena were also observed by Larsson and Jarvis (1999) for the study of solute transport in a macroporous soil and by Dalla Costa (2007) her study on samples of soil blocks cracked. The regularity of the progression-soluble BOD_5 concentration after the concavity reflected the predictable phenomenon of convection-dispersion as studied by several authors (Fevrier and Moszxowicz 2001; Dalla Costa 2007).

The breakthrough curve of TNK obtained on columns A (30 cm) had a different shape of breakthrough curves of CE and BOD5. It should be mentioned that, the obtained concentration values of TNK at the column outlet were very low (between 0.002 and 1.027 mg/l) and thereby the effect of the macrospores previously observed was not visible. Beyond 150000 s a fluctuation of the concentration of TNK contrary to the stabilization observed in the soluble BOD5 was noticed

Figure 4: breakthrough curves of the BOD_5 and TNK. q=0.125 cm/min



4. Conclusion

The thickness of the soil layer for the containment of pollution from waste dumpsites in developing countries is generally determined by its permeability. Designers do not take the influence of phenomena that may occur in soils and strongly affect pollutants migration into account. This study showed that the calculated delay coefficients for pollutants were higher than those measured experimentally and this revealed the inaccuracy of the organic pollutants prediction. The migration of pollutant molecules in comparison to water molecules may be due to the pH variability of the percolated leachate in soil column. The profiles of monitoring the electrical conductivity showed that the depth of migration did not affect the hydrodynamic behaviour of organic pollution. The analysis of breakthrough curves of BOD_5 and TNK revealed that the soil attenuation capacity for organic biodegradable pollution decreased considerably with time. Although the soils manage to trap a part of the organic pollution, the recorded abatements show that these soils did not ensure the protection of water table and groundwater against pollution.

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