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DYNAMIC CHARACTERISTICS OF MUNICIPAL SOLID WASTE WITH DEGRADATION IN BIOREACTOR LANDFILLS

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ABSTRACT

Bioreactor landfills are operated to enhance refuse decomposition, gas production, and waste stabilization. The major aspect of bioreactor landfill operation is the recirculation of collected leachate back through the refuse mass. Due to the presence of additional leachate and accelerated decomposition, the dynamic characteristics of MSW in bioreactor landfills are expected to change. Assessment of dynamic properties of landfills is one of the major geotechnical tasks in landfill engineering. In order to understand the changes in dynamic properties of bioreactor waste mass with time and decomposition, eight small scale bioreactor landfills were built in laboratory and samples were prepared to represent each phase of decomposition. The state of decomposition was quantified by methane yield, pH, and volatile organic content (VOC). A number of Resonant Column (RC) tests were performed to evaluate the dynamic properties (stiffness and damping) of MSW. The test results indicated that the normalized shear modulus reduction and damping curves are significantly affected by the degree of decomposition. The shear modulus increased from 2.11 MPa in Phase I to 12.56 MPa in Phase IV. The increase was attributed to the breakdown of fibrous nature of solid waste particles as it degrades. Therefore, the shear modulus reduction curves should be evaluated based on the degree of decomposition, rather than just the sample composition itself.

Keywords: Dynamic characteristics, bioreactor

INTRODUCTION

A bioreactor landfill is operated to enhance refuse decomposition, gas production, and waste stabilization. Bioreactor landfill can significantly increase the extent of waste decomposition, conversion rates, landfill gas (LFG) capture for environmental recovery projects, landfill capacity, improved opportunities for leachate treatment and storage, reduction of post closure activities, and abatement of greenhouse gases. For these reasons bioreactor landfills are gaining popularity as an alternative to the conventional Subtitle D landfill. The major aspect of bioreactor landfill operation is the recirculation of collected leachate back through the refuse mass. Due to the presence of additional leachate and accelerated decomposition, the dynamic characteristics of municipal solid waste (MSW) in bioreactor landfills are expected to change.

Landfills can be subjected to undrained cyclic loads due to earthquakes; the dynamic response under such loads depends to a large extent on the cyclic stress-strain characteristics of the MSW in shear. A key material property necessary to evaluate dynamic response of MSW is shear modulus (G), which relates shear stresses to shear strains. Normalized shear modulus reduction and material damping

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relationships for MSW have been recommended by various researchers (e.g. Idriss et al. 1995; Matasovic and Kavazanjian 1998, Augello etal. 1998, Elgamal et al. 2004). Augello et al (1998) developed the strain dependent modulus reduction and damping curves from the back-analysis of MSW dynamic properties from OII landfill in Southern California. The majority of the currently used recommendations are primarily based on back-analyses of the seismic response of the OII landfill. But the OII landfill waste includes significant amounts of soil material as well as commercial and industrial waste, and it is a one particular case of landfill (Matasovic and Kavazanjian, 1998). Therefore it is essential to perform laboratory investigations on MSW to better understand its behavior under dynamic conditions. However, only a limited number of researchers had performed laboratory investigations on MSW (Matasovic and Kavazanjian, 1998; and Towhata et al. 2004). This is primarily due to the difficulties in performing such tests, such as the health issues associated with testing waste material, sample disturbance, and the large test specimens required to include the larger waste particles (Zekkos et al., 2006). Moreover most of these researchers did not make clear a distinction between the age of the waste and its degree of decomposition.

The time difference between placement of MSW at bottom of landfill and at top of landfill may be between 15 to 35 years depending on the active filling period of landfill. Therefore, the levels of decomposition of MSW placement between these two MSW are expected to be different (Gabr et al., 2000). Based on the insitu tests, Matasovic and Kavazanjian (1998) also showed that the Poisson's ratio was high at deeper depths and low closer to the surface. This observation confirms that MSW is degraded more at bottom compared to its degradation at top. Therefore, considering MSW properties to be uniform throughout the bioreactor landfill is not a reasonable assumption.

In this paper the dynamic properties of MSW estimated using a series of Resonant Column (RC) tests are presented. The tests were performed at the end of each phase of decomposition. Four different phases of decomposition are considered: anaerobic acidogenic phase, accelerated methanogenic phase, and early and late decelerated methanogenic phase. From the RC results normalized shear modulus and material damping curves were plotted as a function of shear strain for the first and final phases of decomposition. In addition, the effect of presence of soil in MSW was also evaluated.

REFUSE BIODEGRADATION

A complex series of chemical and biological reactions is initiated with the burial of refuse in a landfill. Refuse decomposition has been described in an aerobic phase, an anaerobic acid phase, an accelerated methane production phase, and a decelerated methane production phase (Barlaz et al. 1989). The conversion of cellulose to methane (CH_4) and carbon dioxide (CO_2) is described by Eq. (1).

$$(C_6H_{10}O_5)_n + n\,H_2O \longrightarrow 3n\,CH_4 + 3n\,CO_2 \qquad (1)$$

In the aerobic phase (Phase 1), the oxygen entrained in the refuse at burial is consumed and there is no mechanism for its replenishment based on conventional landfill practice. CO_2 will be the major gaseous product and there will be little to no cellulose and hemicellulose biodegradation. In the anaerobic acid phase (Phase 2), carboxylic acids (acetic, propionic, butyric) accumulate and the pH decreases. These acids accumulate because of an imbalance between the various groups of bacteria required to convert refuse to methane. Phase 2 is characterized by acidic leachate, little gas production, and little to no cellulose and hemicellulose decomposition because environmental conditions are not suitable for the bacteria required for refuse decomposition. In the accelerated methane production phase (Phase 3), suitable environmental conditions develop and the methane production rate increases to some maximum value; the accumulated carboxylic acids are converted to CH_4 and CO_2 ; the pH increases; and cellulose and hemicellulose decomposition begin. In the decelerated methane production phase, the methane production rate decreases, carboxylic acids are depleted and there is an increase in the rate of cellulose plus hemicellulose hydrolysis. While acid utilization limits methane production in Phases 2 and 3, cellulose and hemicellulose hydrolysis limits methane production in

Phase 4. In a laboratory scale simulation, 70–75% of the initial cellulose and hemicellulose were converted to CH4 and CO_2 (Barlaz et al. 1989). In bioreactor landfills, the increased moisture enhances progression of the refuse to Phases 3 and 4 relative to a control landfill. Gas production from landfills is typically modeled using the U.S. EPA Landgem model (1998) as follows:

$$G = WL_0 ke^{-kt} \tag{2}$$

Where, G = annual methane generation for a specific year (t) (m^3CH_4 /year); W = mass of waste buried annually (ton/year); L_0 = methane potential (m^3CH_4 /t of waste): t = time after initial waste placement (year); and k = first order decay rate constant (1/year).

Methane production rates calculated from Eq. (2) for traditional and bioreactor landfills are presented in Figure 1(Hossain et al., 2003). With reference to Eq. (2), L_0 = 170 m^3/t, the default value used for New Source Performance Standards (NSPS) guidelines. The decay rate (k) varies to represent the NSPS default value of 0.05 year $^{-1}$ and enhanced decomposition in a bioreactor (k = 0.15 year $^{-1}$). Eq.(2) was applied to the waste buried annually for 20 years and this figure represents the total methane production for all waste present in the landfill at a given time.

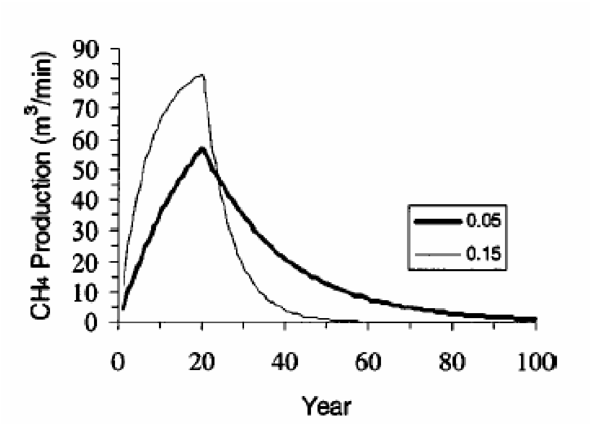

Figure 1 Methane production rate for landfill receiving 286,000 t/year for 20 years (Hossain et al., 2003)

SAMPLE PREPARATION AND EXPERIMENTAL RESULTS

Municipal solid waste (MSW) samples were collected from a transfer station in Burlington, Texas. The standard collection procedure was followed for obtaining a representative well mixed sample. Initially, physical characterization of the waste, including visual inspection of refuse composition, weight percentage of each constituent, moisture content, unit weight, and particle size distribution was completed. Based on the physical characteristics, the average paper, plastic and food waste was determined as 56, 13 and 16%, respectively.

Two sets of bioreactor cells were built in the laboratory as shown in Figure 2. Each set of reactor consists of four 16-gallon reactors to prepare samples at different stages of decomposition. The first sets of reactors were set up without soil, and the second sets with soil to simulate the intermediate covers. Sufficient quantity of moisture was added to adjust the moisture content to 55% (wet weight basis), and to generate a leachate of 1.5 L. Reactors were operated under conditions designated to simulate a bioreactor including: (a) the addition of sufficient moisture to induce leachate production; (b) leachate recirculation; and (c) the addition of an inoculum of anerobically digested sewage sludge. The leachate was neutralized with potassium hydroxide and sulfuric acid for acidic and alkaline conditions as necessary and recycled 4 days a week. All reactors were maintained at a room temperature of 22 – 29 ˚C.

Figure 2 Two sets of bioreactor cells with and without soil representing the four phases of decomposition

The reactors were dismantled and destructively sampled at each phase of decomposition. The stage of decomposition was determined from the gas composition, and by the volatile solids composition. Gas was collected in five-layer gas bags and the volume was measured by pumping it out through a standard pump which pumps at a rate of 0.5 L/min. Methane gas concentration was measured using a gas chromatograph equipped with a thermal conductivity detector. The volatile solids were determined in accordance with Standard Methods APHA Method 2440-E. Samples were dried at 105 ˚C to a constant weight and held in a desiccator. Approximately 100 grams of this dried sample were then placed in ceramic dish and inserted into a muffle furnace at 550°C for 20 minutes. Samples were removed and allowed to cool in a desiccator to a constant weight. The percent weight loss from ignition yielded the total amount of volatile matter.

Refuse Decomposition Results

Methane production rates and the pH of the produced leachate are presented in Figures 2 and 3 respectively. The anaerobic digester sludge and leachate neutralization with recirculation enhanced the refuse decomposition. Each of these reactors were destructively sampled on days 25, 106, 225, and 253. As it can be observed from the methane data in Figure 3, and pH data in Figure 4, the day 25 sample (Reactor 1-1) was in anaerobic acid phase. At day 106 (Reactor 1-3) when the rate of methane production was at peak and pH was about neutral, the sample was in accelerated methane production phase. And at day 225 (Reactor 1-4) and 253 (Reactor 1-2), as presented in Figure 3 and 4, samples were in decelerated methane production phases.

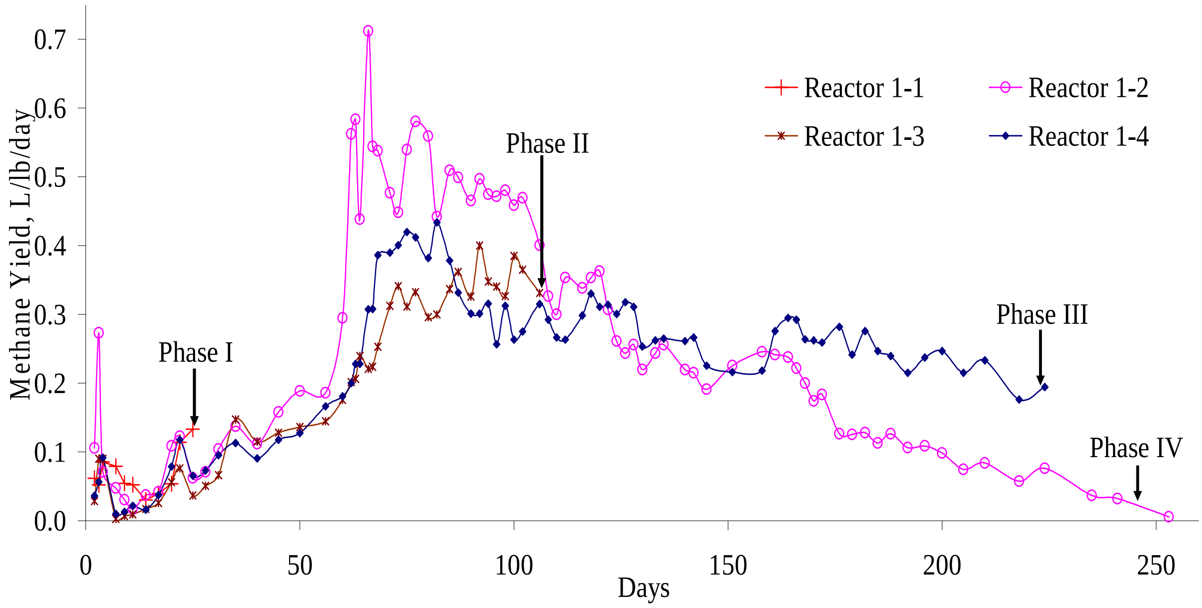

Figure 3 Rate of gas production from reactors at each phase of decomposition

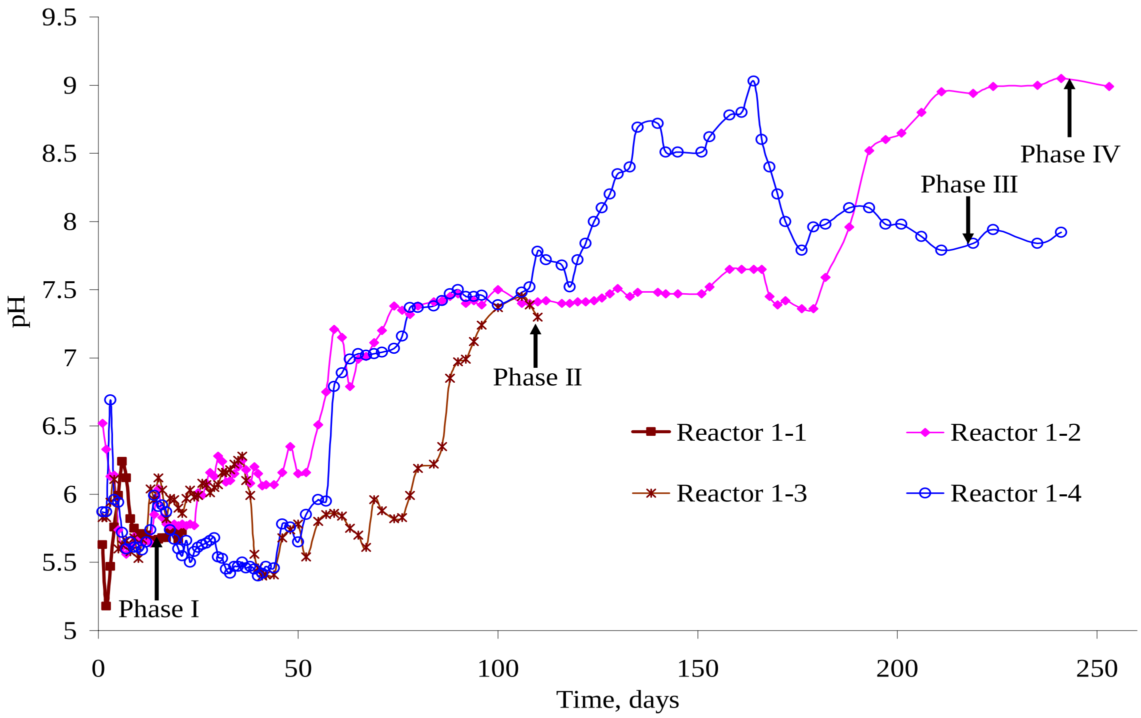

Figure 4 pH of generated leachate from the bioreactor cells

The composition of solids removed from each of the reactor is presented in Table 1. Leachate recirculation had a significant effect on the degradation of the waste. The accelerated degradation is indicated by the significant decrease in degradation. The percent change (utilized) in volatile solids decreased from 0.91% in Phase I to 39.24 % in final phase. Whereas the cumulative methane production increased as the waste gets degraded.

Table 1 Methane Production and Sample Composition in Sampled Reactors

Phase	Time of Reactor Operation	Cumulative Methane Production (L)	% Change in Volatile Solids
I	25	23.49	0.91
II	106	195.03	1.40
III	225	487.73	12.88
IV	253	515.41	39.24

Geotechnical Testing Program
Samples generated from the bioreactor cell at each phase of decomposition were remolded into a 71 mm diameter and 145 mm tall cylindrical specimens. Particles of length greater than 50 mm are cut into lengths of 50 mm. Resonant column (RC) test was performed in conformance with American Society for Testing and Materials (ASTM) Test Method (D4015) on remolded samples, as shown in Figure 5. The RC is a device suitable for testing solid or hollow specimens with shearing strain amplitude of up to 0.4%. It is one of the most reliable, efficient, and pragmatic laboratory test methods used for testing shear modulus (G) and material damping (D). The samples were tested at three different confinements (10, 20, and 30 psi), and the confinements were applied for at least 24 hours before the start of test. Tests were done at five different input voltages (0.25, 0.5, 1, 2, 4, and 5 Vrms) to examine the behavior of the samples at different strain levels.

Figure 5 Resonant column test setup with a 71 mm. diameter solid waste sample

Resonant Column Testing Results and Discussion
Results from the resonant column tests for Phase I and Phase IV samples are presented in Figure 6. With degradation, the matrix structure of solid waste particles are expected to breakdown, leading to smaller particle sizes and higher unit weight with time and decomposition of MSW. Accordingly, the shear modulus of MSW is also expected to change with time. The experimental results show that shear modulus increased from 2.11 MPa in Phase I to 12.56 MPa in Phase IV. In addition, the stronger Phase I samples required higher shear strains to induce plastic deformation, whereas the highly degraded Phase IV samples required lesser shear strain to induce the plastic deformation. The experimental results also showed that the effect of confinement was less in Phase I than in Phase IV. The increase in confinement decreased the threshold strain with modulus reduction.

The material damping ratio curve for Phase I and Phase IV specimens are shown in Figure 7. Damping ratio was also affected by the degradation. However the effect of damping ratio was more pronounced only at strains greater than 10^{-2} %. At higher shear strains, the material becomes highly deformable as it enters into plastic behavior, and therefore the changes in shear modulus and damping will be drastic. For smaller strains the material damping ratio is not significantly reduced with strain, but remained roughly constant at values of about 6 -8 %. Also, the increase in confinement did not significantly affect the damping ratio, it remained the roughly the same for both the phases. More experimental evidence is needed to substantiate these findings.

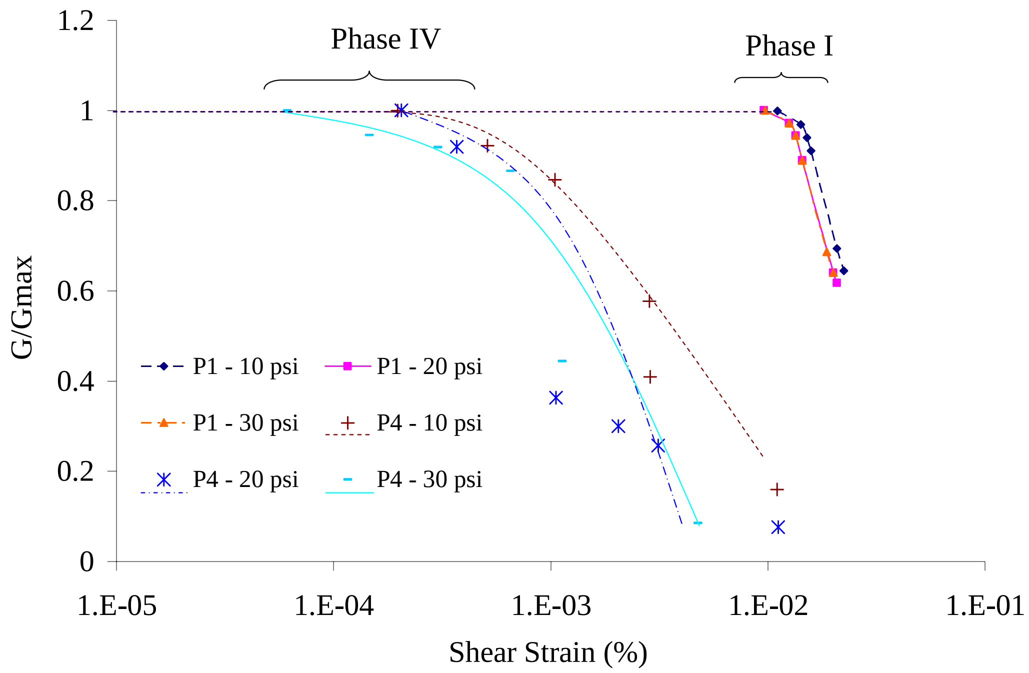

Figure 6 Normalized shear modulus reduction curves from RC

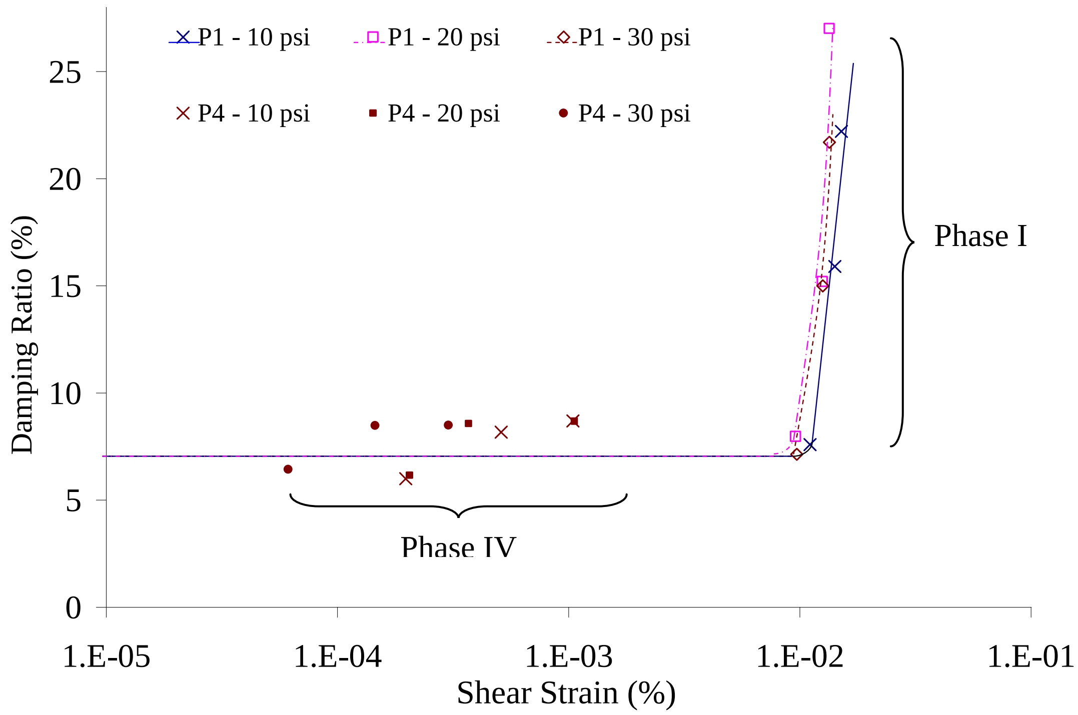

Figure 7 Material damping curve as a function of shear strain.

The results obtained from RC tests are in agreement with those observed by Zekkos et al. (2006). However, Zekkos et al. (2006) did not consider the degree of decomposition of MSW with time.

SUMMARY AND CONCLUSION

Based on the experimental results the following observations are made:

- MSW samples were decomposed anerobically in bioreactor cells to represent the four phases of decomposition. The phase of decomposition was determined from the gas composition, and by the volatile solids composition.
- The experimental results show that shear modulus increased from 2.11 MPa in Phase I to 12.56 MPa in Phase IV.
- As the material degraded, the shear modulus reduction curves shifted to the left and the threshold strain decreased. This shift can be attributed to the breakdown of fibrous nature of solid waste particles as it degrades.
- Damping ratio effects were more pronounced only at strains greater than 10^{-2} %. For smaller strains the material damping ratio is not significantly reduced with strain, but remained roughly constant at values of about 6 - 8 %.
- The results obtained from RC tests are in agreement with those observed by Zekkos et al. (2006). However, Zekkos et al. (2006) did not consider the degree of decomposition of MSW with time.

The preliminary experimental program reported herein indicates that the shear modulus response of MSW in bioreactor landfills is significantly affected by the degree of decomposition.

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