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Evaluating Biomass Temperature vs Biodegradation for Environmental Impact Minimization: Mid Auchencarroch Experimental Landfill

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Abstract : This paper evaluates the effects of landfill management techniques on landfill temperature regime and biomass biodegradation processes. The biodegradation of Mid Auchencarroch experimental project is studied in four cells with different waste composition and landfill conditions. A numerical model is presented evaluating the parameters which control biomass temperature and accelerate the waste biodegradation, protecting public health from associated hazards. The variations of temperature versus landfill emissions at Mid Auchencarroch site are discussed and analyzed which provide useful conclusions in order to minimize associated environmental impacts.

Key words : Biomass temperature; landfill biotechnology; landfill design; landfill emissions; waste biodegradation; solid waste management; sustainable development; public health.

Introduction :

Controlled sanitary landfill method has been selected by landfill operators as an attractive disposal route for household, commercial and industrial remnant waste, as it is an economic solution with minimal environmental impacts. The landfill biodegradation processes are complex, including many factors that control the progression of the waste mass to final stage (Fleming, 1990; Kollias, 2004; Koliopoulos, 1999; Skordilis, 2001; Tchobanoglous *et al*., 1993). The main aim of this paper is to evaluate the effects of different disposed waste compositions and variable waste management conditions in order to enhance and accelerate landfill stabilization, minimizing any associated environmental impacts. Particular evaluation projections of waste biodegradation and biomass temperature are made based on Mid Auchencarroch's experimental landfill data and an associated numerical modelling. The Mid Auchencarroch experimental landfill is a UK Environment Agency (EA) and industry funded research facility (Koliopoulos *et al*., 2006; Koliopoulos, 2000; Wingfield-Hayes, 1997).

Controlled landfill projects should be used for efficient landfill stabilization in short time, during biomass biodegradation. The landfill emissions are an inevitable result of the solid waste biodegradation in landfills and their study is necessary for future efficient designs, controlling them and minimising associated environmental impacts (DOE, 1995; Fleming 1996;

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Koliopoulos *et al*., 2006; El-Fadel *et al*., 2000). Efficient controlled batch anaerobic bioreactors could be used so as to accelerate waste biodegradation in short periods, minimizing any associated environmental risks due to landfill emissions (Derby Evening Telegraph, 1986; DOE, 1989; Elliott *et al*., 2001; Friis *et al*., 2004; Koliopoulos, 2000). Uncontrolled dumps have to close so as to avoid any threats to the public health and to minimize probable environmental impacts.

Many researchers have pointed out that temperature is an important factor of chemical, physical and biological phenomena in a sanitary landfill (Bockreis *et al*., 2005; Yoshida *et al*., 1997, 1999; El-Fadel, 1991; Tabasaran, 1982). Methane production in landfills can be optimized by temperature control. The optimum temperature for methane production has been reported as 41 and 42^{o}C in anaerobic digestion of landfill bioreactor (El-Fadel, 1991; Pfeffer, 1974; Koliopoulos, 2000). Yoshida indicated that the maximum temperature in a landfill can reach to about 65^{o} C with aerobic-anaerobic conditions and around 35-36^{o}C for anaerobic conditions (Yoshida *et al*., 1997, 1999). Few theoretical studies have however been carried out on temperatures in landfills.

Materials and Methods :

This paper analyses the modelling of landfill temperature control based on field data of Mid Auchencarroch (MACH) experimental landfill project, which is located next to Alexandria area, between the Loch Lomond and Kilpatrick hills outside from Glasgow city, in Scotland. It has been constructed in order to assess a number of techniques that promote sustainable landfill design. MACH experimental landfill, is an Environment Agency, DTI and industry funded research facility. MACH experimental batch anaerobic landfill bioreactor has been capped since November 1995. The experimental variables are waste pretreatment, wet biomass pulverization, leachate recirculation and co-disposal with inert material.

The experimental landfill Mid Auchencarroch is a field scale facility which is consisted of four cells each of nominal volume 4,200 m^3. In cells 1 and 3 there is pretreatment by wet pulverization and in cells 2 and 4 the disposed waste is untreated. In cells 1,2 and 3 there is recirculation of leachate and in cell 1 there is addition of inert material 20% by volume. Below the waste composition is presented for the untreated and treated waste input materials at MACH's cells, respectively: Paper-Card: 27% and 34%; Plastic film 6% and 7%; Dense plastic 5% and 8%; Textiles 3% and 3%; Misc.combust. 3% and 3%; Misc. non-combust.0.5% and 2%; Glass 5.5% and 7%; Putrescibles 38% and 24%; Ferrous metal 6.5% and 8%; Non-ferrous metal 1.5% and 2%; Fines 4% and 2% (Koliopoulos, 2000; Wingfield-Hayes, 1997).

In order to measure waste mass temperature at MACH, a driven temperature probe was developed with a removable string of thermocouples to allow maintenance or replacement. There are two probes in each cell; one at the centre and one at the periphery. On each thermocouple string there are three

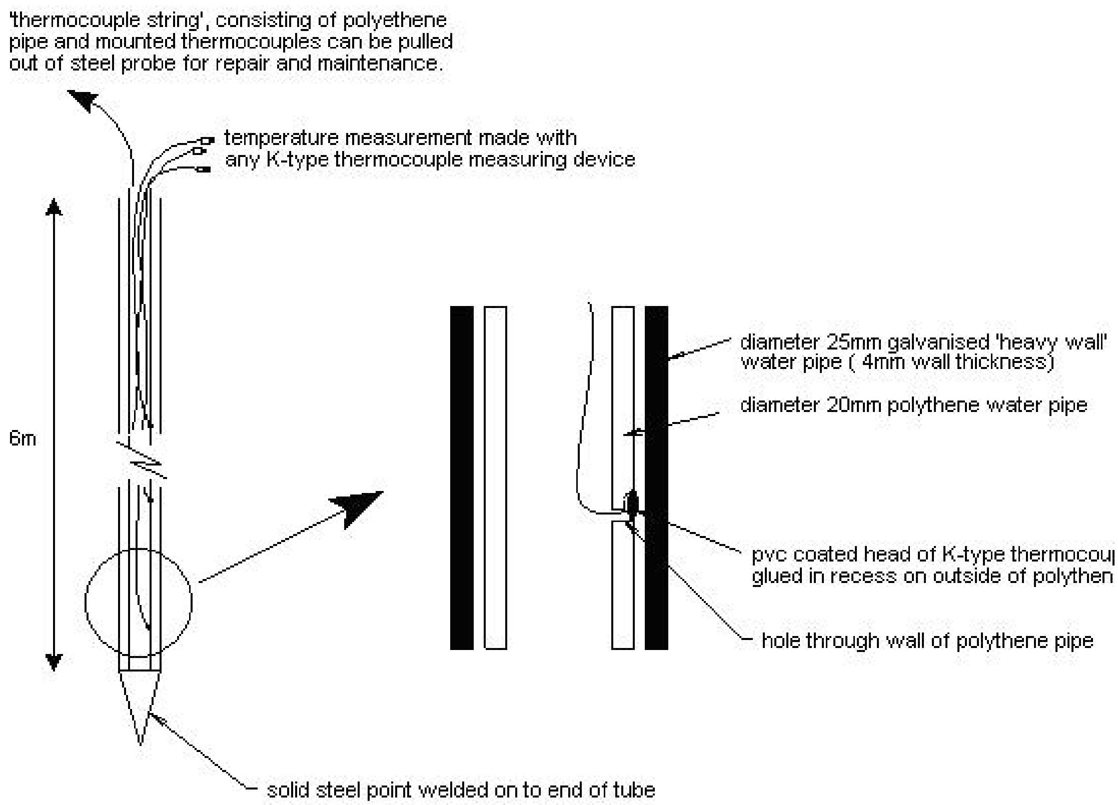

Fig. 1 : Details of driven temperature probe at Mid Auchencarroch site

thermocouples, near the top, middle and bottom of the waste mass. The development of the temperature probe is presented in Figure 1 (Koliopoulos, 2000; Wingfield-Hayes, 1997).

The total MACH waste mass depth is 5 meters, without the top soiled surface cap depth. The maximum temperature at MACH was found at a vertical location of 2.4 m from the surface of the waste mass, based on measurements of the middle thermocouple location which is close to the mid-depth of the site (Koliopoulos, 2000; Wingfield-Hayes, 1997). The temperature attained by a landfill is determined by the balance between the rates of heat production and the rate of heat loss to the surrounding area. Landfill gas generation and heat generation are following the same trends in time (Tabasaran, 1982; Yoshida *et al.*, 1997, 1999).

MACH experimental project examines techniques so as to enhance the waste degradation, pollutant removal processes and control of landfill emissions. The wet-flushing sequential batch bioreactor landfill model is seen as the method of achieving the goal of sustainable development. The temperature experimental field data which are examined for the present paper, cover simultaneously the 24-month period of landfill stabilization since site was capped (Koliopoulos, 2000).

Results :

Potential landfill biodegradation : Evaluating and analyzing the MACH landfill emissions it is clear that methanogenesis was achieved in short time period, as landfill gas peak production and peak temperature reached in the first 105 days of biomass biodegradation since MACH site was capped. Moreover, leachate emissions and their respective pH values stabilized in the first 22-month period of biomass biodegradation since MACH site was capped (Koliopoulos, 2000; Koliopoulos *et al.*, 2006). The actual MACH landfill gas yields for the four cells were calculated by the use of Andreottola and Cossu methane landfill gas yield model (Andreottola *et al.*, 1988; CEC, 1992; Koliopoulos, 2000).

The data which were used from MACH for the calibration of heat generation equations were taken from the middle thermocouple of the centre temperature probe which was located approximately at the landfill mid-depth. The rest temperature probes data show that there was heat loss at the shallow MACH site and their temperature was equal to the ground temperature. The MACH experiment provides temperature data using probes at nominal depths of 3.35 m, 4.40 m, and 5.75 m below the top soiled surface of the cell (Koliopoulos, 2000; Wingfield-Hayes, 1997). Hence, for MACH the higher temperature in the waste mass is taken at the landfill mid-depth.

The long-term exponential experimental heat generation curves are hereby analyzed, based on the available measured MACH experimental data taking into account different waste input characteristics and landfill management techniques. No research has been found in the literature which presents long-term temperature curves for different waste management options like those at MACH landfill batch bioreactor. The following useful heat generation formulas are deduced in the light of these facts in order to evaluate biomass biodegradation parameters under different solid waste management techniques.

The heat generation source term at landfill mid-depth could be taken by the following equation :

$$\alpha = D_{LFG} \, D_{waste} \, Gt \, \Omega \qquad \textbf{(1)}$$

where

a	heat generation source term at landfill mid-depth (Kcal/m3 day)
D_{LFG}	average LFG density (kg LFG/m^3 LFG)
D_{waste}	waste density (kg/m^3)
Gt	LFG production in time (m^3 LFG/1,000 kg waste day)
Ω	heat generation parameter
$\Omega=\mu e^{-lt}$	μ heat generation (Kcal/kg LFG), l biodegradation rate (day^{-1}), t (day)

It has been reported in the literature that k biodegradation kinetic variable depends on the waste input of a landfill. Usually it varies from 0.288 to 0.099 (Christensen *et al.*, 1996; CEC, 1992; Tchobanoglus *et al.*, 1993). The landfill gas peak production at MACH site takes place in the first 105 days. After calibration based on MACH field data, k was found equal to 0.278 for all MACH cells (Koliopoulos, 2000; Koliopoulos *et al*., 2002). The reason that k parameter takes this value for MACH site is explained due to the fact that MACH is shallow and operates as batch bioreactor. Therefore, at MACH site the substrate can be degraded quickly taking into account the field data of the site.

Furthermore, based on equation (1) and MACH field data, the heat generation source terms for the three different examining waste types in MACH cells, after calibration, are the followings :

$$\alpha_{wt1} = 1.18\ D_{waste}\ Gt\ 0.41\ e^{-l\,t} \quad (2)$$
$$\alpha_{wt2} = 1.18\ D_{waste}\ Gt\ 0.68\ e^{-l\,t} \quad (3)$$
$$\alpha_{wt3} = 1.18\ D_{waste}\ Gt\ 0.89\ e^{-l\,t} \quad (4)$$

where

- a_{wt1} heat generation source term at landfill mid-depth for waste type of co-disposal of pulverised waste with inert material (Kcal/m^3 day)
- a_{wt2} heat generation source term at landfill mid-depth for waste type of pulverised waste (Kcal/m^3 day)
- a_{wt3} heat generation source term at landfill mid-depth for waste type of untreated waste (Kcal/m^3 day)
- D_{waste} waste density (kg/m^3)
- Gt LFG production in time (m^3 LFG/ 1,000 kg waste day)
- l biodegradation rate (day^{-1})
- t (day)

During the decreasing period of biogas production l depends on the k kinetic parameter of landfill gas production. The l value was calibrated for shallow landfill conditions like MACH one. Table 1 presents the waste bulk densities and other technical characteristics for the examining four cells of MACH site (Koliopoulos, 2000).

The mid-depth temperature regime and heat transfer in an anaerobic landfill batch bioreactor (1-D) could be calculated taking into account as heat source, the values of the above presented equations and applying them in equation (5). Hence, the general governing equation for the heat transfer in a homogenous landfill mass has the following form (Koliopoulos, 2000):

$$\frac{\partial U(y,t)}{\partial t} - \beta \frac{\partial}{\partial y}\left(\frac{\partial U(y,t)}{\partial y}\right) = \alpha \quad (5)$$

where

$b = k/rCu$

- *k* thermal conductivity (kcal/day m ^oC)
- *r* density (kg/m^3)
- *Cu* heat capacity (kcal/kg ^oC)
- U temperature on the particular node of the grid in vertical location (^oC)
- *t* time (day)
- *y* vertical distance in landfill depth (m)
- α heat generation source term (kcal/m^3 day)

A numerical module was developed solving the coupling of equations (2), (3), (4), (5) and the results were compared with the experimental MACH field data. The validation of the above calculated heat generation formulas for MACH cells is presented in (Figures 2, 3, 4, 5). Based on the results, it is clear that the examining numerical modelling coupling is valid and robust.

Table 1. Technical characteristics of Mid Auchencarroch cells.

Landfill site Case Study	Landfill gas Methane yield (lt gas/kg/MSW)	Specific Heat J/(kg °C)	Density Kg/m^3
MACH Cell 1	21.53	1171.8	1,190
MACH Cell 2	22.67	1329.6	740
MACH Cell 3	21.3	1264.8	1,030
MACH Cell 4	21.65	1329.6	730

According to the above presented data in Figures 2, 3, 4, 5 there is good fitting and simulation in modelling of MACH field heat emissions field experimental data with the calculated ones.

Discussion :

Evaluating the above results it is clear that the waste mixture design (*i.e.* co-disposal with inert material), the water management (*i.e.* leachate recirculation) and the thermal properties of the waste input are important factors for rapid waste biodegradation and temperature control in a landfill. Moreover, waste pretreatment showed that accelerates waste biodegradation based on landfill gas and heat emissions of MACH site. The addition of inert material in cell 1 sets biomass peak temperature in lower levels than the rest cells. Also pulverized waste enhanced waste biodegradation as temperature in cell 3 presented high levels in time. The presented MACH waste management techniques have to be taken into account for future efficient ecological designs of sequential batch anaerobic bioreactors.

The concept of an efficient anaerobic batch landfill bioreactor design of municipal solid waste is feasible in terms of establishing and maintaining a suitable environment for biomass degradation to occur at significant rates. It is possible to enhance and control landfill emissions, heat generation and flush potential pollutants from the biomass, by manipulating the whole process of landfill. Shallow landfill concept can be used as an efficient economic sustainable sequential batch bioreactor.

Environmental impact assessment (E.I.A.) should take place not only for decision making of landfill installation but also during landfill operation (Canter, 1996; Lawrence, 2003; Koliopoulos, 2000). Dynamic numerical models should be used for the analysis of spatial landfill emissions for a given topography in order to take any necessary measures in time. The results of such numerical diagnostic models could be evaluated in E.I.A's, understanding better the trends of landfill emissions in space and time and mapping out any necessary rehabilitation infrastructure works for environmental protection.

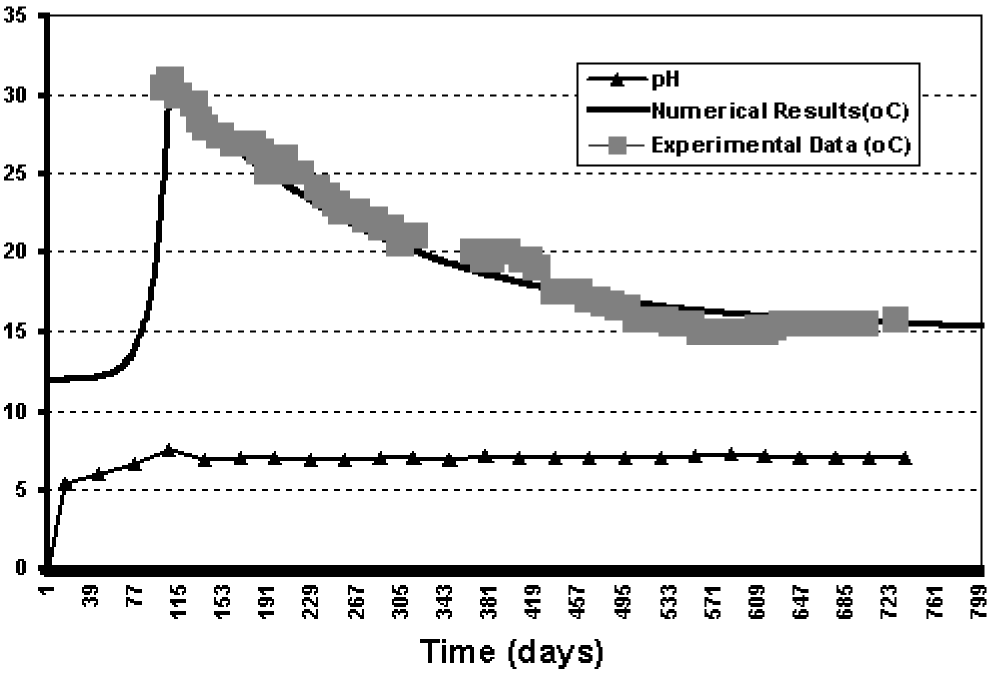

Fig. 2 : Calculated vs measured temperature emissions and pH values at MACH cell 1.

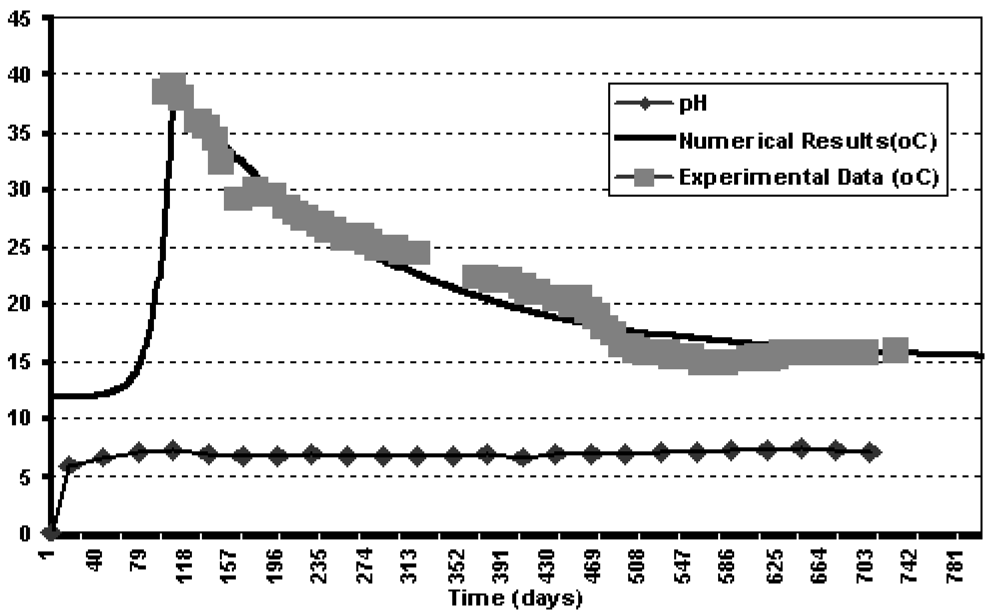

Fig. 3 : Calculated vs measured temperature emissions and pH values at MACH cell 2.

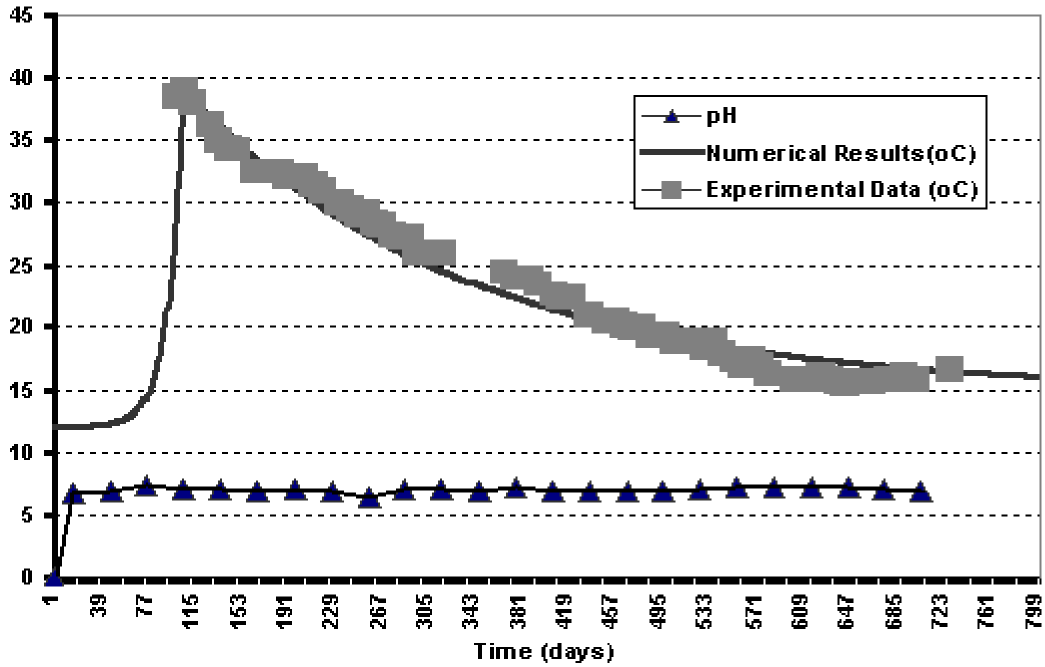

Fig. 4 : Calculated vs measured temperature emissions and pH values at MACH cell 3.

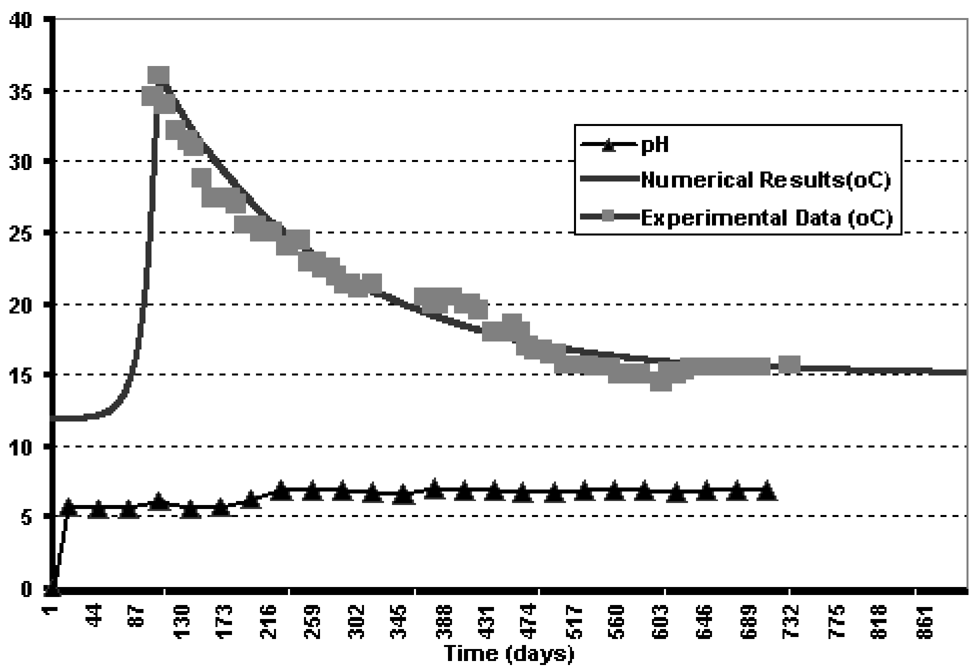

Fig. 5 : Calculated vs measured temperature emissions and pH values at MACH cell 4.

Evaluating MACH's heat generation emissions higher temperatures present cells 2, 3 than cells 4 and 1. The mid-depth landfill peak temperature of 39ºC reached in cell 2 and 3 respectively. On the other hand lower mid-depth peak temperatures reached in cells 4, 1 with a temperature of 36ºC and 31ºC respectively. The latter differences are explained on the fact that different landfill conditions and waste input materials exist at each experimental cell. Hence, different favourable substrates exist in the biomass of the examining MACH experimental cells for thermophilic, mesophilic bacteria at their ecosystem. Moreover, different magnitudes of particular physical, chemical and thermal properties exist for each cell like biomass density, specific heat, moisture content and landfill gas yield.

All the above parameters influence on the stability of waste biodegradation and the associated landfill emissions. Taking into account all the above, higher risk of landfill gas migration present cell 2 than rest of the cells. Lower risk of landfill gas migration presents cell 1 than rest of cells as it has low value of specific heat due to the co-disposal of waste with inert material keeping mid-depth landfill peak temperature at low levels. Probable environmental impacts could be the followings: accumulation of high pressure magnitudes in landfill mass; landfill gas diffusion to environmental resources; vegetation distress; impacts to flora and fauna; liners' damage; explosions and other associated hazards to any related receptors from landfill emissions.

However, pH experimental data show that pH values were around 6 in the first 3 months of waste disposal into the examining cells showing that acidogenesis stage took place during that period. Neutral levels of pH achieved in short time period in 105 days since site was capped, certifying that methanogenesis biodegradation stage took place in short time period for all the examining cells. The latter fact verifies quick site stabilization minimising any associated environmental impacts of long term landfill emissions. The use of efficient controlled anaerobic landfill design is necessary as it keeps waste mass temperature at low levels minimizing the associated risks to the environment.

Conclusions :

The investigation of heat generation and waste biodegradation processes taking into account experimental data, results in a comprehensive integrated model controlling the landfill bioreactor environment better. Landfill gas and biomass temperature field data are of great importance making useful evaluations and predictions of landfill emissions. Dynamic models are necessary not only to evaluate existing sites but also to propose efficient sustainable infrastructure designs.

Uncontrolled dumps should close minimizing any environmental impact threat related to anthropogenic activities next to landfill boundaries. The development of a landfill with controlled waste mass temperature using efficient technology not only will promote public health protection but also will control and manage better environmental impacts for the sustainable development of our society.

MACH experimental heat generation data were modelled in order to develop and assess techniques that enhance the degradation, and pollutant removal from landfills, minimizing associated environmental impacts. Landfill emissions' control has to be improved based on the present study, taking into account different landfill conditions and waste management techniques.

At Mid Auchencarroch experimental site was clear that methanogenesis was achieved in short time based on pH values and heat generation trends of biomass in time. According to pH values for the MACH cells; it is clear that quick site stabilization has been achieved in time avoiding long term landfill emissions and associated environmental impacts. Dynamic models of landfill heat generation and biomass biodegradation are useful so as to be used as diagnostic tools of landfill's behaviour in time taking into account particular parameters of landfill bioreactor operation.

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