

Experimental Assessment and Modelling of Coupled Biochemical-Physical-Mechanical Biodegradation Process of a Municipal Solid Waste Sample from Michigan

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ABSTRACT: Municipal solid waste (MSW) is biodegradable in landfills under anaerobic conditions. The evolution of the biochemical, physical and mechanical characteristics of MSW are interdependent and is investigated first through an experiment and subsequently via a constitutive model. Specifically, a well-characterized MSW specimen was reconstituted with waste constituents obtained from Sauk Trail Hills Landfill in Michigan and was biodegraded in a large-scale experimental setup that enabled simultaneous characterization of the processes with time. A 42-L column accompanied by a system to recirculate and store leachate, and a system to monitor the long-term waste degradation process was constructed. The specimen unit weight, settlement, biogas composition, volume and leachate chemistry were measured with time to assess the progress of waste degradation. The experiment was completed after 1100 days of operation, when degradation appeared to have been complete. This closely-monitored process is modelled using the modelling framework proposed by McDougall (2007), with a focus on biodegradation. A two-stage degradation model is used to describe the anaerobic process and account for hydrolysis of degradable matter in relation to moisture content, product inhibition, cellulose digestibility and microbial controls. To investigate how solid mass loss caused by biodegradation is reflected into settlement, a void change parameter is used that describes the loosening or densification during degradation. The model performed fairly well in predicting the biochemical (volatile fatty acids concentrations) and physical (solid degradable matter) behaviour; however, for the assumptions made in this study, it significantly over-predicted biogas production.

KEYWORDS: municipal solid waste, biodegradation, coupled, anaerobic process

1. INTRODUCTION

Approximately 53% of the municipal solid waste (MSW) generated in the U.S. is disposed of by burial in a sanitary landfill (US EPA, 2014). Solids, liquids and gaseous phases of MSW in a landfill evolve with time due to coupled physical-biochemical-mechanical-hydraulic processes during biodegradation. With the appropriate conditions, anaerobic microorganisms act upon the biodegradable organic fractions including food waste, yard waste and different types of paper and eventually convert them to biogas. The process begins with bacterial hydrolysis of the complex organic waste into simpler forms, leading to mass loss and void creation in the waste matrix. As a consequence, physical properties, such as porosity and unit weight, change. Hydrolysis is followed by acidogenesis and methanogenesis resulting in the dissolution of organic compounds in the leachate and the production of biogas consisting primarily of methane and carbon dioxide (Barlaz et al. 2010). As a result, the phase relationships between solid, liquid and gas phases within the MSW matrix are altered. In order to understand, predict, and possibly control waste decomposition in sanitary landfills, one must first understand the anaerobic process of degradation occurring in the waste matrix.

In this study, the degradation process has been simulated in a large scale experimental setup and a two-stage anaerobic model was implemented to model the experimental setup and calibrated with the experimental dataset. The biodegradation model described by McDougall 2007 is adopted here to describe the hydrolysis, acidogenesis and methanogenesis reactions. This formulation neglects the aerobic stage but since the aerobic waste decomposition represents a minor part of the landfill lifetime it is, therefore, less significant than anaerobic decomposition.

2. EXPERIMENTAL SETUP

2.1 Waste Characterisation

The MSW specimen used in this study was collected from Sauk Trail Hills landfill in Michigan (MI-STH) and was transported in sealed drums to the laboratory. Field composition was characterized according to the procedure described by Zekkos et al. (2010). Waste was segregated into finer and coarser fraction using a 20-mm sieve. The initial total mass, mass percentage on a wet basis, moisture content, and volatile solids (VS) in <20 mm fraction were determined and provided in Table 1.

Table 1. Composition, moisture content and volatile solids of MSW specimen.

Parameter	Value
<20 mm particles (%)	17.5
Paper (%)	42.9
Soft plastic (%)	16.1
Wood (%)	23.5
Initial total weight (kg)	13.52
Average moisture content (%)	16.0
VS in <20 mm fraction (g/g)	0.252

2.2 Degradation Testing of MSW

The specimen was reconstituted based on the field waste composition and used for degradation testing. A 42-L ($d=300$ mm, $h=500$ mm) column accompanied by a system to recirculate and store leachate, and a system to monitor the long-term waste degradation process including biogas, changes in solid weight and volume was constructed and is described in detail by Fei et al. 2014 (Figure 1). The material was generally placed at a loose state, i.e., without significant compaction. Besides the vertical load from a plastic leachate distribution plate and a stainless steel rod for settlement measurement that impose <1 kPa vertical stress, no additional vertical stress was applied to the specimen. The temperature of the column was raised from laboratory temperature to $40\pm3^\circ\text{C}$ using a heating blanket. The initial volume of the MSW was 37.7 L (initial height, $H_0 = 53$ cm), and the initial total unit weight was 3.5 kN/m^3 . On day 4, the drainage valve at the bottom of the column was closed and deionized water was added to completely submerge the specimen. The specimen remained submerged for 15 minutes before the valve was opened and the leachate drained by gravity. Leachate was recirculated three times a week and involved short-term (~15 min) submergence of the specimen followed by gravity drainage of the liquids. Thus, the specimen was maintained at field capacity in between saturations accelerating waste degradation. Leachate samples were analysed for total and soluble chemical oxygen demand (COD) respectively. The specimen unit weight at field capacity and at saturation and the settlement were also measured with time. Biogas composition and volume were also measured to assess the progress of waste degradation. The experiment was stopped after 1100 days of operation and the experimental setup disassembled.

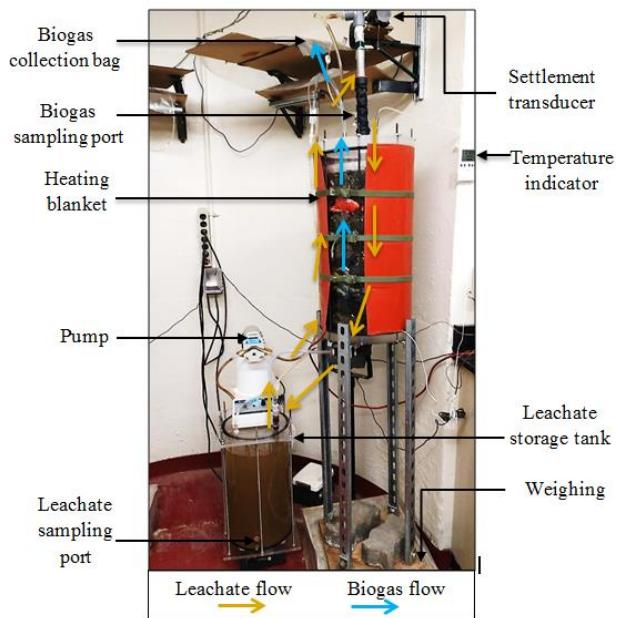


Figure 1. Schematic of the experimental setup for MSW degradation.

2. MODELLING FRAMEWORK

2.1 HBM-Biodegradation Model

The HBM biodegradation model (McDougall 2007) was incorporated in Matlab. The model describes a two-stage anaerobic digester in which volatile fatty acid (VFA) and methanogenic biomass (MB) concentrations are the main field variables. Solid degradable fraction (SDF) depletion is calculated for each time step and is controlled by the VFA and MB concentrations and moisture content.

Cellulose and hemicellulose are the major biodegradable components of MSW. However, in this model mineralisation of only cellulose has been considered which accounts for 91% of the methane potential (Barlaz et al. 1989). The process of cellulose degradation is idealised in three main steps:

- I. Enzymatic hydrolysis of solid cellulose ($\text{C}_6\text{H}_{10}\text{O}_5$) to glucose ($\text{C}_6\text{H}_{12}\text{O}_6$):

$$\text{C}_6\text{H}_{10}\text{O}_5 + \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6$$
- II. Fermentation of glucose to acetic acid (CH_3COOH) which is considered a representative VFA:

$$\text{C}_6\text{H}_{12}\text{O}_6 + 4\text{H}_2\text{O} \rightarrow \text{CH}_3\text{COOH} + 8\text{H}_2 + 4\text{CO}_2$$
- III. Methanogenesis:
 - (i) By acetate cleavage:

$$\text{CH}_3\text{COOH} \rightarrow \text{CO}_2 + \text{CH}_4$$
 - (ii) By hydrogen-scavenging bacteria:

$$8\text{H}_2 + 2\text{CO}_2 \rightarrow 2\text{CH}_4 + 4\text{H}_2\text{O}$$

The overall stoichiometry assuming the fermentation process (acidogenesis and acetogenesis) is relatively fast compared to methanogenesis and hydrogen-scavenging methanogens consumption of all gaseous intermediates (step III(ii)) is



This formulation is used to determine the growth/decay term for the internal variables characterizing the biodegradation,

- c [g.m^{-3}] the VFA concentration in aqueous medium,

- m [g.m⁻³] the methanogen biomass (MB) in aqueous medium.

The HBM model incorporates a formulation and the governing mass balance equations for these two chemical species, are presented in the following sections. These equations describe the reaction rate and are expressed in g.m⁻³aqueous.day⁻¹.

2.1.1 Hydrolysis and acidogenesis/acetogenesis

Hydrolysis and acidogenesis/acetogenesis is the first stage of the biodegradation, which represents the depletion of the organic content and its transformation into VFA. These latter intermediate products serve as a precursor for methanogenic biomass. However, high VFA concentration has inhibitory effects on those reactions, which is also taken into account in the model through an inhibitor factor.

A modified enzymatic hydrolysis function accounts for the influence of the changing digestibility of the degradable fraction, product inhibition and moisture content on hydrolysis:

$$r_g = \theta_E b \phi P \quad (1)$$

where, r_g denotes the rate of VFA accumulation [gVFA m⁻³ aqueous day⁻¹] and the four governing factors are:

- θ_E is the effective volumetric moisture content which is determined from the hydraulic model.
- b [g.m⁻³ aqueous.s⁻¹] is the maximum VFA growth rate under the most favourable environmental conditions, which normally occurs at the early stage of hydrolysis reaction.
- $\phi = 1 - [(S_0 - S)/S_0]^n$ is the relative digestibility decreasing with the solid degradable matter depletion, where S_0 [kg.m⁻³] is the initial solid degradable fraction and n is the structural transformation parameter.
- $P = \exp(-k_{VFA}(c))$ is the inhibition factor accounting for the inhibitory effect of high VFA concentration, in which k_{VFA} [g.m⁻³] is an inhibition constant.

Note that for simulating the experiment, where complete submergence is achieved followed by drainage to field capacity and the flow/hydraulics component of the model is not considered, the initial effective moisture content is treated as the average field capacity moisture content of the waste specimen after recirculation.

2.1.2 Methanogenesis

The second stage of the biochemical reactions occurring in the MSW transforms the VFA generated from first stage to methanogen biomass. The MB production rate r_j is calculated through a Monod kinetic equation and the VFA consumption rate r_h is directly linked to the methanogen biomass accumulation through a substrate yield coefficient Y .

$$r_j = \frac{k_0 c}{(k_{MC} + c)} m \quad (2)$$

$$r_h = \frac{r_j}{Y} \quad (3)$$

where k_0 [day⁻¹] is the maximum specific growth rate, k_{MC} [g.m⁻³ aqueous] is the half saturation constant. The MB decay r_k is given by

$$r_k = k_2 m \quad (4)$$

where, k_2 [day⁻¹] is the methanogen death rate.

2.1.3 Governing Equations

The combined growth and decay of VFA and MB in the biodegradation model are described by the following two equations:

$$[r_g - r_h] = \frac{\partial c}{\partial t} \quad (5)$$

$$[r_j - r_k] = \frac{\partial m}{\partial t} \quad (6)$$

Two simultaneous ordinary differential equations are solved iteratively by updating system parameters until a consistent solution is obtained which agrees well with the experimental data. The solid degradable fraction is depleted in each timestep using the following equation

$$S^{t+\Delta t} = S^t - \theta \cdot \frac{162}{60} r_g \Delta t \quad (7)$$

where S_t is the solid degradable fraction remaining in timestep t and $t + \Delta t$ is the next time step. This is derived from the overall stoichiometry which indicates 60 g of acetic acid (representative VFA) is a result of the solubilisation of 162 g of cellulose. The stoichiometry of the hydrolytic step shows that 162 g of cellulose consumes 18 g of water; hence the effective volumetric moisture content is also decreased in each timestep by

$$d\theta = \frac{18}{162 \rho_{H_2O}} dS \quad (8)$$

where, ρ_{H_2O} is the density of water.

2.1.3 Methane Generation

The HBM model allows methane production to be quantified in relation to the amount of solid degradable matter remaining (McDougall 2008). Assuming the solid degradable fraction to consist purely of cellulose, the degradable fraction depletion data in conjunction with the stoichiometry is used to calculate cumulative methane production: 1 mole of cellulose produces 3 moles of methane.

2.1.4 Biodegradation-induced settlement

A constitutive relationship between decomposition of solid degradable fraction, i.e. a change in solid phase volume V_s , and the induced change in void volume V_v (McDougall and Pyrah 2004), is implemented to calculate the change in void ratio in the MSW matrix and subsequently, the strain due to biodegradation ε_B is calculated.

$$dV_v = \Lambda dV_s \quad (9)$$

$$de = (e - \Lambda) \frac{dV_s}{V_s} \quad (10)$$

$$\varepsilon_B = \frac{de}{1+e_0} \quad (11)$$

where, Λ is the decomposition (or degradation)-induced void change parameter, e is the void ratio and e_0 is the initial void ratio.

2.2 Initial Conditions

The solid fraction is segregated into degradable and inert phases for input into the HBM model. Initial solid degradable fraction (S_0) and degradable phase density are determined from the waste composition as provided in Table 2. Note that the degradable and inert phase densities are rather similar indicating there is no significant change in the solid phase density as degradation proceeds. It is observed that 30% by dry weight of the MSW solids are considered degradable.

Table 2. Calculation of solid degradable fraction from initial waste composition.

Waste component	% dry wt.	Degr-adable solids (%)	Inert solids (%)	Density of solid constituent (kg/m ³)	Degradable phase density ρ_{sd} (kg/m ³)	Inert phase density ρ_{si} (kg/m ³)
Paper	39	23.7 ^a	15.8	810 ^b		
Wood	27	2.7 ^d	24.5	600 ^c		
Soft Plastic	18	0	18.1	970 ^b	882 ^c	895 ^c
<20 mm	15	3.8 ^f	11.4	1530 ^g		
Total	30	70				

^aDegradable fraction in paper waste is considered to be 60 % (Barlaz et al. 1990)

^bOlivier and Gourc 2006

^cWeighted average

^dDegradable fraction in wood is considered to be 10 %

^eZobel and van Buitenen 1989

^fDegradable fraction in <20 mm soil-like material has been assumed to be the organic fraction as determined by volatile solids content.

^gZekkos et al. 2006

An initial VFA concentration of zero and initial MB concentration of 300 mg/L is adopted to best match the experimental data. Initial VFA concentration has virtually no influence over long-term concentrations and hydrolysis while initial MB concentrations do influence VFA accumulation and solid matter conversion. The initial effective volumetric moisture content for the MSW specimen after recirculation was 27 %.

2.3 Modelling Strategy

As placed physical waste characteristics, i.e., initial mass, height and volume, are defined. Initially simulation was run considering the default parameters as provided in McDougall, 2007. However, the results fit the experimental data poorly. As a result all the biodegradation parameters were strategically adjusted to optimise fit between HBM and measured experimental data. Final selected parameter values for the selected MSW composition are provided in Table 3.

Table 3. HBM-Biodegradation model parameters derived for MI-STH specimen

Model parameters	Value
Maximum hydrolysis rate, b	125000 gVFA/m ³ aqueous/day
Product inhibition factor, k_{VFA}	8.5×10 ⁻⁴ m ³ /g
Structural transformation parameter, n	1.0
Maximum specific growth rate for -methane, k_0	0.13 day ⁻¹
Methanogen death rate, k_2	0.0005 day ⁻¹
Half saturation constant, k_{MC}	1000 g/m ³
Cell/substrate yield coefficient, Y	0.3
Degradation induced void change parameter, Λ	0.7

3. RESULTS

3.1 VFA and MB concentrations

Figure 2 shows a good fit between the experimental data and the model prediction of the VFA concentrations.

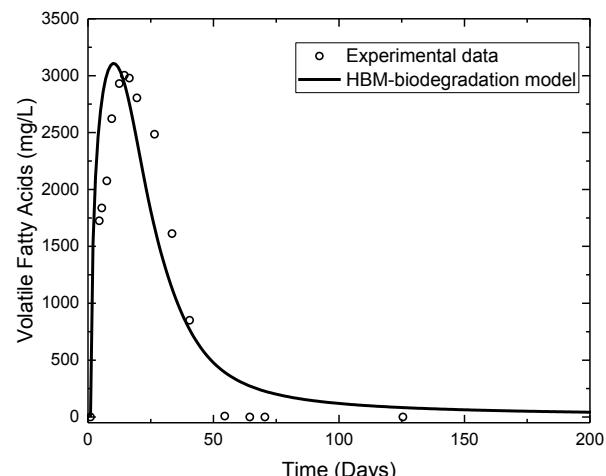


Figure 2. VFA concentrations measured in MI-STH specimen and predicted by the HBM-biodegradation model.

The VFA concentration starts from an initial value of zero and reaches a peak value of 3000 mg/L around day 15 and decays out soon reaching a long-term residual value indicative of established methanogenesis. The model predicts slower decay of VFA than the measured data. The measured VFA concentration reduces to values close to zero at day 50, whereas the model reaches that limit at around day 300 (not shown in the Figure). The maximum VFA concentrations are constrained by the product inhibition factor, whereas their subsequent decay is triggered by MB accumulation. The residual input parameters were therefore tuned by a combination of an increase in maximum hydrolysis rate (to stimulate initial VFA accumulation), a reduction in the product inhibition factor (to allow higher peak VFA concentration) and an increase in methanogen growth rate (to accelerate MB accumulation and thereby accelerate post-peak decay in VFA concentrations). Figure 3 shows methanogenic biomass (MB) accumulation predicted by HBM starting from an initial value of 300 mg/L, reaching a peak in 100 days (when VFA concentrations have reached a residual value) and then completely depleted at around 300 days. It is evident that depletion of VFA is directly proportional to MB growth. Note that MB concentrations were not measured during the

experiment (Fei et al. 2015).

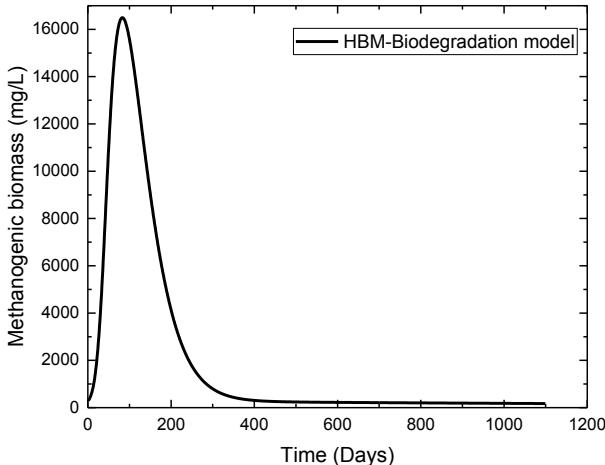


Figure 3. Methanogenic biomass concentrations predicted by the HBM-biodegradation model.

3.2 Solid degradable fraction

Figure 4 shows that the stock of solid degradable fraction (initial = 92.8 kg/m³ of total volume) was almost completely mineralised during the course of the simulation and all metabolic processes slowed down as a result. Except for the initial 20 days, the solid degradable fraction depletion predicted by HBM fit well with the experimental data. The initial “rise” in the experimental data during the first 20 days is due to the initial adjustment of the solid components in the waste matrix and large changes in volume during the first few recirculations, after which the biodegradation process begins. It is observed that MB growth depends on the amount of solid degradable fraction or organic matter remaining. With the complete depletion of solids at around 300 days, the MB concentrations also decay to negligible values. The maximum hydrolysis rate, cellulose growth rate, the structural transformation parameter and the initial MB concentration significantly influence the solid degradable fraction in the waste matrix. Note that during the experiment there was no direct measurement of solids depletion. It is estimated indirectly by considering the consumption of degradable solids proportional to the measured biogas (CH₄ and CO₂) production (solids depletion follow the nature of biogas generation rate, but match the experimental data in the end) which is a reasonable assumption considering the stoichiometry of the anaerobic process.

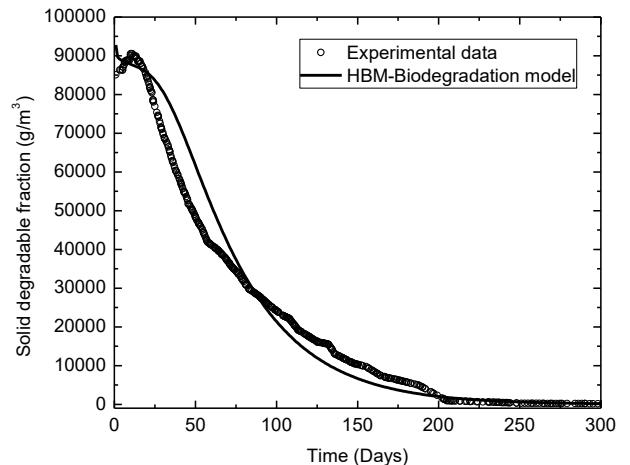


Figure 4. Solid degradable fraction measured in MI-STH specimen and predicted by the HBM-biodegradation model.

3.3 Biogas production

Figure 5 shows the cumulative methane generation for the specimen. It is observed that the total volume of methane collected during the experiment is 570 L (CH₄:CO₂ = 60:40) while the model predicts a total of 1490 L (CH₄:CO₂ = 50:50). Clearly, biogas production is over-predicted by the model due to the simplified stoichiometric assumption of solid degradable matter containing only cellulose. Apart from cellulose, hemicellulose is another principal biodegradable component of MSW; while the other major organic component, lignin, is at best only slowly degradable under methanogenic conditions and acts as a recalcitrant. (Barlaz et al. 1990). Moreover, the organic fraction in <20 mm material may also influence the gas generation. These and several other factors possibly affect the biogas generation from MSW and should be investigated further.

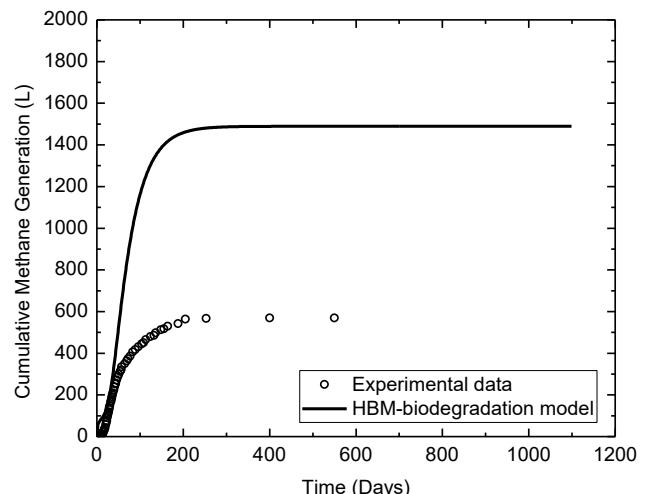


Figure 5. Cumulative methane generation measured in MI-STH specimen and predicted by the HBM-biodegradation model.

3.4 Biodegradation induced settlement

The model prediction of the evolution of the biodegradation strain is also shown in Figure 6 along with the experimental data. Biodegradation induced strain, as predicted by the model, is a function of the volume of solids and the void ratio. The general trend of the model is generally consistent with the experimental data. However, there is underestimation of

settlement, where the final surface elevation of the MSW specimen in the experimental setup was measured as 37 cm (i.e., 27.7% strain), while the model predicts the final elevation as 47 cm (i.e., 11.5% strain). A value of 0.7 has been used in this study to approximately match the slope of the biodegradation settlement curve of the model and the experiment. A Λ value of 0.7 is less than the derived void ratio based on the experimental data (void ratio varies between 1.66 and 2.08) and indicates loosening and possible weakening of the material after degradation. The decomposition-induced void change parameter is effectively a constitutive link between the mechanical consequences of decomposition and their biochemical causes (McDougall and Pyrah 2004). Note that in the experiment, long-term settlement of the waste specimen was found to follow three phases, as discussed in Fei and Zekkos 2013. Immediate compression associated with the first few leachate recirculation through the waste mass, was observed between days 1 and 10. Active biodegradation took place from day 10 to day 200 and the remaining was residual compression. In this study, only biodegradation strain has been modelled. Attributing other components of the settlement would reduce the difference between experimental and measured values. Note that in this study, both the experiment and the model consider negligible vertical stress on the specimen.

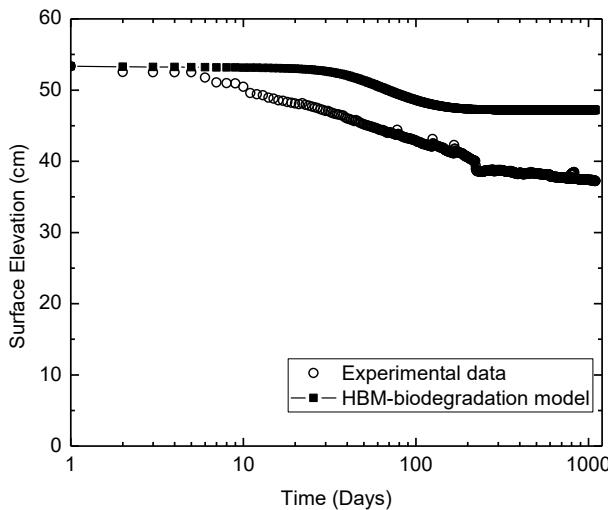


Figure 6. Surface elevation measured in MI-STH specimen and predicted by the HBM-biodegradation model.

4. CONCLUSION

An attempt has been made to model the coupled biochemical-physical-mechanical process through the simulation of the degradation process in a large scale experimental setup and the corresponding modelling using the HBM-biodegradation framework. The VFA and MB concentrations (biochemical) are dependent on the solid degradable fraction (physical), which in turn is coupled with biodegradation strain (mechanical). For a given waste composition, the model parameters are calibrated against the experimental data. However, further work is needed to be carried out for the prediction of biogas generation as the model over-predicts the methane yield.

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