A new landfill settlement model is proposed by coupling microbiological kinetics to simulate and predict municipal solid waste (MSW) landfill settlement. The model can be used to evaluate the effect of bacterial metabolisms on MSW landfill processes including settlement. The model is based on three mechanisms, namely, biodegradation of organic carbon mass, stress variation and moisture removal from waste particles (IMR) and pore spaces. Model simulation indicates that the contribution from biodegradation is small within a short period of simulation time. The landfill settlement has been dominated with water removal induced settlement where landfilling solid waste has high percentage of biodegradables and moisture content. To examine and simulate MSW landfill settlement process, a lab scale column experiment was carried out with synthetic MSW. The observed MSW landfill settlement in column experiment was used to verify the proposed model. The simulation and experiments suggested that effect of water removal will influence primary stage of settlement and this process will be introduced as a new mechanism for landfill settlement modelling. However, a careful demarcation between mechanically induced settlement and effect of internal moisture present in waste particles has to be explained by considering absorptive properties of waste particles, level of compaction and age of the waste.

Key Words: municipal solid waste, landfill, settlement, void volume, biodegradation

1 INTRODUCTION

Landfill settlement is an important concern in MSW landfill management and operation. Landfill settlement continues with time and can approach 25%-50% of the initial landfill thickness\(^1\). This prolonged settlement process is due to the bacteria mediated biodegradation. Inaccurate estimation of MSW landfill settlement may hinder the proper use of landfill site. Thus, prediction of long term MSW landfill settlement is important. In the past, many researchers have proposed theoretical and numerical analysis to predict the MSW landfill settlement. These models can be classified into; soil mechanics based models, rheological models, empirical models and biodegradation induced models\(^3\). Many of these models are based soil mechanics and empirical equations rather than natural phenomena occurred in MSW landfill. Importance of settlement models based on biodegradation has been emphasized\(^2\).

There are two main mechanisms for MSW landfill settlement: mechanical settlement and biodegradation induced settlement. As a result of biodegradation, MSW landfill settlement is more complex compared to settlement in soil. First order kinetic theory has been employed in most of the available MSW landfill settlement models to simulate the biodegradation and landfill gas generation\(^3\). Relationship between moisture in solid waste and involvement of bacteria in biodegradation has not been considered in published models.

In this study, landfill settlement has identified as two stages, namely primary and secondary. The
primary stage of settlement is mainly due to compression of new pore space which has occurred due to the removal of leachate from waste matrix with self weight. The secondary stage of settlement is mainly due to the reduction of pore space with the combined effect of biodegradation and self weight compression.

Thus, water removal induced settlement is proposed as a new mechanism to express MSW landfill settlement in where solid waste shows high moisture content. The coupled model proposed in this study can be used to simulate landfill settlement considering microbial kinetics.

2. COUPLED MICROBIAL KINETICS-MECHANICAL-WATER REMOVAL SETTLEMENT MODEL

2.1 Biodegradation process background

Carbon mass conservation theory was used in the model. The model equations and nomenclature are presented in the appendix. Landfill is consisted of solid, liquid and gas phases. The solid phase was divided into three sub phases: hardly biodegradable (HB), easily biodegradable (EB) and inorganic. Five types of bacteria are involved in biodegradation process. These are bacteria attached to solids (Sbiof), anaerobic-hydrolytic (AnH), aerobic-hydrolytic (AeH), anaerobic (an) and aerobic bacteria (ae). Organic carbon loss from solid phase to liquid phase occurs in two ways: 1) dissolution, 2) bacteria mediated hydrolysis.

Fraction of organic carbon coming into liquid phase is used for the landfill gas production by anaerobic/aerobic bacteria living in liquid phase. Dissolved oxygen is consumed by the aerobic and aerobic-hydrolytic bacteria. Thus, effect of oxygen distribution was incorporated into the model.

Bacterial growth kinetics has been expressed in single Monod and double Monod kinetics. Influence of temperature on microbial growth kinetics is expressed in Arrhenius type equation (5a). Loss of organic carbon was converted into a biologically created air-void volume (equation 7a). It is assumed that biologically created air-void volume is totally contributed to biologically induced settlement.

2.2 Mechanical settlement process

Stress on landfill solid waste is one of the main mechanisms for settlement\(^5\). The stress can be self weight or external load. Effective stress is actual stress on waste mass by reducing the upwards stresses such as pore water pressure and pore gas pressure\(^3\). The bulk density change is calculated by using the equation 13a. Then, mechanically induced settlement is calculated by using the equation 12a and 8a. The solid waste mass reduction due to biodegradation causes to reduce the stress with time. The effect of stress reduction results swelling of solid waste mass. Therefore the selection of parameters for expressing mechanical settlement is important.

2.3 Water removal induced settlement process

Landfill settlement experiment with fresh waste containing high moisture content (above 60% of weight) has resulted high settlement rate within a short time\(^6\). This was explained with newly introduced mechanism of void volume created

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_{\text{HB}} \text{ (kg/m}^3)</td>
<td>1200</td>
</tr>
<tr>
<td>(\rho_{\text{EB}} \text{ (kg/m}^3)</td>
<td>1050</td>
</tr>
<tr>
<td>Temperature ((^\circ)C)</td>
<td>25</td>
</tr>
<tr>
<td>(Y_{\text{CShar}})</td>
<td>0.6</td>
</tr>
<tr>
<td>(Y_{\text{CBShar}})</td>
<td>1</td>
</tr>
<tr>
<td>(Y_{\text{CanH}})</td>
<td>1.5</td>
</tr>
<tr>
<td>(Y_{\text{CBanH}})</td>
<td>1</td>
</tr>
<tr>
<td>(Y_{\text{CaeH}})</td>
<td>1.5</td>
</tr>
<tr>
<td>(Y_{\text{CBaeH}})</td>
<td>1</td>
</tr>
<tr>
<td>(Y_{\text{docan}})</td>
<td>2</td>
</tr>
<tr>
<td>(Y_{\text{CBan}})</td>
<td>1</td>
</tr>
<tr>
<td>(Y_{\text{docae}})</td>
<td>1</td>
</tr>
<tr>
<td>(Y_{\text{CBae}})</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1 Highly sensitive parameter values used in the model

<table>
<thead>
<tr>
<th>Column</th>
<th>Composition (%)</th>
<th>70 EB</th>
<th>18HB</th>
<th>12NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of waste column (m)</td>
<td>1.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial density (t-wet/m(^3))</td>
<td>0.882</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation time (days)</td>
<td>320</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*EB: Easily Biodegradable, NB: Non Biodegradable, HB: Hardly Biodegradable

| *EB: Easily Biodegradable, NB: Non Biodegradable, HB: Hardly Biodegradable

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with drying out of solid waste particles due to internal moisture removal and pore moisture removal. In the proposed model, empirical equation (11a) was used to calculate the water removal induced settlement. Moisture content and velocity was calculated in accordance to amount and rate of water added. Unsaturated Richard’s equation was used in moisture calculations (equations are not shown). Highly sensitive parameter values used in the model are shown in the Table 1. The parameters are in agreement with reported studies. 7,8

Fig.1 shows the flow of operational sequence of the model.

3. EXPERIMENTAL MATERIALS AND METHODS

3.1 Waste characteristics and experiment setup

In order to observe settlement mechanism, MSW collected from different sources was shredded and filled into a plexiglass column. The waste was filled manually and softly compacted by hand without using any external load. The used solid waste was identified as easily biodegradables (EB) which is mainly comprised of kitchen waste (vegetable, fish, meat, rice and other food waste), hardly biodegradables (HB) which is comprised of paper (office paper, news papers) and cardboards, non biodegradables (Inorganic or non biodegradable) which is comprised of plastics (high density and low density plastics). In the simulation, initial organic carbon concentrations were assumed to match with the experimental compositions. Table 2 shows the initial characteristics of the column experiment. Water was supplied to the column to simulate the rainfall and dry periods at different times. Dissolved organic carbon content, settlement, removed leachate volume were measured together with other parameters.

4. RESULTS AND DISCUSSION

4.1 Effect of Leachate removal

Experiment Column was operated as a flushing type simulated landfill for a period of 320 days. Although the experiment was conducted in the laboratory environment, environment temperature was not controlled. Observed settlement percentage in Column was 30%.

Fig.2 depicts the comparison between volume of water added and leachate discharge volume in experiment Column. Net leachate volume discharge was estimated by deducting the amount of added water from the total volume of generated leachate. Water phase in the landfill exists in four sub phases; namely capillary water, gravitational water, hygroscopic water and water inside the waste particles. In here the hygroscopic water refers the water film adhered to the surface of waste particles and the water inside the particles is defined as the cell plasma water. The result affirms that the contribution of water dissipation from the sub phases, especially from water inside the waste particles is the main factor in the primary stage of settlement. However the level of contribution depends on the initial moisture content, waste composition, placement density, leachate salinity, type of landfill operation etc.
4.2 Biologically induced settlement

In order to calculate the biologically induced settlement, following assumptions were employed in the model.

1. Biologically induced settlement is occurring due to air-void volume created with the mass loss of solid waste.
2. Air void volume created with biodegradation will be equal to biologically induced settled volume.
3. Settlement occurred in vertical direction.
4. Bacteria are involved in biodegradation
5. Dissolution is involved to remove organic carbon from solid phase to liquid phase.

Air-void volume occurred with biodegradation was computed by using equation (7a). Fig. 3 shows the predicted bulk density change with depth. Bulk density has increased with depth and change is small. This suggests that the biological phenomena in landfill influence settlement process and settlement will continue for long time period.

4.3 Mechanically induced settlement

In landfill environment, mechanical stress is influenced by self weight, external load, pore water pressure and pore gas pressure. In this paper, effect of external load, pore water pressure and pore gas pressure is not presented. In the laboratory experiment, measurement started after the solid waste placement. Therefore no external load was being applied. Equation (8a) was used to calculate mechanical settlement. The change of self weight stress was calculated by using (12a). The negative mechanical settlement values were observed with model as stress was reducing with time.

4.4 Proposed model with microbial kinetics

The proposed landfill settlement model is based on bacteria mediated biodegradation process explanations. Therefore the model is sensitive to microbiological process occurred in landfill environment. Thus this model could be used to predict the landfill settlement occurred with enhanced biodegradations in landfill bioreactors, aerobic-anaerobic landfills, and semi-aerobic landfills. Fig. 4 shows the experiment and simulation of dissolved organic carbon variation. Dissolved organic carbon varies from 20477 mg/l to 388 mg/l within 320 days of operation. The Fig. 3 highlights that model predicts the biodegradation more precisely. Organic carbon in solid waste is released to liquid phase as a result of dissolution and microbial activities. The dissolved organic carbon has been decreased with time. This reducing pattern of dissolved organic carbon could be due to temperature influence during the winter season as environmental temperature is not controlled in the experiment (temperature data are not shown) because low temperature may slow down microbial activities. The measured methane gas concentration was very low (data are not presented) which suggested that activity of methane producing bacteria was low. Thus, domination of physicochemical dissolution of organic carbon has to be verified over the bacteria involved hydrolysis process.

To verify the proposed model observed settlement from the laboratory experiment was used. The coupled model predictions are shown Fig. 5. Contribution from the biodegradation to total settlement was about 3%. The small amount of biodegradation induced settlement is possible in laboratory scale experiments. The low value may have attributed with low temperature used in modelling. Therefore prediction of proposed model is reasonable. About 90% of total settled
solid waste volume is caused by leachate discharge from the waste matrix. The observed settlement was dominated with settlement due to water removal effect. The unexplained settlement could be due to the dissipation of entrapped gas in and among the solid waste particles. However, the challenges and shortcomings which arise with the changes in absorptive properties of the solid waste with time must be incorporated in the explanation effect of water removal on settlement.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

Observed settlement was mainly due to settled volume owing to water removal effect. However microbial biodegradation of solid waste will be continuing with time and may be a dominant mechanism for landfill settlement in its secondary stage of settlement. The following conclusions can be drawn from the study.

(1) Bacteria mediated biodegradation in landfill can be predicted by using the model.
(2) Biodegradation induced settlement can be calculated with the proposed model.
(3) The proposed model can be used a comprehensive model for evaluating landfill processes.

Although, pore size distribution has changed with biodegradation, in the presented results effect of deformation with time was not accounted. If moisture present in solid waste is higher than 60%, water removal effect has to be considered in landfill settlement predictions (unpublished data). Our future work is to develop the propose model for deforming conditions in where landfill porosity is changing with time. The model will be verified with the field scale experiment data.

ACKNOWLEDGMENT: Authors are grateful to Research Institute for East Asia Environments, Kyushu University, Japan.

Appendix Model Formation

(1a)
\[ \theta_s + \theta_l + \theta_g = 1 \]

(1b)
\[ \theta_s = \theta_{ma} + \theta_{ea} + \theta_{shar} \]

Solid Phase Mass Balance Equation

(2a)
\[ \frac{\partial \theta_{shar} C_{acs-shar}}{\partial t} = -\beta_{shar} \theta_{shar} C_{acs-shar} f_{dc} (C_{doc,eq} - C_{doc}) - \theta_{shar} \left( \frac{1}{Y_{C_{biof}}} + \frac{1}{Y_{C_{biof}}} \right) R_{biof} \]

(2b)
\[ \frac{\partial \theta_{seas} C_{acs-eas}}{\partial t} = -\beta_{eas} \theta_{seas} C_{acs-eas} f_{dc} (C_{doc,eq} - C_{doc}) + \theta_{seas} \left( \frac{R_{biof}}{Y_{C_{biof}}} - \theta_{i} R_{avH} \left( \frac{1}{Y_{C_{biof}}} + \frac{1}{Y_{C_{biof}}} \right) \right) \]

\[-\theta_{i} R_{avH} \left( \frac{1}{Y_{C_{biof}}} + \frac{1}{Y_{C_{biof}}} \right) + \theta_{i} \left( \frac{K_{dH,x_{avH}} X_{avH} + K_{dH,x_{avH}} X_{avH}}{Y_{C_{biof}}} \right) + \theta_{seas} \left( \frac{K_{dH,x_{biof}} X_{biof}}{Y_{C_{biof}}} \right) \]
Liquid phase Mass Balance Equation

\[ \frac{\partial \theta}{\partial t} C_{\text{doc}} = -\frac{\partial u C_{\text{doc}}}{\partial Z} + \beta_{\text{shar}} \theta \frac{\partial}{\partial Z} C_{\text{acw-shar}} \int_{\text{dc}} \left( C_{\text{doc},\text{eq}} - C_{\text{doc}} \right) + \beta_{\text{era}} \theta \frac{\partial}{\partial Z} C_{\text{acw-era}} \int_{\text{de}} \left( C_{\text{doc},\text{eq}} - C_{\text{doc}} \right) + \theta \int_{\text{ar}} \left( \frac{1}{Y_{\text{dor},\text{eq}}} + \frac{1}{Y_{\text{bcan}}} \right) - \theta \int_{\text{ar}} \left( \frac{1}{Y_{\text{doc},\text{eq}}} + \frac{1}{Y_{\text{cban}}} \right) + \theta K_{\text{doc}} X_{\text{en}} + \theta K_{\text{doc}} X_{\text{e}} \]

Bacteria Mass Balance Equation

\[ \frac{\partial \theta}{\partial t} X_{\text{shif}} = R_{\text{shif}} - K_{d\text{shif}} X_{\text{shif}} \]

\[ \frac{\partial \theta}{\partial t} X_{\text{anH}} = -\frac{\partial u X_{\text{anH}}}{\partial Z} + \theta R_{\text{anH}} - \theta K_{d\text{anH}} X_{\text{anH}} \]

\[ \frac{\partial \theta}{\partial t} X_{\text{e}} = -\frac{\partial u X_{\text{e}}}{\partial Z} + \theta R_{\text{e}} - \theta K_{d\text{e}} X_{\text{e}} \]

\[ \frac{\partial \theta}{\partial t} X_{\text{en}} = -\frac{\partial u X_{\text{en}}}{\partial Z} + \theta R_{\text{en}} - \theta K_{d\text{en}} X_{\text{en}} \]

Bacteria growth kinetics

\[ \mu_{\text{max}} = \frac{A \exp \left( -\frac{E_1}{RT} \right)}{1 + B \exp \left( -\frac{E_2}{RT} \right)} \]

\[ R_{\text{shif}} = \mu_{\text{max,shif}} \frac{C_{\text{acw-shar}}}{K_{\text{cshif}} + C_{\text{acw-shar}}} X_{\text{shif}} \]

\[ R_{\text{anH}} = \mu_{\text{max,anH}} \frac{C_{\text{acw-era}}}{K_{\text{canH}} + C_{\text{acw-era}}} K_{D\text{anH}} + D O X_{\text{anH}} \]

\[ R_{\text{en}} = \mu_{\text{max,en}} \frac{C_{\text{acw}}}{K_{\text{canen}} + C_{\text{acw}}} K_{D\text{ene}} + D O \frac{X_{\text{en}}}{X_{\text{anH}}} \]

Gas Phase Mass Balance equation

\[ \frac{\partial \theta}{\partial t} C_{\text{CH}_{1+y}} = -\frac{\partial u C_{\text{CH}_{1+y}}}{\partial Z} + \theta \left( \frac{\theta}{D_{\text{CH}_{1+y}}} \frac{\partial C_{\text{CH}_{1+y}}}{\partial Z} \right) - \frac{\partial v C_{\text{CH}_{1+y}}}{\partial Z} + \theta \left( \frac{R_{\text{en}}}{Y_{\text{en}}} \right) \]

\[ \frac{\partial \theta}{\partial t} C_{\text{O}_{2}} = -\frac{\partial u C_{\text{O}_{2}}}{\partial Z} + \theta \left( \frac{\theta}{D_{\text{O}_{2}}} \frac{\partial C_{\text{O}_{2}}}{\partial Z} \right) - \frac{\partial v C_{\text{O}_{2}}}{\partial Z} + \theta \left( \frac{R_{\text{e}}}{Y_{\text{en}}} \right) \]

\[ \frac{\partial \theta}{\partial t} C_{\text{CO}_{2}} = -\frac{\partial u C_{\text{CO}_{2}}}{\partial Z} + \theta \left( \frac{\theta}{D_{\text{CO}_{2}}} \frac{\partial C_{\text{CO}_{2}}}{\partial Z} \right) - \frac{\partial v C_{\text{CO}_{2}}}{\partial Z} + \theta \left( \frac{R_{\text{e}}}{Y_{\text{en}}} \right) \]

\[ \frac{\partial \theta}{\partial t} C_{\text{N}} = -\frac{\partial u C_{\text{N}}}{\partial Z} + \theta \left( \frac{\theta}{D_{\text{N}}} \frac{\partial C_{\text{N}}}{\partial Z} \right) - \frac{\partial v C_{\text{N}}}{\partial Z} + \theta \left( \frac{R_{\text{e}}}{Y_{\text{en}}} \right) \]
\[
\theta^\mu_{\text{co}_2} = \theta_s + H_{\text{co}_2} \theta_l
\]

\[
\theta^\mu_{\text{co}_2} = \theta_s + H_{\text{co}_2} \theta_l
\]

\[
V_s = -\frac{K_s}{\mu_s} \left[ \frac{\partial P}{\partial Z} \right] \]

\[
P_s = RT \sum_i \frac{C_{x_i}}{M_n}
\]

\[
(6e)
\]

\[
(6f)
\]

\[
(6g)
\]

\[
(6h)
\]

\[
(7a)
\]

\[
(8a)
\]

\[
\delta \varepsilon_{\text{m}_{\text{w}}} = C_c \cdot \log \left( \frac{\sigma_{\text{co}_2}}{\sigma_r} \right)
\]

\[
\text{C}_c \quad \text{Could be compression ratio or swelling ration according to applied external load on top of solid waste}
\]

\[
(9a)
\]

\[
(10a)
\]

\[
(11a)
\]

\[
(12a)
\]

\[
(13a)
\]

\[
\text{Nomenclature}
\]

Frequency factor \( A_r \quad h^{-1} \)

Dimensionless factor in Arrhenius expression \( B \quad \text{-------} \)

Concentration of organic carbon in EB \( C_{\text{ecr-ecr}} \quad \text{kg} / \text{m}^3 \)

Concentration of organic carbon in HB \( C_{\text{ecr-shar}} \quad \text{kg} / \text{m}^3 \)

Dissolved organic carbon \( C_{\text{do}} \quad \text{kg} / \text{m}^3 \)

Equilibrium concentration of dissolved organic carbon \( C_{\text{ecr-shar}} \quad \text{kg} / \text{m}^3 \)

Compression ratio/swelling ratio \( C_c \quad \text{-------} \)

Concentration of gas “i” in gas Phase \( C_{x_i} \quad \text{kg} / \text{m}^3 \)

Concentration of methane \( C_{\text{ch}_4} \quad \text{kg} / \text{m}^3 \)

Concentration of oxygen \( C_{\text{o}_2} \quad \text{kg} / \text{m}^3 \)

Concentration of carbon dioxide \( C_{\text{co}_2} \quad \text{kg} / \text{m}^3 \)

Concentration of nitrogen \( C_{\text{n}_2} \quad \text{kg} / \text{m}^3 \)

Diffusion coefficient of methane \( D_{\text{ch}_4} \quad \text{m}^2 / h \)

Diffusion coefficient of carbon dioxide \( D_{\text{co}_2} \quad \text{m}^2 / h \)

Diffusion coefficient of oxygen \( D_{\text{o}_2} \quad \text{m}^2 / h \)

Activation energy for bacteria (*symbols subscript varies with the type of bacteria) \( E_1 \quad \text{kJ} / \text{mol} \)

Inactivation energy for bacteria (*symbols subscript varies with the type of bacteria) \( E_2 \quad \text{kJ} / \text{mol} \)

Potential for dissolved organic carbon fraction in solid phase \( f_{\text{dc}} \quad \text{-------} \)

Gravitational acceleration \( g \quad \text{m} / \text{s}^2 \)

Henry’s constant for carbon dioxide \( H_{\text{co}_2} \quad \text{-------} \)

Henry’s constant for oxygen \( H_{\text{o}_2} \quad \text{-------} \)

Decay coefficient for bacteria (*symbol’s subscript varies with type of bacteria) \( K_d \quad h^{-1} \)

Half saturation coefficient (HSC) \( \text{Sh} \quad \text{-------} \)

HSC of AnH bacteria to carbon \( K_{\text{ch}_4} \quad \text{kg} / \text{m}^3 \)

HSC of AnH bacteria to dissolved oxygen \( K_{\text{do}} \quad \text{kg} / \text{m}^3 \)
HSC of AeH bacteria to dissolved oxygen \( K_{d_{a_{eH}}} \) kg/m³

HSC of AeH bacteria to carbon \( K_{C_{a_{eH}}} \) kg/m³

HSC of An bacteria to dissolved oxygen \( K_{d_{o_{a_{n}}} } \) kg/m³

HSC of An bacteria to dissolved carbon \( K_{d_{o_{c_{a_{n}}} }} \) kg/m³

HSC of Ae bacteria to dissolved carbon \( K_{d_{o_{c_{a_{e}}} }} \) kg/m³

HSC of Ae bacteria to dissolved oxygen \( K_{d_{o_{a_{e}}} } \) kg/m³

Coefficient of volume relationship \( k \) m³/kg

Gas permeability \( k_g \) m²

Molecular weight of gas “m” \( M_m \) Kg/mol

Moisture content related parameter \( M_{alpha} \)

Gas pressure \( P_g \) Pa

Growth rate of bacteria \( R_{bacteria} \) kg/m³/ℎ

(*symbols subscripts vary with the type of bacteria)

Universal gas constant \( R \) j/K.mol

Concentration of bacteria \( X \) kg/m³

(*symbols subscripts vary with the type of bacteria)

Temperature \( T \) K

Reference time \( t_{-ref} \) day

Water velocity \( u \) m/h

Volume of voids \( V_v \) m³

Total volume \( V_T \) m³

Volume of air-void occurred with biodegradation \( V_{BD} \) m³

Volume occurred with internal water removal \( V_{WR} \) m³

Volume of settled air-void occurred with biodegradation \( V_{BS} \) m³

Volume of settled void occurred with water removal \( V_{WS} \) m³

Velocity of gas \( v_g \) m/h

Carbon yield coefficient of Shar \( Y_{C_{shar}} \) kg/kg

Carbon conservation yield coefficient of Shar \( Y_{CBS_{shar}} \) kg/kg

Carbon yield coefficient of AnH \( Y_{C_{a_{nH}}} \) kg/kg

Carbon conservation yield coefficient of AnH \( Y_{CBS_{a_{nH}}} \) kg/kg

Carbon yield coefficient of AeH \( Y_{C_{a_{eH}}} \) kg/kg

Carbon conservation yield coefficient of AeH \( Y_{CBS_{a_{eH}}} \) kg/kg

Dissolved carbon yield coefficient of Ae \( Y_{d_{oc_{a_{e}}} } \) kg/kg

Carbon conservation yield coefficient of Ae \( Y_{CBS_{d_{o_{c_{a_{e}}} }} } \) kg/kg

Dissolved carbon yield coefficient of An \( Y_{d_{oc_{a_{n}}} } \) kg/kg

Carbon conservation yield coefficient of An \( Y_{CBS_{d_{o_{c_{a_{n}}} } } } \) kg/kg

Methane yield coefficient of An \( Y_{an_{CH4}} \) kg/kg

Oxygen consumption yield coefficient of AeH \( Y_{O_{2_{a_{eH}}} } \) kg/kg

Oxygen consumption yield coefficient of Ae \( Y_{O_{2_{a_{e}}} } \) kg/kg

Carbon dioxidde yield coefficient of An \( Y_{an_{CO2}} \) kg/kg

Carbon dioxidde yield coefficient of Ae \( Y_{ae_{CO2}} \) kg/kg

Coefficient of organic carbon dissolution \( \beta \) m³/kg.h

(*symbols subscripts vary with easily and hardly biodegradables)

Total strain \( \varepsilon \)

Mechanical strain \( \varepsilon_m \)

Biological strain \( \varepsilon_b \)

Water removal strain \( \varepsilon_w \)

Volumetric ratio of solid phase \( \theta_s \) m³/m³

Volumetric ratio of hardly biodegradable \( \theta_{Shar} \) m³/m³

Volumetric ratio of easily biodegradable \( \theta_{Seas} \) m³/m³

Volumetric ratio of inorganic \( \theta_{Sino} \) m³/m³

Volumetric ratio of gas phase \( \theta_g \) m³/m³

Volumetric ratio of liquid phase \( \theta_l \) m³/m³

Modified Henry’s constant for oxygen \( \theta_{HO_2} \)

Modified Henry’s constant for dissolved oxygen \( \theta_{HCO_2} \)

Maximum growth rate of bacteria \( \mu_{max} \) ℎ⁻¹

(*symbol subscript varies with bacteria type)

Bulk density of solid waste \( \rho_b \) kg/m³

Viscosity of gas \( \mu_g \) Pa.ℎ

Tortuosity of gas pathway in landfill \( \xi_g \)

Particle density of hardly biodegradable \( \rho_{har} \) kg/m³

Particle density of easily biodegradable \( \rho_{eas} \) kg/m³

Effective stress \( \sigma \) Pa

Total stress \( \sigma_T \) Pa

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