Evaluation of Stability Parameters for Landfills

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ABSRACT

There are more than three thousand landfills in the United States, in which approximately 55% (1998, U. S. EPA 1999) of the MSW generated in the US is buried. The majority of the landfills are conventional, but in the last two decades new types of landfills, called leachate recycle and bioreactor landfills, have been designed and tested as an enhanced environment for biochemical degradation of municipal solid waste. All the landfills are regulated under Subtitle D of the Resource Conservation and Recovery Act (RCRA). The shortage of time and money has limited the amount of research done on waste stability analysis. The purpose of this study was to evaluate the importance of lignocelluloses in biodegradation and the secondary settlement based on dry density and typical landfill evaluating parameters.

Both parts of the study samples were collected and analyzed from eleven landfills. In the first part of the study, bioreactor landfills were found more effective, faster in the degradation of VS and cellulose as compared to conventional landfills. The time required for stabilization is reduced to about 1/3 that of conventional landfills. The lignocelluloses degradation that occurs in these landfills is happening in two phases. In the initial, rapid degradation phase, the primary degradation substrate is cellulose. In the second phase, after cellulose degraded to 15-20% of the waste, degradation of the remaining cellulose along with lignin and the hemicelluloses takes place. The start of lignin and hemicellulose degradation results in an increase in the biochemical methane potential (BMP).

In the second part of the study, the addition of moisture to the landfills presented a contentious issue. Moisture is encouraged for MSW refuse degradation, but for settlement it reduces compressibility. In leachate recycle landfills, the dry density is higher than in conventional landfills; therefore there is more available room for further MSW load. The increase can reach up to 40 percent in total volume.

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Introduction

Landfills are used for disposal of solid waste. Originally, the materials in landfills reflected the generation of refuse but now they are used for the disposal of the reduced municipal solid waste (MSW) after the removal of recyclables. At present, in the United States there are more than three thousand landfills, in which approximately 55% (1998, U. S. EPA 1999) of the MSW generated in the US is buried. These landfills are modern well-engineered landfill facilities that are located, designed, operated, monitored, and financed to insure compliance with federal regulations. The federal regulations were established to protect human health and the environment. These regulations under Subtitle D of the Resource Conservation and Recovery Act (RCRA) include:

- restrictions requiring them to be located away from wetlands, flood plains and other restricted areas (Subpart B);
- prevention of the movement of leachate by using clay reinforced or synthetic (plastic) liners installed at the base of the landfill before the solid waste is put in (Subpart E);
- prevention of trash from being blown offsite and to reduction of odors and the spread of disease by using clean fill material coverage throughout the day (Subpart E);
- monitoring the groundwater (Subpart E);
- care for the postclosure (Subpart C); and
- conducting of a risk assessment, have a corrective action plan for gas and leachate production and handling (Subpart D).

In addition, the EPA encourages the collection of the potentially harmful landfill gas (methane is a greenhouse gas that contributes to global climate change) (Barlaz et at., 1997), the conversion the gas into energy, and the usage of the landfill gas as a renewable fuel source through its Landfill Methane Outreach Program.

If the moisture input is minimized for leachate control, the decomposition of the refuse in landfills may require decades or even centuries. About two decades ago, the idea of operating landfills as bioreactors with enhanced leachate recycling and supplemental water addition was proposed. By increasing the moisture content and the flux of the moisture through the landfill, the environment for microbiological processes is more optimal, and most importantly the time required for stabilization decreases. During the last two decades several studies were conducted to test and evaluate the effects of leachate recycling. Studies showed that the benefits of the leachate recirculation are:

- the degradation of the municipal waste accelerates,
- the gas production increases in the short term, but the time interval when gas is generated decreases
- leachate and gas are generated during the early stage when the liner system is still new and least likely to fail
- the quality of the leachate improves
- the earlier re-use of the landfill for beneficial usage is possible biodegradation of potential contaminants is faster.

However, the moisture introduced to the system sometimes is not well-distributed. The water finds its own pathways and as a result, some parts of the landfill show higher degradation, and higher stability than others. Therefore, future studies should be conducted on methods to improve water distribution within landfills.

Completed landfills have to be monitored for 30 years by law after closure. “This includes methane removal and constant monitoring of water quality in the surrounding area. These areas are usually converted into parks or golf courses because they settle unevenly making them unsuitable for structures.” [1]

The ability to predict the stability of a landfill is very valuable. The faster the landfill reaches its stability the earlier the monitoring and other viable site utilization can start (park, golf course, recreational facilities, industrial activities, etc.) (Ling et al 1998.). The progression of stability can be used to predict methane production, future leachate generation, and degree of settlement. Therefore, the ability to predict how long landfills should be monitored after active usage would be very useful environmentally and economically. To be able to predict the stability of landfills, changes in the composition of the contents, and changes in the structure of the components of the MSW has key importance.

The purpose of this study was to evaluate the importance and significance of lignocelluloses, the age of the refuse and the dry density of the refuse in municipal solid waste landfills. In terms of lignocelluloses, closer attention was paid to the degradation rate and degradation pattern of lignocelluloses (cellulose, hemicelluloses, and lignin), and the relationship between lignocellulose content and biochemical methane production potential (BMP) and volatile solids (VS) reduction. Meanwhile, dry density was compared to traditional MSW parameters for further conclusions. These parameters have been used to compare refuse data, but the significance of their values with regard to predicting the stability of landfills has not been evaluated.

Chapter 2

Literature Review

Landfills

Conventional landfills

Traditional landfills operate as waste containment facilities, which encapsulate and store MSW. In the past, landfilled refuse was often not covered properly and this led to fires and pollution problems. There was little effort to control storm water runoff and downward migration of water and that resulted in stream and groundwater pollution. Other problems associated with open landfills and dumps such as fires, rodents, odors, leachate and explosive gas, were addressed by the concept of sanitary landfills. With the federal regulations the design and operation of the landfills were established to protect human health and prevent soil and groundwater contamination. These regulations are contained under Subtitle D of the Resource Conservation and Recovery Act (RCRA).

In conventional landfills, the handling of the generated by-products, such as leachate and landfill gases, is passive. Both leachate and landfill gases are not allowed to move from onsite. Leachate is produced when rainwater infiltrates the landfill and contacts the waste inside. In these landfills, the leachate is collected and treated ex-situ. Therefore, to reduce the additional cost of the expensive disposal of the generated leachate, the volume of leachate was reduced by preventing water from infiltrating the landfill. By minimizing or preventing moisture input, the decomposition of the refuse in landfills can take decades or even centuries. Landfill gases are generated as a result of anaerobic biodegradation of organic matter in refuse, which is 50-70% of the MSW. The main gas is methane, which is an explosive, greenhouse gas. The other significant landfill gas is carbon dioxide which also is a greenhouse gas. To ensure that the leachate and the landfill gases are not moving off-site, compacted soil barriers (more than 2 feet thick clay layers) or geosynthetic (HDPE geomembrane) barriers are used. Current RCRA regulation require double lining, which is two composite layers separated by a drainage layer.

Leachate recycling

Currently the increasing amounts of waste, decreasing landfill space, increasing landfill costs, and environmental concerns challenge the feasibility of traditional landfill practices and encourage the search for better solutions in waste disposal. Leachate recycling provides an alternative to traditional landfill operation. During leachate recycling, the leachate, generated as moisture percolates through the landfill, is mixed with waste materials and reintroduced into the waste. The quantity of leachate produced by a landfill is highly correlated with the amount of precipitation around the landfill. Leachate recycling is carried out using horizontal infiltration trenches, vertical injection wells, spray irrigation or shallow pond infiltration.

The increase in the moisture content by using leachate recycling results in accelerated biodegradation, more efficient methane production, enhanced stabilization and even faster decrease in leachate strength than occurs in conventional landfills (Lee, Pohland, Harper, Otiento). The period of methane generation under ideal condition can be reduced to 5-10 years, compared to the typical conventional landfills where it takes 30-50 years (Jones-Lee et al 2000). If sufficient moisture is provided (40-60%), the rate of degradation is enhanced, whereas insufficient moisture (<20%) will retard degradation. (Christensen, Kjeldsen et al. 1989).

In the Sonoma county solid waste stabilization study (EMCON), three different types of cells were tested. The cell into which no moisture other than the atmospheric precipitation penetrated had the slowest rate and least amount of methane production. The cell that received clean water instead of recycled leachate produced methane as rapidly as the cell with leachate recycling. However, the initial rate was slightly slower.

The disadvantage of using leachate recycle landfills is the increased potential for groundwater pollution associated with the increased hydraulic load (Lee et al. 1985). Therefore, highly reliable liner leak detection systems double-composite-liner has to be installed at new, leachate recycling landfills, where the lower composite liner serves as a leak detector for the upper liner.

About two decades ago, the idea of applying enhanced leachate recycling appeared (Pohland 1975, Leckie et al. 1979, Ham and Booker 1982). By increasing the moisture content and the flux of the moisture through the landfill, the environment for the microbiological processes and decomposition became more suitable. In the last two decades, several studies were conducted on testing and evaluating the effects of leachate recycling. Studies showed that the benefits of the leachate recirculation are reasonably good. By using that technology

- the degradation of the municipal waste accelerates,
- the gas production increases in short term, but the time interval over which gas is generated decreases
- leachate and gas are generated during the early stages of decomposition when the liner system is still new and least likely to fail
- the quality of the leachate improves
- earlier re-use of the landfill for beneficial usage is possible
- the biodegradation of potential contaminants is faster.

A report by Townsend et al. (1996) indicated that a landfill in Florida, where leachate recycling was applied, had a lower Biochemical Methane Potential (BMP) than the control areas, where it was not applied. Metha's and Barlaz's (2002) research on a Californian landfill was consistent with Townsend's. It also indicated that by producing an environment with a higher amount of moisture content the pH is more likely to be in the optimal range pH 6.8- 7.4 for methanogenesis decomposition (Zehnder 1978).

Bioreactor landfills

The bioreactors are similar to the landfills with enhanced leachate recycling but they also apply supplemental water and sometimes biosolids are added. Increasing the moisture content and applying biosolids can improve the environment for microbiological decomposition. The usual moisture content in leachate recycling landfills is 30 %; while in bioreactors it is 40-50%. To further speed refuse decomposition, aeration can be applied. Aeration can be short-term to enhance initial degradation, or can be long-term to promote faster decomposition and earlier stabilization. The problem with aerated landfills is that the risk of fire increases because of the heat generated by aerobic decomposition.

For bioreactor operation, additional leachate storage, piping, leachate pumping stations and distribution systems are required. The bioreactor landfills require close monitoring and control of conditions within the landfill. In these landfills the operator can adjust several parameters to increase the stabilization and gas generation. The parameters that the operator can influence are moisture content, recirculation frequency, placement of the waste, temperature, nutrient addition, microbial inoculation, and buffer addition. Appropriate management can enhance fast landfill stabilization, and a high rate of methane production (Shearer et al 2001).

The advantages of bioreactor landfills are more space available in landfills for incoming wastes, and easier methane and leachate management because of shorter generation times and the time required for postclosure decreases. There some disadvantages as well. It requires more energy; expertise and money to operate a bioreactor landfill than a conventional one.

Utilizing bioreactors shortens the time required: for gas generation, to decrease the pollution threat, and to reduce post-closure maintenance. Also, it extends the lifetime of the landfill. Landfill gas and leachate generation occur while the protective containment system is relatively new and least likely to fail. Environmental liabilities associated with prolonged waste decomposition are, therefore, significantly reduced for future generations.

In bioreactor landfills, waste decomposition results in the conversion of biodegradable solid wastes into gas, thereby creating additional landfill space. In conventional landfills, this settlement usually occurs after landfill closure when it is too late to use the space. By accelerating the decomposition process, new landfill space is created sooner, which may be reused for additional waste placement. Recycling valuable landfill space could potentially extend the landfill life by 20% (Augenstein et al 1997).

Refuse composition

The composition, and therefore, the nature of the MSW placed into landfills depends on several factors. These factors are location, season, cultural practices, extent of leachate recycling, climate, collection frequency, and technology changes. The waste generation varies geographically, both between and within counties. Each region and area has its own waste characteristics, therefore the landfills are not homogenous, but very much heterogeneous. Over the years, this composition has changed dramatically. Surveys from the early 1900s show that a city's waste typically included thousands of horse carcasses along with huge amounts of coal and wood ash, food and yard waste, street sweepings and other debris. Not surprisingly, the vast cultural and technological changes of the past century have transformed the contents of municipal waste. [3] (http://antoine.fsu.umd.edu)

The rate of waste generation increased year by year until 1988. Since then, per capita waste generation has remained nearly constant. The well-established "consume and throwaway" attitude, has become a staple of developed countries lifestyle.[3] In 1999, more than 230 million tons of MSW was produced by U.S. residents, businesses, and institutions, which is approximately 4.6 pounds of waste per person per day. The same number in 1960 was 2.7 pounds per person per day. EPA started to regulate and force waste recycling. In 1999, the average contribution of different materials to the MSW generated was: paper - 38.1%, yard waste - 12.1%, food waste - 10.9%, plastics - 10.5%, metals - 7.8%, rubber, leather, and textiles - 6.6%, glass - 5.5%, wood: -5.3%, and other - 3.2% [2] (EPA 2002).

More than 55% of the landfill waste is paper, wood and yard waste. The lignocelluloses are the main degradation product of these materials in landfills. Municipal solid waste usually consists of more than 60 % lignocelluloses (40-50 % cellulose, 12% hemicelluloses and 10-15 % lignin) on a dry weight basis. Therefore, the most significant component of MSW is lignocelluloses. According to Barlaz (et al., 1990), more than 90 % of the methane potential is accounted from cellulose and hemicellulose.

The paper making industry separates lignocellulose fibers and uses them in specific dosage for different material quality. High quality office paper is nearly pure cellulose while cardboard has significantly more lignin. An understanding of these components can help to understand the chemical and biological processes resulting in stability in anaerobic landfills.

Lignocelluloses

Lignocellulose is the term for combined cellulose, hemicelluloses and lignin together, which are the main parts of plant cell walls.

Structure

The three major wood cell-wall constituents are cellulose, hemicelluloses and lignin. There is a very close physical and chemical relationship between cellulose and lignin. The structure of the plant cell can be very complex and different for each plant species; however, a closer look shows that the general construction is the same. Figure 1-1 shows the structural relationship between the cellulose, hemicelluloses and lignin parts of the cell wall. Around the inside hollow (lumen) part; spiral layers of cellulose are located. This layer gives flexibility and strength to the cell-wall structure. Further outside, the hemicelluloses surround the cellulose elements and provide both link and even chemical bonding between the cellulose and the further outside located lignin. The lignin gives high resistance against various chemicals and enzymes. This complex of compounds forms a unique material. The inside parts of a cell wall are highly flexible due to the linear but hydrophobic chains of cellulose; meanwhile the outside parts, due to the amorphous but also hydrophobic lignin, are highly resistant.

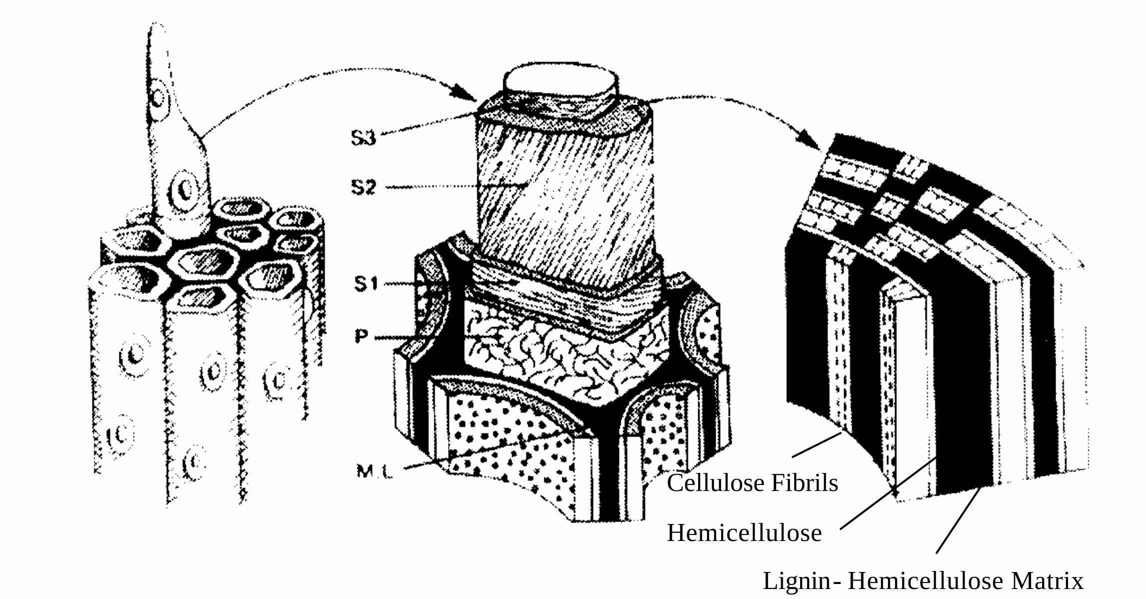

FIGURE 1-1. SCHEMATIC ILLUSTRATION OF THE STRUCTURAL LOCATION OF CELLULOSE, HEMICELLULOSE AND LIGNIN IN THE CELL WALL
(PEKKA MAIJALA ET AL 2000)

Chemical composition

The three major polymeric components, i.e. cellulose, hemicelluloses, and lignin, constitute 97-99% of the total dry mass of wood, and 65-75% are polysaccharides. (Zsolt Szengyel et al 2000), (Fengel, Wegener, et al 1989)

Cellulose

Cellulose is a long linear chain of covalently-linked sugar molecules that is chemically very stable, extremely insoluble, and also responsible for wood's remarkable strength. Cellulose is the main component of plant cell walls, and the basic building block for many textiles and for paper. The purest natural form of cellulose is cotton. The sugar units building up the cellulose structure are linked when water is eliminated by combining the -OH group and H. (Highlighted in Figure 1-2. in gray.) They are joined by single oxygen atoms (acetal linkages) between the C-1 of one pyranose ring and the C-4 of the next ring. Every other chain unit is rotated 180 degrees around the main axis, and their linkage is a chair configuration.

Linking just two of these sugars produces a disaccharide called cellobiose [2]. Cellulose is a polysaccharide produced by linking additional sugars in exactly the same way. The length of the chain varies greatly, from a few hundred sugar units in wood pulp to over 6000 in cotton. The cellulose does not melt or dissolve in common solvent because of the strong hydrogen bonds between the chains. As a carbohydrate, the chemistry of cellulose is primarily the chemistry of alcohols, and it forms many of the common derivatives of alcohols, such as esters, ethers, etc. Cellulosic materials tend to form crystalline structures in part. Less-ordered regions called “amorphous regions” separate these crystalline domain parts. These amorphous regions are the potential points for chemical and biochemical attacks, because of less resistance. (Dorée et al. 1947; The Merck index 1968).

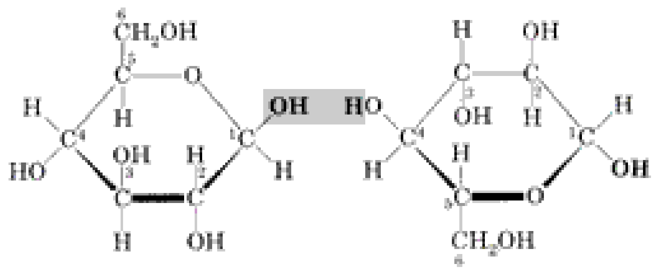

FIGURE 1-2. STRUCTURE OF CELLULOSE

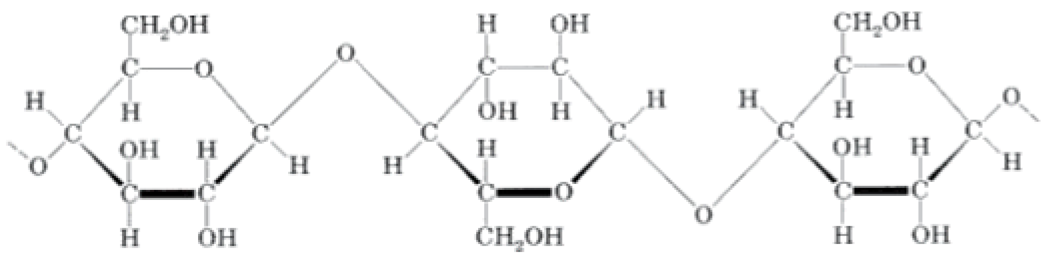

FIGURE 1-3. STRUCTURE OF CELLOBIOSE

Hemicelluloses

Structure, composition

In lignocellulosic biomass, hemicellulose is the linking material between cellulose and lignin. They act as a sort of glue between the cellulose and the lignin because of their loose structure and high content of -OH and –COOH groups. The hemicelluloses are named after their main residual in the backbone. For example, xylans consist of D-xylose units and glucomannans, which consist of D-glucose and D-mannonse units. The different types of wood (soft or hard) have different portions of components. Xylan and mannan fractions are present in soft and hardwoods in a reverse way. In softwood, the mannan content is higher; meanwhile in hardwoods, the xylan has higher concentration.

The hemicelluloses are very hydrophilic because of their chemical structures. Hemicelluloses are usually built up of short, highly branched heteropolymers of glucose, xylose, arabinose, galactose, mannose and different kinds of uronic acids.

Measurement of hemicelluloses

Chromatography is an easy, fast and effective way to separate and analyze the five wood sugar residues (glucose, xylose, galactose, arabinose, and mannose). In one study, both liquid chromatography (LC) and paper chromatography (PC) were used to quantify the sugars in 10 wood and pulp samples (Pettersen, Schwandt et al. 1984). Chemically pure sugar compounds were used to set the standard curve. High Performance Liquid Chromatography (HPLC) was used because it has an automatic sample injector and a system controller which provides continuous operation even through an entire day. Two series of different concentrations of hemicelluloses were run by both LC and PC. The results showed that for both the lower (glucose around 900 µg, for the hemicelluloses: 84 - 139 µg) and higher (for glucose around 2,000 µg, for xylose 1,000 µg, for mannose around 500 µg and for galactose 50-60 µg) concentrations of the wood sugars, a linear relationship was valid except for the higher loading of arabinose (50-60 µg). In this case, the linearity was not good. The chromatographic analysis showed that there is a difference in the relative composition of the sugars in hard-, softwoods and in pulps.

The LC precision is better than PC for glucan and xylan, not as good for galactan, and about the same for arabinan and mannan. The overall comparison of the LC and PC results show that the LC precision is better than PC, based on a 95% confidence level. Galactan was a distinguished exception for good precision, possibly because of the elution position of galactose from the LC column.

Lignin

The secondary wall of plant cells consist mostly of lignin. Lignin is a three dimensional macromolecule with covalent bonds and a very high molecular weight. Regarding the chemical structure and composition of lignin, it is hydrophobic and acts like a “water-proof” cover surrounding the cellulose fibrils and it is also one of the most complex natural polymers. Wood materials typically contain 20-35% lignin.

Lignin was studied in several media other than landfills and it was found that the lignin fraction and anaerobic decomposition in bioreactors and in lumens are negatively correlated. Studies also indicated that the lignin resistance to microorganisms in grasses is significantly less than in wood products (Barlaz 1997).

The relationship between lignin and cellulose was studied by several researchers. Several of them showed negative correlation between the two parameters. In other words, the presence of lignin limits the bioavailability of cellulose. Lignin, in general, is very resistant to any chemical and biological attack. The larger the fraction of lignin, the less cellulose will decompose and form methane. One research project showed that cellulose decomposition is affected by the physical and not the chemical separation of lignin. This is indicated by results where almost all of the cellulose was able to decompose after the lignin was physically separated (Stinson J. A., Ham R. K. et al 1995).

Another aspect of cellulose decomposition were studied and reported. It was stated that the effects of using printing ink on newspaper are negligible in the decomposition of cellulose by an anaerobic microorganism (Stinson J. A., Ham R. K. et al 1995).

In Figure 1- 4., the three-dimensional network of this polymer is shown (according to K. Freudenberg and A. C. Neish, 1968)

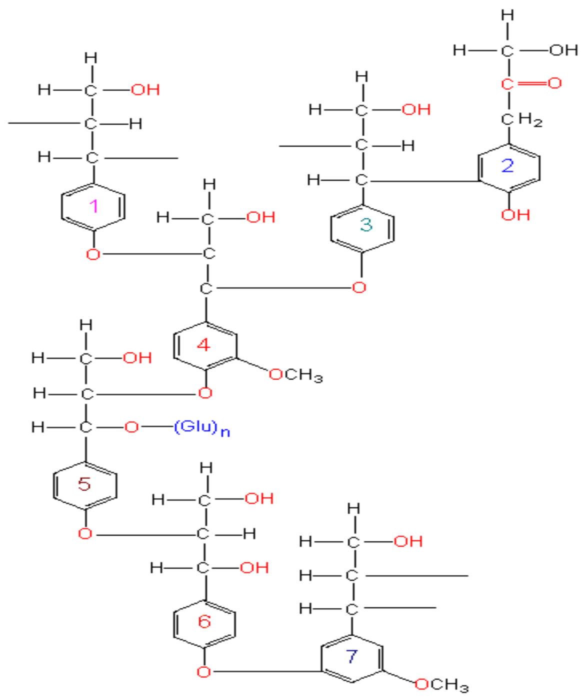

FIGURE 1-4. THE TYPICAL STRUCTURE OF LIGNIN
(source: http://www.biologie.uni-hamburg.de/b-online/e26/9.htm)

Plastics

Plastics are another very important component of MSW. The presence of plastics in landfills can be critical, because they have a very slow rate of decomposition, and they tend to slow methane production. However, there is an increasing trend of plastics in MSW. Since 1960 the amounts of plastics have increased 10 times. Even nowadays, between 1990 and 1999, plastics have increased by 2.5 % of the total % of MSW. Additionally, in the last couple of years, the plastics recycling rates in the United States not only remain comparatively low, but also took a downturn. According to an Environmental Protection Agency (EPA) publication, the plastics industry recycled approximately 5.2% of its product in 1997 and that margin was only expected to grow to 6% or 7% by the year 2000.

Plastics are polymers. Polymeric materials are characterized by long chains of repeated molecule units known as "mers" that are basic units made of carbon, hydrogen, oxygen, and/or silicon. Figure 1-5.

shows the typical structure of plastics. The plastic's macroscopic properties are determined by the way the chains intertwine.

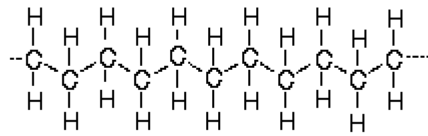

FIGURE 1-5. THE TYPICAL STRUCTURES OF PLASTICS

The two main structural forms of plastics are *amorphous, which have* strength and toughness, and *crystalline,* which shares more with crystals, and typically will have less flexibility than amorphous plastics. Some examples for amorphous plastics include polyvinyl chloride (PVC), polycarbonate (PC), and polystyrene (PS), and for the crystalline plastics are polyamide (PA; nylon), polyethylene (PE), polypropylene (PP), polyester (PET, PBT), and polyphenylene sulfide (PPS).

There are seven types of plastics. The first type is polyethylene terephthalate (PETE). The code designation for PETE is . The second is high-density polyethylene (HDPE). Typical of this category are milk, detergent & oil bottles, toys, containers, and plastic bags. The third type is vinyl/polyvinyl chloride (PVC), which includes food wrap, vegetable oil bottles, blister packages and automotive parts. The fourth type is low-density polyethylene (LDPE), which is used for plastic bags, shrink wraps, garment bags and container parts. The fifth type is polypropylene (PP), and it is used for refrigerated containers, some bags, most bottle tops, some carpets, and some food wraps. The sixth type is polystyrene (PS). Its uses include throwaway utensils, meat packageing, and protective packing. Finally, the seventh category is others, which usually includes layered or mixed plastics.

Degradation, decomposition in landfills

The decomposition of the MSW is mainly anaerobic biodegradation of complex polymers (cellulose, other polysaccharides, proteins) into methane. The decomposition is anaerobic, because in the landfills the MSW are separated from the atmosphere, and the enclosed system runs out of oxygen during the early stages of organics degradation. Furthermore, the degradation’s main constituents are complex polymers, lignocelluloses, because MSW usually consist of 40-50 % cellulose, 12% hemicelluloses and 10-15 % lignin on a dry weight basis (Wang, Byrd, Barlaz al et. 1994).

Microbiological decomposition

There is four main phases of biological and chemical decomposition in landfills with leachate recycling based on laboratory-scale tests (Figure 1-6). The phases, in order, are: aerobic, anaerobic, accelerated methane and finally the decelerated methane phase. (Barlaz et al. 1989)

In the aerobic phase (1), when the waste is initially put in, plenty of oxygen is available and the microorganisms begin the biodegradation of the MSW. By the end of this phase, both the oxygen and nitrate are consumed, with soluble sugars serving as a carbon source for microbial activity. In the fresh refuse, all the tropic groups (cellulolytics, acetogens, and methanogens) are required for the decomposition of the refuse. Methanogens are present but in a small, limited population. As the waste is further compacted and the oxygen depleted in the site, conditions become anaerobic. In the anaerobic acid phase (2), as a consequence of an imbalance between the fermentative, acetogenic and methanogenic activity, the carboxylic acids accumulate and the pH decreases. Cellulose and hemicellulose degradation begins and methane gas production is detectable. Figure 1-7 illustrates the overall anaerobic decomposition of the refuse samples and the formation of methane and carbon dioxide.

The four main reactions of decomposition are hydrolysis, fermentation, acetogenesis and methanogenesis. During hydrolysis the complex polymers cellulose, proteins, fats, other polysaccharides are broken down to monomers (soluble sugars, amino acids, long-chain carboxylic acids) by cellulolytic and other hydrolytic bacteria. In the second reaction, fermentative microorganisms ferment the hydrolysis products into short-chain carboxylic acids, ammonia, hydrogen and carbon dioxide. Along with these, alcohol and acetate, which are direct precursors of methane are also formed. The third main reaction is when acetogens oxidize propionate, butyrate, and other fermentation products to acetate, hydrogen, and carbon dioxide. The final step of anaerobic decomposition is carried out by methanogenic bacteria, which convert the acetate, hydrogen, and carbon dioxide into methane, and have an optimum pH of 7.

The third phase of decomposition is also known as the accelerated methane production phase (3), and during it the methane gas concentration reaches its maximum. The carboxylic acids decrease, while the pH and also the population of the tropic bacteria, increase. In this stage the principal supporting substrate of the methane production is the accumulated carboxylic acids. In the final step, i.e. the decelerated methane production phase (4), the rate of methane production decreases as the acetogenic population increases, and the carboxylic acids are depleted. In phase four, the pH, the cellulolytic and methanogenetic populations, and the methane concentration stay at similar values as they were in phase three.

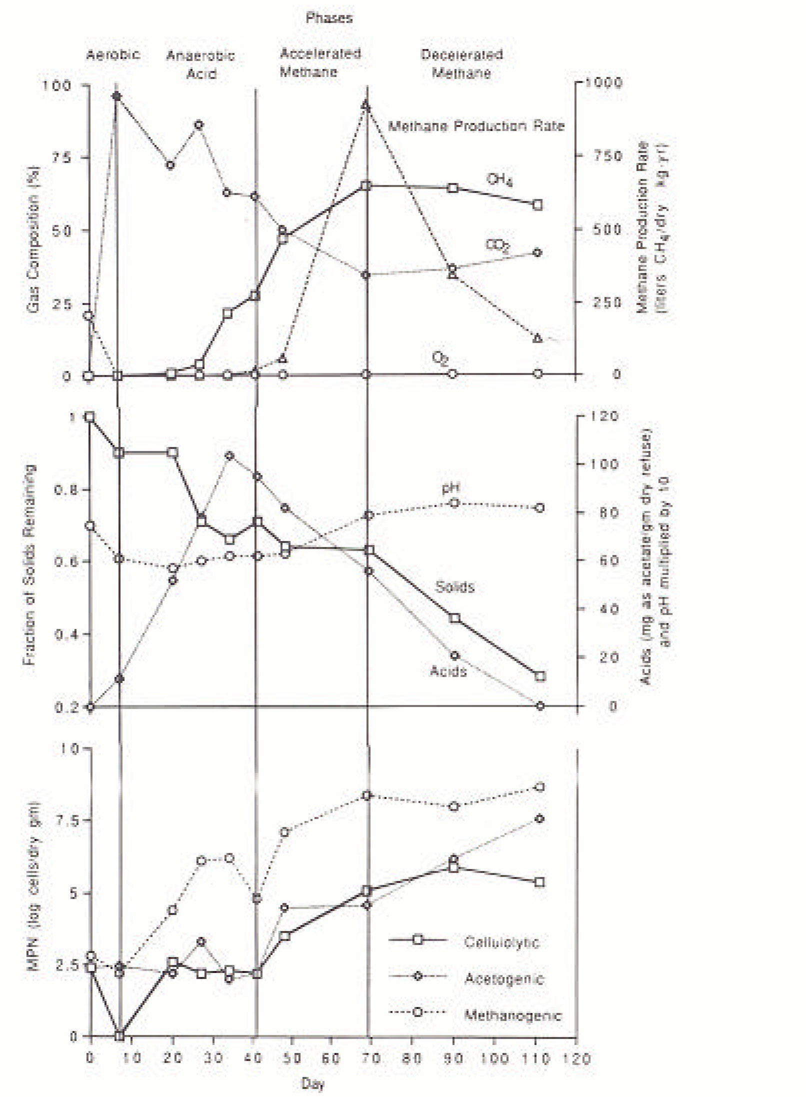

FIGURE 1-6. OBSERVED TREND IN REFUSE DECOMPOSITION WITH LEACHATE RECIRCULATION (BARLAZ ET AL., 1989)

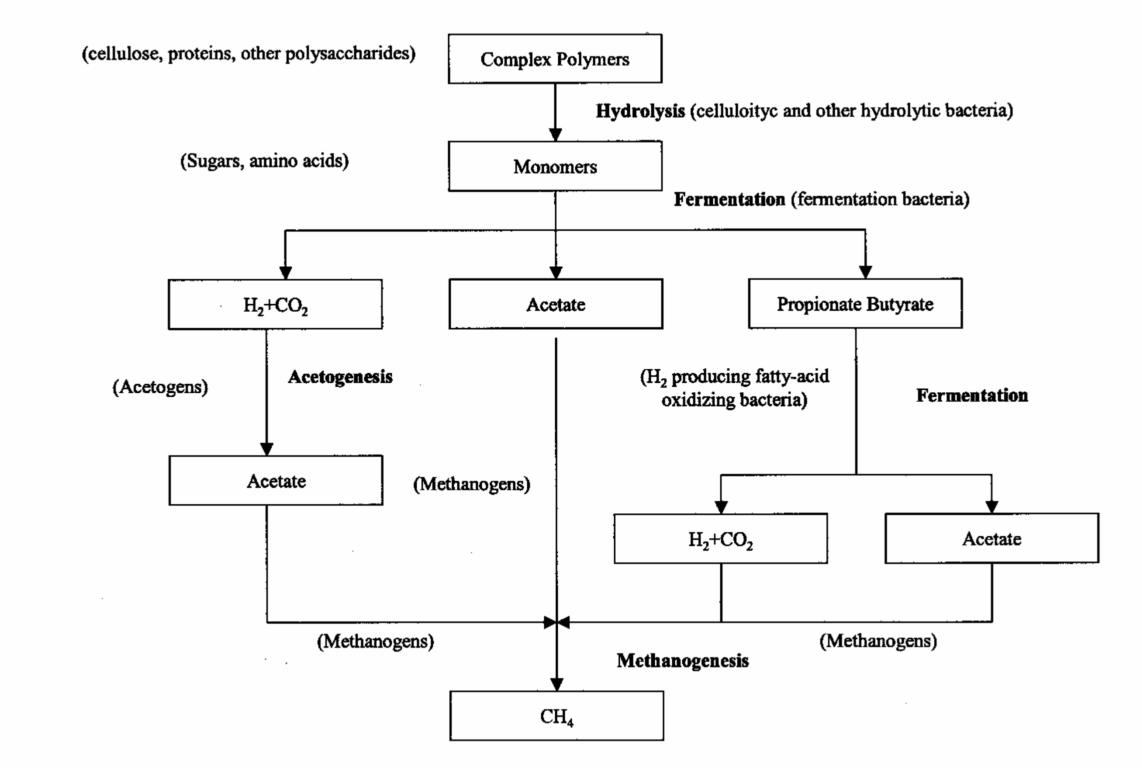

FIGURE 1-7. OVERALL PROCESS OF ANAEROBIC DECOMPOSITION
(BARLAZ ET AL., 1996)

Decomposition limiting factors

There are more limitations of decomposition in full-scale landfills compare than in lab-scale landfills, for where the above results were obtained. For example, the time required for each phase would be longer, the presence of nitrate could inhibit methanogenesis, the real samples sometimes can represent different phases of decomposition, and, finally, because of the presence of significant sulfate concentrations, electrons would be diverted from methane production to sulfate reduction.

There are several factors that influence, limit or enhance the production of methane, including moisture, oxygen availability, pH, particle size, temperature, inoculum addition, and nutrient concentrations.

The rate of degradation is typically determined by the availability of oxygen. The greater the amount of oxygen available the faster the rate of degradation. In other words, in the aerobic phases the rate of degradation is significantly faster than in the anaerobic phase, where no oxygen is available. However, in the case of MSW landfills the degradation is always anaerobic, therefore degradation takes a longer time.

The amount of methane production can be limited by acid utilization (Figure 1-6. phase 2,3) and by solid hydrolysis (in phase 4). Meanwhile, the hydrolysis rate of cellulose and hemicelluloses increases with a decrease in the carboxylic acid concentration.

The most important limiting factors are moisture and pH. For methanogenesis, the ideal pH is neutral, i.e. 7. Studies also have shown that there is a positive correlation between the amount of moisture present and methane production (Metha et al.2002). In contrast, some other studies have concluded that the pH does not have any role in the rate and quantity of the methane production during MSW decomposition in landfills.

Theoretical methane production

It is well-documented that methane production is a measure of the rate and quantity of MSW decomposition. Theoretical methane production can be expressed by a mass balance equation based on complete cellulose and hemicelluloses conversion to methane.

$$C_nH_aO_b + [n(a/4) - (b/2)]H_2O \rightarrow [(n/2)/(a/8)+(b/4)]CO_2 + [(n/2)+(a/8)-(b/4)]\ CH_4$$

In reality, the BMP calculated from the equation is much higher than the BMP measured from samples. The reason for it is not resolved. According to Barlaz (1994), it can be explained by the absence of available carbohydrates, and by toxicity, which limits cellulose conversion to methane. However, in his further research cellulose spikes were added into refuse samples and the results indicated that the reason for the difference between the measured and the calculated BMP probably was not caused by toxicity, but possible was due to the limited availability of degradable carbohydrates.

Lignocelluloses in decomposition

As we already know, the lignocelluloses are the main constituents undergoing landfill decomposition. Both cellulose and lignin are degrading, but their degradation rate in the landfills is very different. The cellulose quantity clearly decreases with the age due to degradation. However, the lignin percentage seemingly increases according to Booker's lysimeter test, because lignin is very poorly decomposed under anaerobic conditions (Bookter, Ham et al 1982). (A lysimeter is a device for collecting water from the pore spaces of soils and for determining the soluble constituents removed in the drainage). Therefore, when the easily decomposed organic material is broken down, the lignin expressed percentage wise will increase. Thus, the change of the ratio of cellulose to lignin can be used to estimate the aging, i.e. "decomposition stage" of the landfill.

The literature on the relationship between the age of the refuse sample and the cellulose and lignin ratio is inconsistent. According to Wang, Byrd and Barlaz (1994), there is no observable trend between age (depth) and the cellulose/lignin ratio. However, according to Bookter and Ham's lysimeter test (1982) there is a well-defined relationship, which can be expressed as: $1/Y= 0.255+0.137t$. In the equation, Y stands for the cellulose to lignin ratio; and t is the time since the placement of the refuse in the landfill, in years. However, this set of data is based on only four data points, therefore its validity is questionable. The cellulose/lignin ratio was used in the data comparison because it was believed to be more appropriate than just the cellulose concentration (Wang et al. 1994).

Bookter (et al.1982) came up with ranges of cellulose to lignin ratios that indicate different stability stages of the waste. When the cellulose/lignin ratio is high, around 4, then the waste is fresh. When the ratio is lower, between 0.9-1.2, then the waste is partly stabilized; and when the ratio is very low, around 0.2, then the waste is fully stabilized.

According to Booker, moisture is another important parameter of the degradation of the landfills because it has a moderator function. The higher the moisture contents the faster the rate of decomposition.

The measured quantity of lignocelluloses does not give enough information about the produced methane. By measuring cellulose and hemicelluloses the bioavailable carbohydrates are still unknown, which influences the methane potential (Wang et al. 1994). The lignin in MSW is very heterogeneous and the amount of it depends on the type of majority paper. Lignin concentration varies from office paper (delignified) to wood branches and newspapers (highly lignified). Lignin has a controlling function; it is a physical and chemical barrier to microbial attack. Jung and Vogel (et al. 1986) reported that increasing lignin concentrations decrease the digestibility of cellulose in eight grass species. However, in other studies like Dehority and Johnson (1961) indicated that concentration of lignin and the degradability of cellulose are not correlated.

According to Owen (et al., 1993) the presence of lignin reduces methagenic degradability. Parts of the MSW refuse that has low lignin concentration such as office paper and grass has higher methane production potential, than branches, leaves that have higher lignin concentration.

Settlement

Settlement is a very significant problem during practical landfill development (Sowers 1973, Wall and Zeiss 1995). The reduction in the number of Municipal Solid Waste (MSW) landfill facilities along with an increase in their size has made it imperative to achieve maximum utility of landfill volume. Exploitation of settlement can provide additional volume. The settlement of landfills is caused by compression and waste decomposition.

There are four main mechanisms involved in settlement. They are mechanical (distortion, crunching and reorientation), ravelling (movement of fine particles into large voids), physical-chemical change (corrosion, oxidation, combustion) and bio-chemical decomposition (fermentation, decay) (Edil et al., 1990). The degradation and decomposition of the refuse also is affected by the applied landfill operation. The method of operation can apply moisture and add nutrients to enhance degradation, and can control the temperature in the landfill. The temperature, moisture, and gas present or generated within the landfill are environmental factors that affect the magnitude of the settlement. The magnitude can be influenced by other factors such as initial refuse density, void ratio, content of decomposable materials, fill height, and leachate level and fluctuation (Edil et al., 1990).

The settlement with the four main mechanisms occurs in four distinguishable stages (Park et al., 2002). The first one is initial compression, the second is primary compression and the third is secondary compression. Initial compression occurs immediately after the external load is applied in the landfill, and the main mechanism is mechanical. The equation used to calculate initial compression is:

$$E_s = \frac{\Delta q H_o}{S_i}$$

Where E_s = modulus of elasticity (kN/m^2)

Δq = stress increase in stratum (kN/m^2)

H_o= initial height of refuse (m)

S_i = settlement due to initial compression (m).

Primary compression occurs quickly, usually within a month of load application (Sowers 1973). Primary compression is due to the dissipation of gas and pore water from void spaces. The magnitude of primary compression during the first month is higher than the secondary compression, but eventually both of them cause almost the same order of magnitude of compression. Primary compression is usually described by Terzaghi's theory, calculated by the following equation:

$$S_p = H_i C_{ce} \log\left[\left(p_o + \Delta p\right) p_o\right]$$

Where S_p = settlement due to primary compression (m)

H_i = height of refuse after primary compression (m)

C_{ce} = modified primary compression index

p_o = existing overburden pressure at midlevel of layer

Δp = increment of overburden pressure at midlevel of layer.

Secondary compression takes place over a longer period of time (years) and it is due to creep of the refuse skeleton and biological decay (Sowers 1973). According to a study by Coduto and Huitric (1990), biological decomposition affects between 18 - 24 % of the refuse thickness. Secondary compression becomes more evident when the filling of the landfill is finished (Edil et al., 1990). The magnitude of secondary compression is calculated by the following equations, which assume a linear relationship between settlement and the logarithm of time. $S_s = H_p C_{ae} \log\left(t/t_p \right)$

Where $C_a = \Delta e / \Delta \log t$;

$C_{ea} = C_a / \left(1 + e_p\right) = \Delta strain / \Delta \log t$.

Where C_a = the slope of the void-ratio versus log-time curve

C_{ea} = the slope of the strain versus log-time curve; rate of secondary compression.

Several factors can influence primary and secondary compression. According to Sowers (1973), secondary compression linearly increases with initial void ratio. A study conducted by Wall and Zeiss (1995) stated that the addition of water has a significant effect on initial and primary settlement. Initial compression reached 26%, and the height of the refuse decreased by 17 %. Primary compression, after 30 days, can result in an additional 15 % refuse compression. On the other hand, secondary compression was not significantly increased by water addition. In the same study, the magnitude or rate of secondary settlement was not found to be significantly affected by biodegradation either in conventional or enhanced landfills.

Besides the physical compression, biochemical degradation takes place in the landfill. As was mentioned in the refuse composition section (2.), the refuse typically contains 40-50 % cellulose, 10-15 % lignin and 12 % hemicelluloses (Barlaz et al., 1990). Approximately 25- 40 % of MSW is available for biological decomposition (Barlaz et al.,1989.; Ham and Booker 1982.) Biodegradation occurs through four stages as was described in Microbiological decomposition (3.1.) and refuse decomposition trend is shown in Figure 1-5. "Observed trend in refuse decomposition with leachate recirculation". The decomposition loss in refuse adds to the secondary settlement.

There are four main models which trying to provide a single equation for both primary and secondary compression.

a) Logarithmic function (Yen and Scanlon, 1975) expressed the strain rate (m) in terms of strain rate parameters.

$$m = \frac{1}{Ho}\frac{dS}{dt} = c - d\log t$$

Where m = the strain rate (T^{-1}),

S = the settlement (L),

Ho = the initial height of the landfill,

c and d = strain rate parameters (T^{-1}).

Sohn and Lee integrated this strain rate to give the settlement over time as

$$S = Ho\int m.dt = Ho\left(ct - \frac{d}{\ln 10}(t\ln t - t\right)_{to}^{t1}$$ where to is the age of the fill at the beginning of the settlement computation period and t1 is the age at the end of this period. Limits for obtaining a positive settlement give $t1 \leq 10^{c/d}$

b) Rheological model: Edil (1990) proposed the reheological model of Gibson and Lo (1961) for secondary compression to predict long term settlement as

$$\frac{S}{Ho} = e(t) = \Delta s\ (a + b\{1 - e^{[-(l/b)t]}\})$$

where ε(t) is strain,

Δσ= compressive stress (M/L^2)

a = primary compressibility parameter (L^2/M)

λ/b = the rate of secondary compression (T^{-1}).

Plotting $\log_{10}(\Delta\varepsilon(t)/\Delta t)$ versus $\log_{10} t$ we get the slope of the line = $-0.434(\lambda/b)$ and the intercept as $\log_{10}(\Delta\sigma\lambda)$. Denoting t_k as the time to complete primary compression we get

$$a = e(t_k)/\Delta s - b\{1 - e^{[-(l/b)t_k]}\}$$

c) Power Creep Law: Edil (1990) applied the power creep law as $\frac{S}{Ho} = e(t) = \Delta s\, m(t/t_r)^n$

Where m = reference compressibility (L^2/M),

n = rate of compression.

d) Hyperbolic function has been used first by Ling et al. (1998) as

$$\frac{S}{Ho} = e(t) = \frac{t}{\frac{Ho}{ro} + \frac{Hot}{S_{ult}}}; \text{ thus } \quad \frac{t}{e(t)} = \frac{Ho}{ro} + \frac{Ho}{S_{ult}}t$$

where S_{ult} = ultimate settlement of the fill at $t(\propto)$

Using all four predictions, Park (et al., 2002.) showed that landfills operated with recycling have higher total settlement than the ones without. According to Wall (1992.) settlement prediction with the rheological and power-creed laws is less accurate than with the Sower's model. The other two methods (logarithmic and hyperbolic methods) were not compared to the model by Sowers. Another study by Ling (et al., 1998.) compared hyperbolic function with power and logarithmic functions. It was found that the long-term settlement prediction by the hyperbolic function gave a better prediction than the power and logarithmic models.

Wall and Zeiss (1995.) conducted a study to evaluate the effects of biodegradation on settlement and to study time reduction though leachate recirculation in the landfills. They found that biodegradation has very little effect on the secondary settlement rates. Total mass of solids decomposed during the test period (250 days) was 1 % whereas the secondary settlement at the same period accounted for 4 % deformation.

The settlement in large landfills is significant; and it causes large increases in dry density and in landfill capacity. The density increases as the strain (ratio of settlement to initial height) in porous media increases. The magnitude of settlement by vertical expansion depends on the thickness and the age of the refuse. Both hydraulic conductivity and permeability are related to the strain and density. The hydraulic conductivity (m/s) decreases as the effective stress (kPa) or the dry density (kg/m^3) increases and the refuse permeability decreases with an increase in refuse strain (Bleiker (et al., 1995)).

Bleiker (et al., 1995) summarized dry density ranges from several landfill studies in a table, which is shown as Table 1-1.

TABLE 1-1. TYPICAL LANDFILL DENSITIES FROM BLEIKER (ET AL., 1996)

Source	Density kg/m^3	Comments
Landva & Clark (1990)		
Minimum	694	Excavated surface pits and measure mass and volume
Maximum	1653	Includes cover material and absorbed moisture
Oweis & Kehra (1986)		Estimated from degree of consolidation of underlying
Minimum (old refuse)	1122	clay layers
Maximum (old refuse)	1286	
During active filling	673	
Ham & Booker (1982)		Refuse density in test lysimeters constructed
1.2 m of refuse	458	with "normal compactive effort"
2.4 m of refuse	491	
Sowers (1973)	600	No explanation provided
Lukas (1992)		No explanation provided
Poor compaction	321	
Good compaction	642	
Best compaction	963	

The values in Table 1-1 vary based on the different amounts of cover material included in the refuse samples, the different water contents of the refuse, and the different magnitude of settlement that the refuse has undergone (Bleiker et al., 1995).

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CHAPTER 3

The following chapter, Evaluation of Stability Parameters for Bioreactor Landfills has been published and presented at the SWANA 7th annual symposium in Louisville, Kentucky, 2002.

EVALUATION OF STABILITY PARAMETERS FOR BIOREACTOR LANDFILLS

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Abstract

Samples from several conventional, bioreactor and leachate recycle landfills were collected to evaluate the degradation rate and degradation pattern of lignocelluloses (cellulose, hemicelluloses, and lignin), and the relationship between the lignocelluloses and biochemical methane potential (BMP) and volatile solid (VS). It was found that degradation of VS and cellulose in bioreactor landfills is much faster than in conventional landfills. These data suggest that the time to stabilization is reduced to about 1/3 that of conventional landfills. In the initial, rapid degradation phase, the primary degradation substrate is cellulose. After cellulose is reduced to a range of 15-20% of the waste, degradation of the remaining cellulose along with lignin and the hemicelluloses takes place. This onset of lignin and hemicellulose degradation results in an increase in the BMP.

Introduction

Landfills are the primary method for disposal of municipal solid waste (MSW) in the US. At present, there are more than three thousand landfills in the United States, in which approximately 55% (U. S. EPA, 1999) of the MSW generated in the US is buried. The modern landfill is a well-engineered facility where the operation and monitoring are highly regulated (RCRA Subtitle D).

Leachate recycle and bioreactor landfills were developed to speed the degradation of MSW and improve leachate quality. Studies were conducted starting in the 1970s on the practice and effectiveness of leachate recycle landfills (Pohland, 1975; Leckie, 1979; Ham and Booker, 1982). In leachate recycle landfills, the generated leachate is recycled and this increases the moisture content in the actively degrading refuse. These landfills have improved liner systems to prevent leachate loss to the environment.

Bioreactor landfills are the most advanced type of landfill. These combine leachate recycle with additional moisture, and may include biosolids and nutrient addition. The moisture content theoretically reaches 40-55 percent compared to 15-30 % moisture content in conventional landfills. Additionally, the time projected to achieve stabilization is significantly less compared to conventional landfills (Kilmer et al. 1999, Pohland et al. 1975, Watson et al. 1993).

The ability to predict the stability of a landfill is very important in terms of environmental and economical aspects. Stability measurements can be used to predict future methane production, leachate generation, and settlement. The stability of landfills has been evaluated by biochemical and physical parameters such as biochemical methane potential (BMP), volatile solids (VS), cellulose, and lignin. The BMP is a well-documented parameter, but there is still a large amount of uncertainty in its measurement and interpretation (Barlaz et al., 1997). Methane production depends on the amount of available polysaccharides, the moisture content, the pH of the landfill and the quantity of plastics, food and paper in the waste.

In 1999, the average contribution of materials to MSW was: paper: 38.1%, yard waste: 12.1 %, food waste: 10.9 %, plastics: 10.5 %, metals: 7.8 %, rubber, leather, and textiles: 6.6 %, glass: 5.5 %, wood: 5.3 % and other: 3.2 % (EPA 2002). More than 55% of the landfill waste is paper, wood and yard waste. The main component of these materials is lignocelluloses. Therefore, to understand and evaluate landfill stabilization characterization of lignocelluloses is important. Lignocelluloses are also the main source of biochemical methane production, which is used to indicate the state of stabilization of landfills.

The purpose of this study was to evaluate

- the extent of degradation and degradation pattern of the components of lignocelluloses; cellulose, hemicelluloses, and lignin.
- the relationship between the lignocelluloses, BMP and volatile solids
- the degradation rates of VS, BMP, cellulose and lignocelluloses in conventional, bioreactor and leachate recycle landfills,

- the characteristics of rapidly (5 year degradation) and slowly (5 to 50 years) degradable materials.

Material and Methods

The MSW samples were collected from eleven landfills operated as bioreactors, leachate recirculation, or conventional. Waste was collected from various locations within the landfill and at different stabilization stages.

Table 1 summarizes the different types and operations used at these landfills. The number of analyzed samples was more than 250. The methods used for parameter characterization, including on-site and offsite analytical measurements, are described in the following sections. The age of the refuse was determined by looking at dates on newspapers in the samples and from site records. Because all samples did not have readable newspapers, the samples used for age related rates were limited to 51 out of 250 samples.

Sample Collection

The refuse samples from the landfills were collected using a drill rig outfitted with a 36-inch bucket auger. It is known that sampling is one of the biggest sources of variability in landfill studies. The majority of the samples were collected from different depths. One sample not shown in Table 1 was from the oldest landfill in Louisville, Kentucky, where only one depth was sampled. This sample was provided to insure that one sample was very stable. The refuse samples, after collection and measurement of the wet and dry densities, were put into coolers and sent to the Virginia Tech Environmental Engineering Laboratory.

TABLE 3- 1. SUMMARY OF THE SAMPLED LANDFILLS

Type of Landfill	Type of Operation	Status
Bioreactor		
King George, VA	Anaerobic	Bioreactor not in operation yet, 8 years old
Metro, WI	Aer/Anaer	Bioreactor and control, 1 year of operation
Middle Peninsula, VA	Anaerobic	3 years old
Spruce Ridge, MN	Anaerobic	6 years old
Leachate Recirculation		
Atlantic, VA	Anaerobic	3 years old
Evergreen, OH	Anaerobic	7 years old
Maplewood, VA	Anaerobic	Leachate recirculation cells not yet in operation, 8 years old
Conventional		
Green Valley, IL	Anaerobic	
Kettleman Hills, CA	Anaerobic	
Central, FL	Anaerobic	Filled in 1998, high amount of C&D waste
Riverbend, OR	Anaerobic	3, 8, 11 years old, very wet

Laboratory Analysis

In the laboratory, several parameters were measured in order to characterize stability. These parameters were pH, moisture content, volatile solids, cellulose, the major hemicellulose sugars (xylose, mannose, arabinose, and galactose), lignin, and biochemical methane potential.

The moisture content was measured according to method 2540-B (APHA et al., 1995). For this analysis, 500-1000 g of wet, unshredded MSW were put into an aluminum pan and dried at 105 ^{o}C until constant weight. (Usually less than two days.) The moisture content is expressed as a percentage of the weight loss during drying divided by the original weight.

The volatile solids were measured by using the 2540-E method (APHA et al., 1995). A 100-200 mg sample of dry, milled refuse was placed into an aluminum pan, and then into a muffle furnace (550 ^{o}C) for 20 minutes (after that no additional weight loss was expected). The volatile solids are reported as the percentage by weight lost by ignition.

The pH was measured by mixing 50% (% by weight) wet unshredded MSW sample and distilled water into a 1 L glass beaker. When the mixture reached equilibrium at 20 ^{o}C (about 5 hours), the pH probe was placed into the beaker and the reading was obtained.

Cellulose and the hemicelluloses were measured by applying AST Method E 1758-95^{e1} (1995). This method was chosen, because it is suitable for materials found in municipal solid waste samples. The dried, shredded samples were taken from plastic bags used to store the processed samples, and 300±10 mg placed into a 16x100 mm glass tube. The cellulose was hydrolyzed in two stages to convert cellulose and hemicelluloses into their sugar monomers. In the first stage, 3.00±0.01 mL of 72% w/w sulfuric acid (H_2SO_4) was added to the samples and stirred until mixing was complete. The glass tubes containing the samples were then placed in a 35 ^{o}C water bath for one hour. In the second stage, the digested samples were transferred into 250 mL septa bottles and 84 mL of nanopure water dilution was added. The bottles were autoclaved for an hour at 121 ^{o}C and 15 psi. After the autoclave cycle was completed, the bottles were allowed to cool down for 20 minutes at room temperature. The samples were filtered using 1.2 µm glass fiber filters. The volatile suspended solids remaining after combustion at 550^{o}C in the muffle furnace were defined as lignin.

The filtrate was neutralized to pH between 5-6, with a slurry form of $Ba(OH)_2$. The barium(II) sulfate precipitate was centrifuged and then filtered though a 0.45 micrometer pore size membrane and a reversed-phase cartridge. Finally, the glucose and the main four hemicelluloses were detected using HPLC with reflective index detector and HPX-87C column. The water flow rate was set to 0.5 ml/min for easier peak separation. Both glucose and the four main hemicelluloses (xylose, arabinose, galactose, and mannose) standard curves were run prior to the analysis of D(+) xylose, D(+) mannose, D(+) galactose, D(+) arabinose, and D(+) glucose. Figure 1-1 shows a HPLC chromatogram for the 5 sugars.

The biochemical methane potential (BMP) analysis was modified from a procedure developed by Barlaz (Shearer et al., 2001). Two hundred milligrams of dry, shredded MSW were added to a 250 mL Boston round septa bottle. Then, 100 mL of revised anaerobic media was added to each bottle. The media was made following Barlaz's methods except for two modifications. The vitamin solution was not included, and anaerobic digester biosolids from the Peppers Ferry Wastewater Plant, Fairlawn, VA were added as an inoculum at 10% by volume (Stinson and Ham, 1995). The bottles were incubated for 45 days at 35 ^{o}C. One-liter Teflon gas sampling bags were connected to each bottle at the end of the incubation period for twenty minutes while agitating the bottle to relieve excess pressure. A 100 microliter sample was taken from the gas-sampling bag and injected into a GC with a carbosieve packed column and flame ionization detector (FID). The volume of gas in the gas-sampling bag was measured using a 60 mL plastic syringe. This test was run in triplicate with one blank for every six bottles. The amount of methane measured in the blanks was deducted from that of the samples. The BMP was reported in units of milliliters of methane per gram of dry MSW at STP (mL CH_4/g).

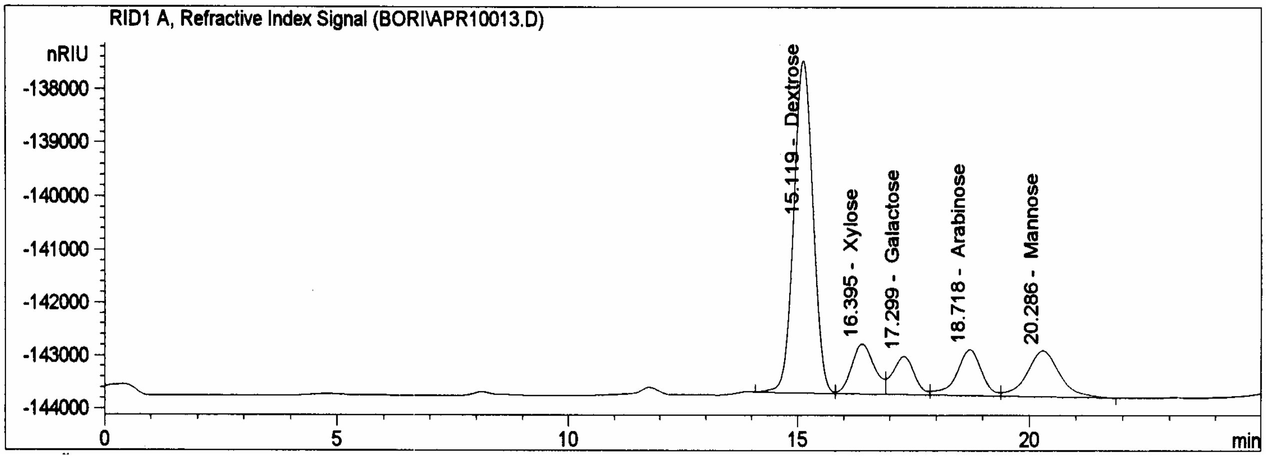


FIGURE 3-1. HPLC CHROMATOGRAM WITH THE SEPERATED CELLULOSE AND HEMICELLULOSE PEAKS

Results and Discussion

The type of landfill and its characteristics are expected to have a large effect on the rate of biological degradation. The main purpose of developing leachate recycle and bioreactor landfills was to increase the rate of decomposition, thereby allowing more effective use of the site and more effective collection of methane. Therefore, the expected trend for the more advanced landfills is faster decomposition. Figure 3- 2a shows the BMP, and Figure 3- 2b shows VS changes over time for the different types of landfills. The data in Figure 3- 2a clearly shows that the methane production rate, as indicated by the change in BMP in the bioreactor landfills, is faster than in the conventional landfills. The projected age, where no more methane will be produced, using a zero order degradation rate, is approximately 13 years for the bioreactor landfills and 35 years for conventional landfills. Although this is an estimate, it shows the benefits of bioreactor landfills.

When BMP reaches 10 mL CH_4/g a landfill is considered stable (Kelly et al, 2002). To reach this BMP value, the time needed for stabilization is 12 years for the bioreactors and 30 years for conventional landfills. However, these numbers are heavily dependent on pH, moisture, and temperature in the landfill. For the bioreactor and the conventional landfills, the early age data were not included in the analysis because gas production is assumed to start at the end of the first full year of landfill operation (Tchobanoglous et al. 1993). However, for the leachate recycling landfills, all the data are for a time period of less than 2 years. This is not enough data for estimating stabilization times for leachate recycling landfills.

The volatile solid degradation, shown in Figure 3-2b, confirms that the degradation in bioreactors is faster than in conventional landfills. For conventional landfills, the volatile solids do not change over the time period of the tests. The degradation rate for the leachate recycle landfills is similar to the bioreactor landfills but more data are needed to verify this trend. The data show very high variability, and that is due to heterogeneous characteristics within a landfill and unique landfill biodegradation properties. The time to reach stability (where only plastics remain), occurs at a projected age of 12 years, and this time is in agreement with the results from the BMP degradation tests (Figure 3-2a). The projected age was determined by using a zero order degradation rate.

The MSW decomposition is affected by the presence of both rapidly and slowly decomposable materials. Rapidly decomposable matter degradation takes approximately 5 years in a conventional landfill while the slowly decomposable materials take 5 to 50 years to degrade (Tchobanoglous et al. 1993). The data in Figure 3-2 for both conventional and bioreactor landfills show a pattern suggesting these fast and slowly degradable materials are related to specific components in the waste. Around 40 months, the BMP starts to increase and reaches its maximum around 60 months (approximately 5 years). This increase from 40 to 60 months appears to be related to an increase in lignin and hemicellulose bio-availability. Figure 3-3a shows the degradation of lignin and hemicelluloses starts at 40 months. Figure 3-3b shows the BMP with a depiction of the pattern.

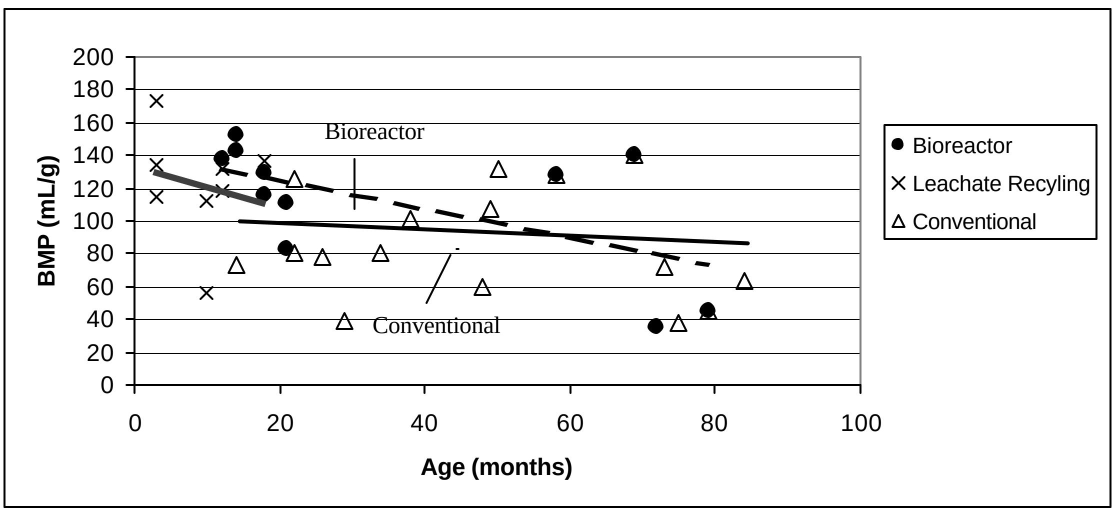


FIGURE 3-2 A. DEGRADATION OF BMP IN THREE TYPES OF LANDFILLS

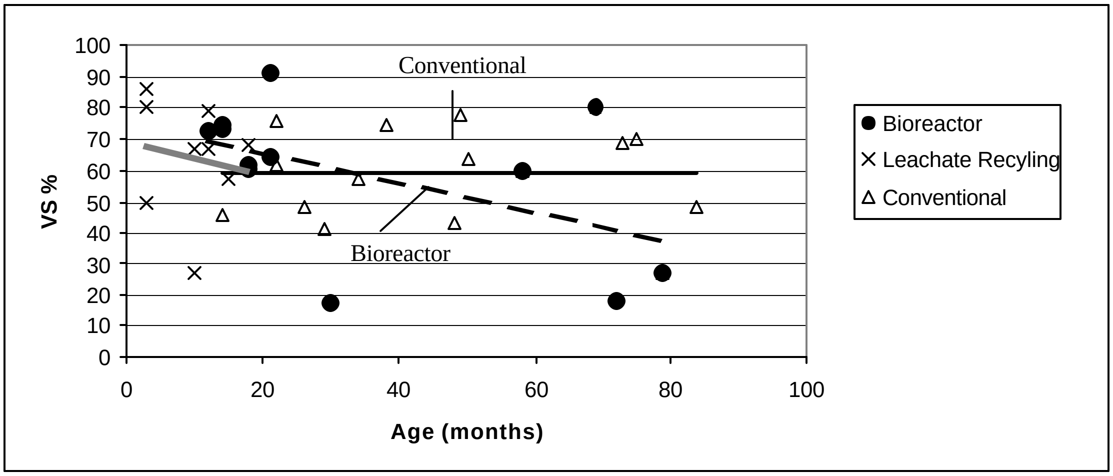
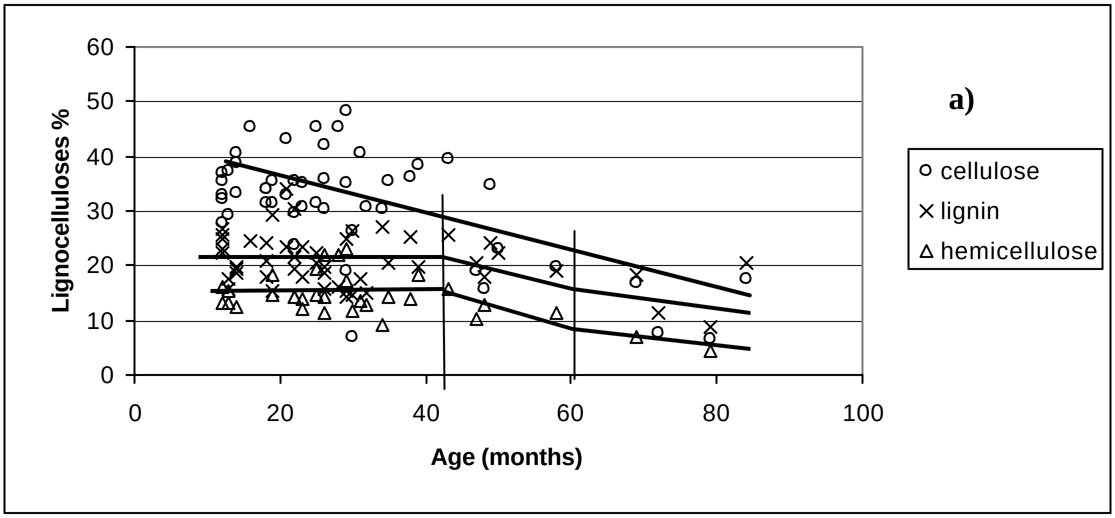


FIGURE 3-2 B. DEGRADATION OF VS IN THREE TYPES OF LANDFILLS



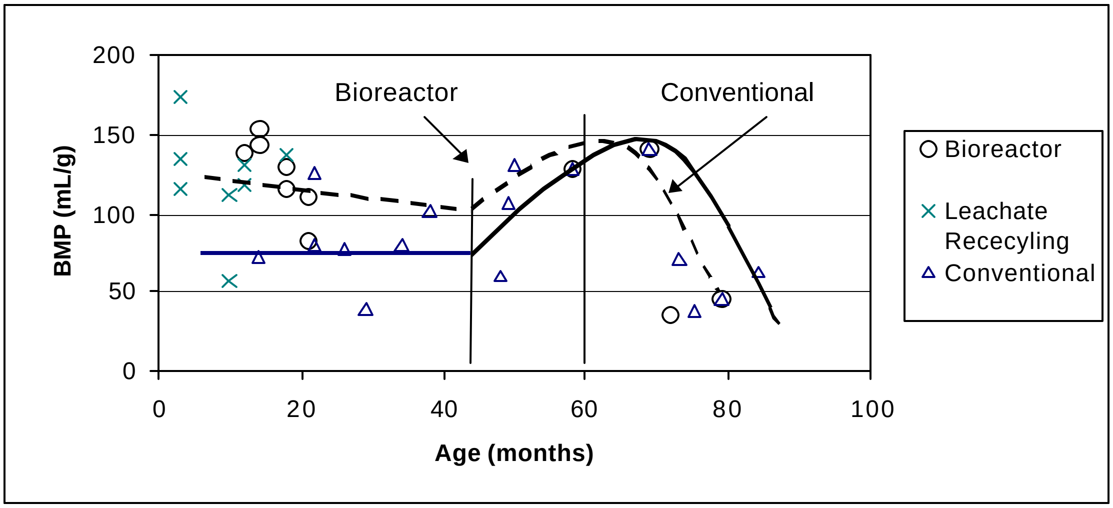


FIGURE 3-3. THE EFFECT OF CELLULOSE AND LIGNOCELLULOSES ON BMP AND VS DEGRADATION

The rate of methane production and volatile solid degradation is strongly related to the amount of degradable cellulose, hemicelluloses and lignin in the landfill and to their degradation behavior. In Figure 3-4a through Figure 3-4c the cellulose and lignin degradation in three different types of landfills is shown. Figure 3-4a presents bioreactor landfill data, where the cellulose, which is most likely free cellulose, is rapidly degraded. Free cellulose can be found in office paper, which is comprised of nearly pure cellulose. The available cellulose can be gone by the end of 8 years. The lignin is initially resistant to degradation until about 40 months when it starts to degrade in a similar manner as cellulose. Figure 3-4b shows conventional landfill data. The pattern is similar to the bioreactor landfill but with a slower degradation rate. The 40 months seems like a critical breaking point in this case as well. Additionally, in Figure 4b hemicelluloses are shown with a degradation rate of nearly zero until around 40 months. The rate parallel to the rate of cellulose and lignin degradation. The estimated time for lignin and hemicelluloses exhaustion is 9 years. The leachate recycling landfills, shown in Figure 3-4 c, are showing really fast cellulose degradation rate (slope = 0.93), but the available age data is limited, so the range from where the conclusions can be stated is very narrow, only one fifth of the previous age ranges. These early age data are very scattered and unstable, therefore these are not included in the other data sets.

From Figure 3-4 a through c it can be seen that cellulose is a faster degradable material than lignin and hemicelluloses. Therefore, the initial methane produced is coming mainly coming from cellulose degradation. Approximately five years later the slowly degradable lignocelluloses (lignin, hemicelluloses) start to break down as well. The availability and decrease in the amount of lignin and hemicelluloses can be seen in the BMP and VS versus age figures (Figures 3-2 and 3-3).

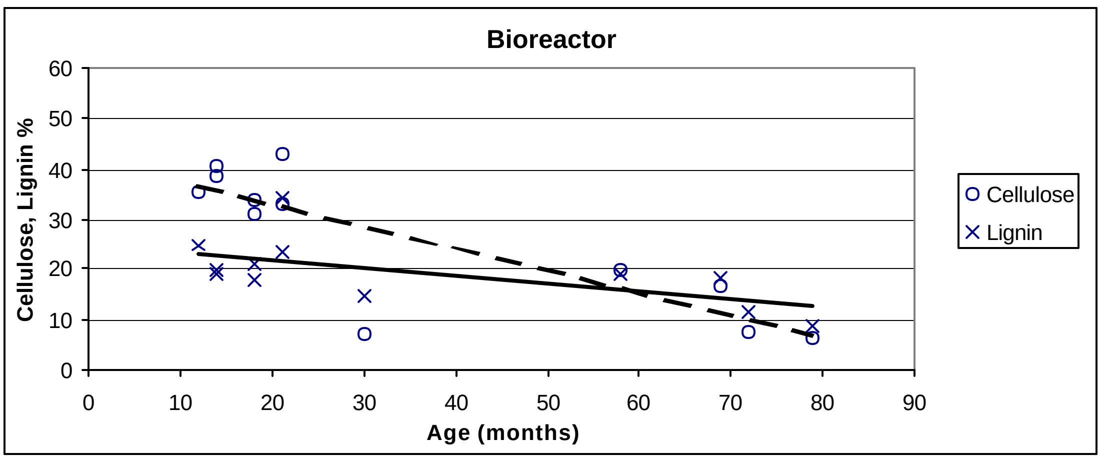


FIGURE 3-4 A. LIGNOCELLULOSES DEGRADATION IN BIOREACTORS

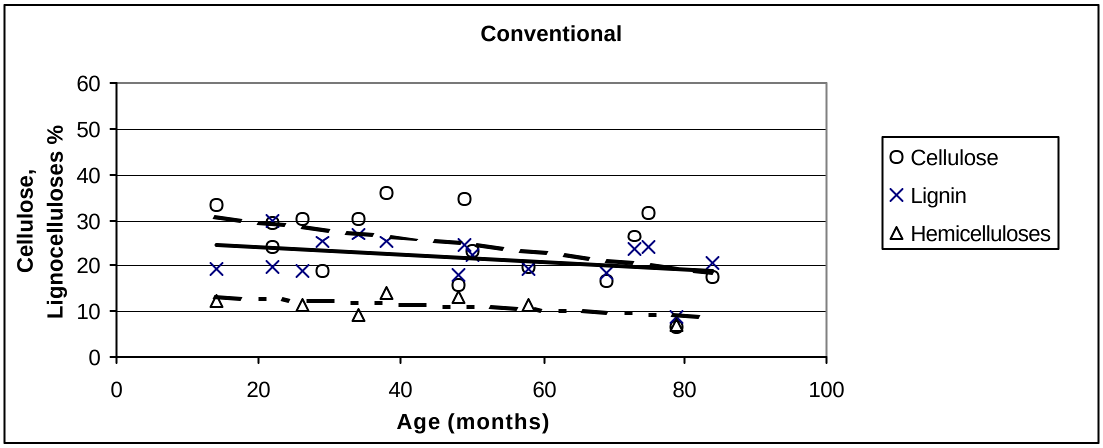


FIGURE 3-4 B. LIGNOCELLULOSES DEGRADATION IN CONVENTIONAL LANDFILLS

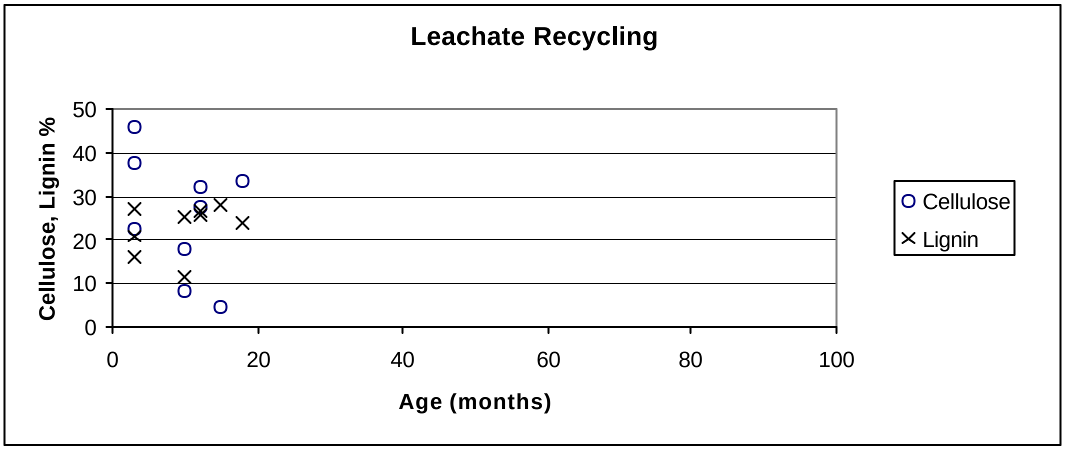


FIGURE 3-4 C. LIGNOCELLULOSES DEGRADATION IN LEACHATE RECYCLING LANDFILLS

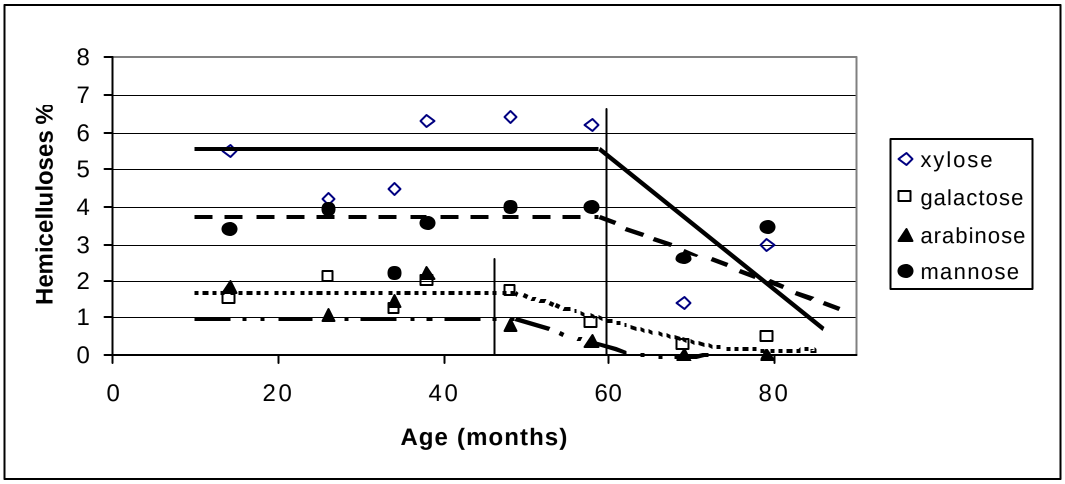


FIGURE 3-5. DEGRADATION OF HEMICELLULOSES FROM MAPLEWOOD AND SPRUCE RIDGE LANDFILLS

Figure 3-4 shows the degradation trend for cellulose, lignin and the sum of the hemicelluloses (xylose+ galactose+ arabinose+ mannose). Figure 3-5 shows the degradation of the individual hemicelluloses. The data are from the Maplewood and Spruce Ridge landfill control cells. The two major hemicelluloses are xylose (43 % of the total hemicelluloses) and mannose (28 %). Their degradation trend shows an initial lag until age 60 months, when they start to degrade. Arabinose (13 %) and galactose (16 %) are the two minor hemicelluloses; their degradation begins earlier than xylose and mannose. Instead of 60 months, arabinose and galactose start to degrade around 40-45 months, and they are gone within the next 30-40 months. By age 70- 80 months (6-7 years), arabinose and galactose are not detectable in landfill refuse.

Based on the data in Figure 3-3, the lignocelluloses begin to degrade around 4 years and this results in an increase in BMP. More insight can be gained in this degradation pattern from the data shown on Figure 3-6 a and b. These data show the relationship between lignocelluloses and cellulose. Figure 3-6 a and b clearly shows that the pattern of cellulose degradation has a significant influence on the time when the other lignocelluloses begin to degrade. It appears that the easily degradable cellulose, likely pure cellulose, degrades first and then the combined cellulose and hemicelluloses become biologically available. Lignin also degrades along with the hemicelluloses. This occurs when cellulose reaches a fraction of about 15-20%. This pattern might be related to development of different microbial populations and production of enzymes specific for degradation of the bound sugars. It could also occur as a result of the heat generated by degradation of the free cellulose. Further study of this pattern is needed because it appears to be critical to the stabilization of waste and in defining the benefits of landfill bioreactors.

By combining Figures 3-2, 3-3 and 3-6, it is clear that the easily decomposable cellulose is going to degrade significantly and in this period cellulose provides the majority of the BMP and VS degradation that takes place. For a landfill bioreactor, this time period is reduced from 5 to about 2 years. Once the cellulose declines to 15-20 percent, lignin and hemicelluloses decompose. Shortly before these begin to degrade, the BMP increases. The effect of added moisture to convert a landfill into a bioreactor on the degradation of this fraction will determine the design and benefits of landfill bioreactors.

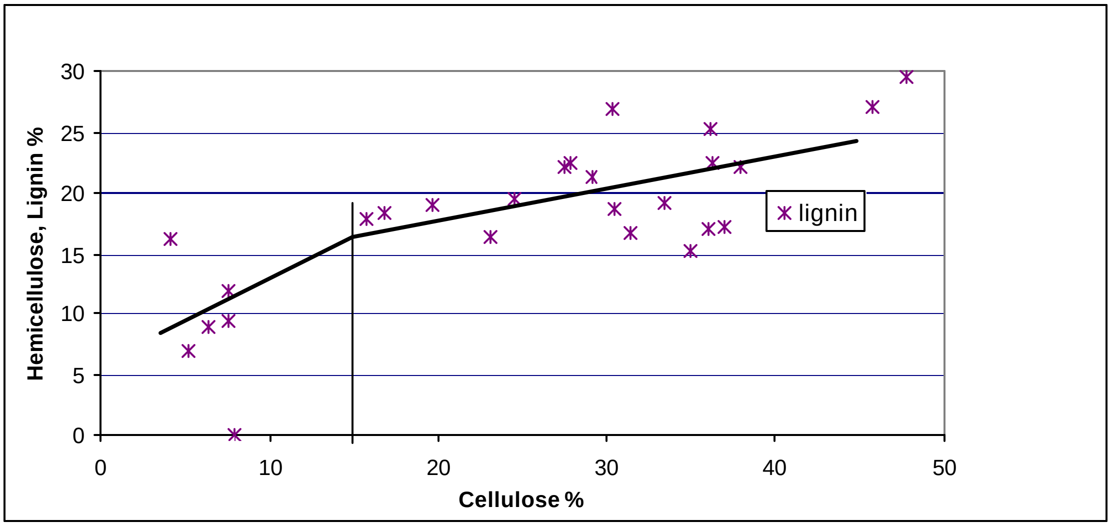


FIGURE 3-6 A. RELATIONSHIP BETWEEN CELLULOSE AND LIGNIN USING DATA FROM SEVEN LANDFILLS

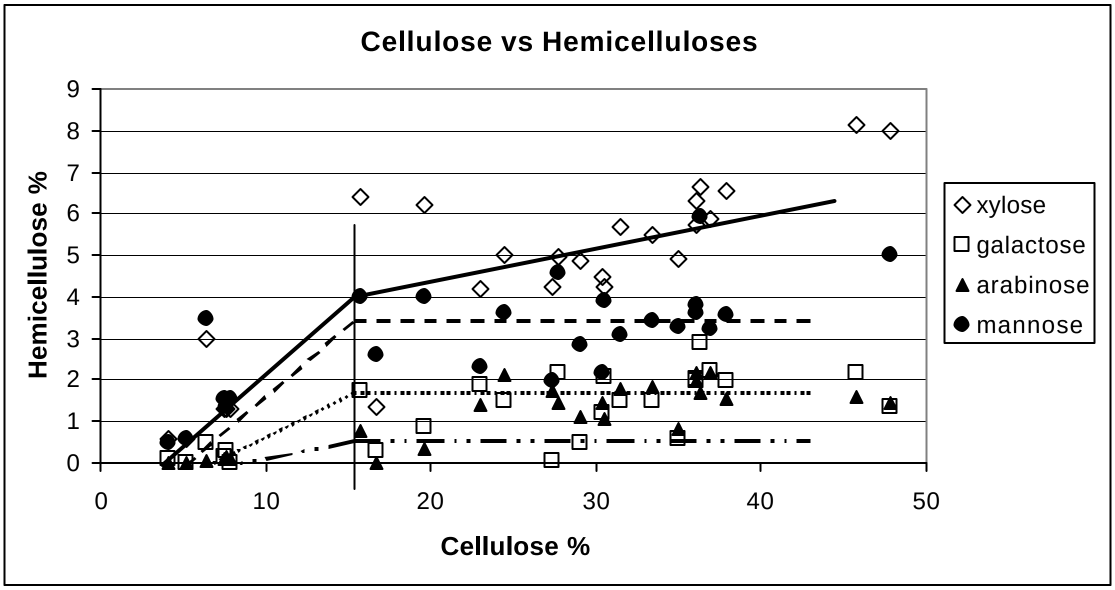


FIGURE 3-6 B. RELATIONSHIP BETWEEN CELLULOSE AND HEMICELLULOSES USINF DATA FROM SEVEN LANDFILLS

Conclusions

- Degradation of volatile solids and cellulose is much more rapid in bioreactor landfills compared to conventional landfills. Preliminary data suggests that the time to stabilization is reduced to about 1/3 that of conventional landfills.
- In the initial, rapid degradation phase, the primary degradation material is cellulose.
- After cellulose is reduced to a range of 15-20% of the waste, degradation of the remaining cellulose along with lignin and the hemicelluloses takes place.
- The onset of lignin and hemicellulose degradation is proceeded by an increase in the BMP.
- BMP is not the best indicator parameter of fresh MSW.

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CHAPTER 4
EVALUATION OF STABILITY PARAMETERS FOR DRY DENSITY AND SETTLEMENT IN CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

Abstract

Samples from several conventional and leachate recycle landfills were collected to evaluate the secondary settlement based on the effect of temperature and moisture and the relationship between the dry density and the traditional MSW parameters such as volatile solids (VS), cellulose, and lignin. It was found that the temperature at any given time may not provide enough information for accurate prediction of the settlement or dry density. Although, moisture addition was encouraged for MSW refuse degradation, but for settlement it is reduce compressibility. The relationship between dry density and VS, cellulose and lignin is reverse; therefore, as the MSW decomposes the dry density increases. It was also found that in leachate recycle landfills, the dry density is higher (2500 lbs/yd^3) than in conventional landfills (1500 lbs/yd^3). There is more available room for further MSW load, 40 percent volume increase, and the lifetime of the landfill can increase before closure.

Introduction

The reduction in the number of Municipal Solid Waste (MSW) landfill facilities along with the increase in their size has made it imperative to achieve maximum use of landfill volume. The settlement of landfills is caused by compression and waste decomposition and has been modeled using Terzaghi's soil consolidation theory, which includes secondary compression terms, or on rate process theories such as the power creep model presented by Edil (1990) and Ling et al (1998). Sower's approach is the most widely used (Yuen and Styles 2000), it considers primary and secondary consolidations separately. The landfill waste is very heterogeneous and has anisotropic material behavior. Therefore, characterization and evaluation of the settlement of these materials is more complex (Yuen and Styles 2000). Distortion, mechanical interaction such as long-term reorientation and delayed compression are dominant factors in waste compressibility (Park et al., 2002). Several factors effect the degradation and the decomposition of organic solids, such as temperature, moisture content, waste composition and nutrients.

MSW compresses under its own weight, and typically is 10 to 30 percent of its original height within the first two years of burial. After approximately 5 years, the compression-settlement decreases to less than 5 percent per year. Several field scale experiments have been conducted and have shown that MSW landfills with leachate recirculation provide rapid biodegradation and settlement (El-Fadel, M. and Al-Rashed, H. 1998; Wall and Zeiss 1995). The primary settlement of MSW waste occurs shortly after fill placement, i.e. within a few months. The major concern is to determine the rate and extent of secondary settlement (Ling et al 1998, Yuen and Styles 2000).

Although, settlement behavior has been measured, it has not been related to specific landfill chemical characterization parameters. Further, these physical and chemical parameters, beside settlement and MSW compaction, have not been evaluated in bioreactor, leachate recycle and conventional landfills.

The purpose of this study was to evaluate

- the secondary settlement based on the relationship between the dry density and the traditional MSW parameters such as volatile solids (VS), cellulose, and lignin in leachate recycle, and conventional landfill environments
- the effect of temperature and moisture on settlement in both lab and full-scale landfills.

Materials and Methods

In this paper, MSW samples were collected from both lab-scale and full-scale landfills. For the lab-scale analysis, seven columns were filled with fresh refuse from the Metro landfill, Milwaukee, Wisconsin. Meanwhile, for the full-scale study eleven landfills were tested.

Lab-scale columns

The seven columns were 8 feet in length, 18 inches in diameter, and made of 1-inch thick high-density polyethylene (HDPE). Four sampling pots were located along each column length at 1, 3, 5, and 7 feet. (Kelly 2002.)

Waste settlement was measured through a reduction in wire length within each column. Columns were constructed so that a 275 lb steel weight placed on a perforated plate rested upon the refuse inside each column.

Running hot water around the outside of the columns controlled the temperature in each column. The heat was retained by 3-inch fiberglass wrap around the columns. That retained temperature was measured and used in the analysis.

Full- scale landfills

Refuse samples came from eleven landfills operated as either bioreactor, leachate recirculation, or conventional. Waste was collected from various locations within the landfill and at different stabilization stages. Table 4- 1 summarizes the different types and operation and status of the landfills. The number of analyzed samples was more than 250.

TABLE 4- 1. SUMMARY OF SAMPLED LANDFILLS FOR FULL-SCALE ANALYSIS

Type of Landfill	Type of Operation	Status
Bioreactor		
King George, VA	Anaerobic	Bioreactor not in operation yet, 8 years old
Metro, WI	Aer/Anaer	Bioreactor and control, 1 year of operation
Middle Peninsula, VA	Anaerobic	3 years old
Spruce Ridge, MN	Anaerobic	6 years old
Leachate Recirculation		
Atlantic, VA	Anaerobic	3 years old
Evergreen, OH	Anaerobic	7 years old
Maplewood, VA	Anaerobic	Leachate recirculation cells not yet in operation, 8 years old
Conventional		
Green Valley, IL	Anaerobic	
Kettleman Hills, CA	Anaerobic	
Central, FL	Anaerobic	Filled in 1998, high amount of C&D waste
Riverbend, OR	Anaerobic	3, 8, 11 years old, very wet

The methods used for parameter characterization, including on-site and offsite analytical measurements, are described in the following sections.

Sampling

MSW landfills were sampled using a drill rig outfitted with a 36-inch bucket auger to collect refuse from different depths. The MSW wet density was obtained in the field using a realistic approach. Each ten-foot segment was placed into a roll-off box and weighed. This weight divided by the volume determined the wet field density. The dry density was calculated from the wet density and the measured moisture content. Both wet and dry densities are reported in pounds per cubic yard (lbs/yd^3).

Ten-pound samples were collected from the top, middle, and bottom of each ten-foot section and shipped to Virginia Tech, Blacksburg, VA in coolers. Samples were received from various landfill sites (Appendix A) wrapped in HDPE plastic bags, double bagged, secured via duct tape to ensure air-tightness and housed in commercially available ice-coolers. These were stored in a laboratory freezer at $4^{o}C$ to retain the in-situ moisture and pH of the waste.

Laboratory Analysis

In the laboratory, several parameters were measured in order to characterize stability. These parameters were pH, moisture content, volatile solids, cellulose, the major hemi cellulose sugars (xylose, mannose, arabinose, and galactose), lignin, and biochemical methane potential.

The moisture content was measured according to method 2540-B (APHA et al., 1995). For this analysis, 500-1000 g of wet, unshredded MSW were put into an aluminum pan and dried at 105 ^{o}C until constant weight. (Usually less than two days.) The moisture content is expressed as percentage of the weight loss during drying divided by the original weight.

The volatile solids were measured using the 2540-E method (APHA et al., 1995). A 100-200 mg sample of dry, milled refuse was placed into an aluminum pan, and then into a muffle furnace (550 ^{o}C) for 20 minutes (after that no additional weight loss was expected). The reported volatile solids are the percentage by weight of refuse lost.

The pH was measured by mixing 50% (by weight) wet unshredded MSW sample and distilled water into a 1 L glass beaker. When the mixture reached equilibrium at 20 ^{o}C (about 5 hours), the pH probe was placed into the beaker and the reading was obtained.

Cellulose was measured by applying AST Method E 1758-95^{e1} (1995). This method was chosen, because it is suitable for materials found in municipal solid waste samples. The dried, shredded 300 ± 10 mg samples were taken out from plastic bags used for keep its moisture and properties, and placed into a 16x100 mm glass tube. The cellulose was hydrolyzed in two stages to convert cellulose and hemicelluloses into their sugar monomers. In the first stage, 3.00 ± 0.01 mL of 72% w/w sulfuric acid (H_2SO_4) was added to the samples and stirred till completely mixed, and then the glass tubes were placed into the 35 ^{o}C water bath for one hour. In the second stage, the digested samples were transferred into 250 mL septa bottles with 84 mL of nanopure water dilution. The bottles were autoclaved for an hour at 121 ^{o}C and 15 psi. After autoclave cycle completion, the bottles were allowed to cool down for 20 minutes at room temperature. The samples were filtered using standard TSS glass fiber filters. The volatile suspended solids remaining after the 550 ^{o}C muffle furnace was considered to be lignin.

The filtrate was neutralized to pH between 5-6 using a slurry form of $Ba(OH)_2$. The barium(II) sulfate precipitate was centrifuged and then filtered though a 0.45 micrometer pore size membrane and a reversed-phase cartridge. Finally, the glucose was detected using HPLC with reflective index detector and HPX-87C column.

The biochemical methane potential (BMP) was modified from a procedure developed by Barlaz (Shearer et al. 2001). Two hundred milligrams of dry, shredded MSW were added to a 250 mL Boston round septa bottle. Then, 100 mL of revised anaerobic media was added to each bottle. The media was made following Barlaz's methods except for two modifications. The vitamin solution was not included, and anaerobic digester biosolids from the Peppers Ferry anaerobic digester, Fairlawn, VA were added as inoculums at 10% by volume (Stinson and Ham et al 1995.) The bottles were incubated for 45 days at 35 ^{o}C. One-liter Teflon gas sampling bags were connected to each bottle at the end of the incubation period for twenty minutes while agitating the bottle to relieve excess pressure. A 100 micro liter sample was taken from the gas-sampling bag and injected into a GC with a carbosieve packed column and flame ionization detector (FID). The volume of gas in the gas-sampling bag was measured using a 60 mL plastic syringe. This test was run in triplicate with one blank for every six bottles. The amount of methane measured in the blanks was deducted from that of the samples. The BMP was reported in units of milliliters of methane per gram of dry MSW at STP (mL CH_4/g).

Results and Discussion

The dry density of the MSW refuse measured on-site increased as VS and lignocelluloses decreased due to biological degradation. There are four main mechanisms involved in settlement. They are mechanical (distortion, crunching and reorientation), ravelling (movement of fine particles into large voids), physical-chemical change (corrosion, oxidation, combustion) and bio-chemical decomposition (fermentation, decay) (Edil et al., 1990). Therefore, the dry density increases as the particles in the MSW refuse go thorough distortion, reorientation and compression (Park et al., 2002). The solid waste compresses under its own weight, as well as under the additional weight of the new load (Edil et al., 1990). Therefore, the density increases closer to the bottom of the landfill. The degradation and decomposition of the refuse is affected by the landfill operation. The operation can apply moisture and add nutrients to enhance the degradation, and can control the temperature in the landfill. The temperature, moisture, and the gas present or generated within the landfill are environmental factors that affect the magnitude of the settlement. The magnitude of settlement can be influenced by other factors such as initial refuse density or void ratio, content of decomposable materials, fill height, and leachate level and fluctuation (Edil et al., 1990).

Several studies showed that refuse decomposition in leachate recycle and bioreactor landfills is faster than in conventional landfills (Townsend et al., 1996; Metha et al., 2002; Shearer et al., 2001.). Therefore, it was expected that the settlement would be more significant and the primary consolidation would be faster in the leachate recycle and bioreactor landfills than in traditional landfills.

The data in Figure 4-1 shows the relationship between dry density and VS, cellulose, and lignin of the refuse. The data represented in Figure 4-1 was gathered from six landfills. The dry density increased with the decrease in VS, cellulose, and lignin content of the refuse. More compaction and denser environment had been reached where the waste has been there longer and more decomposition had been accomplished. It was expected that the density would reach its maximum at the bottom of the landfill. However, the highest density was not always at the very bottom of the landfill. According to the data from these six landfills, the maximum density more often occurs at the layer above the bottom of the landfill.

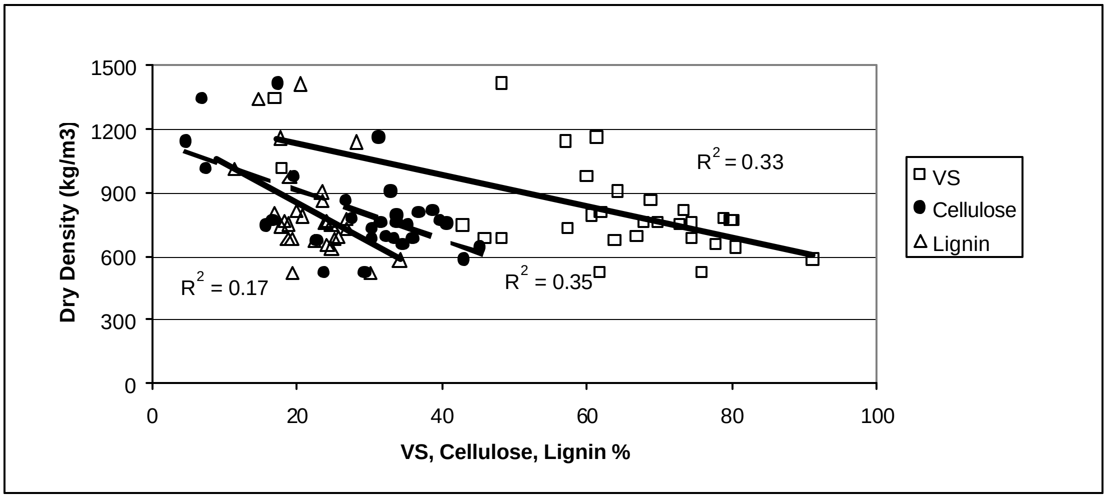

FIGURE 4-1. RELATIONSHIP BETWEEN DRY DENSITY AND VS, CELLULOSE AND LIGNIN BASED ON DATA FROM SIX DIFFERENT LANDFILLS

The average moisture content in leachate cycle is 42%; while in the conventional landfill it is 33%, with standard deviations of 10 and 12, respectively. Figures 4-2 through 4-4 show how the moisture content in different landfill operations affects the physical and biochemical properties of the refuse. Figure 4-2 shows the relationship between the volatile solids and dry density. It indicates an inverse relationship; as the VS decreases the dry density increases. In the leachate recycle landfill, the degradation rate is faster (slope=30) and the relationship between the two parameters is stronger (R^2=0.62) than for the conventional landfill, where the degradation is very slow (slope = 10) and also the correlation is poor (R^2=0.16). The same trend is observed in Figures 4-3, 4-4 and 4-5. That is, the dry density for the leachate recycle landfills is much greater as the refuse is degraded compared to conventional landfills.

In Figure 4-3, the relationship between cellulose and dry density (lb/yd^3) in both conventional and leachate recycle landfill can be seen. In conventional landfills, the dry density changes little over a wide range of cellulose values. However, in the leachate cycle landfill, a 10 % decrease in the cellulose resulted in a 500 lb/yd^3 increase in dry density. The relationship between the two parameters was stronger (R^2=0.57) than in the conventional landfill (R^2=0.06).

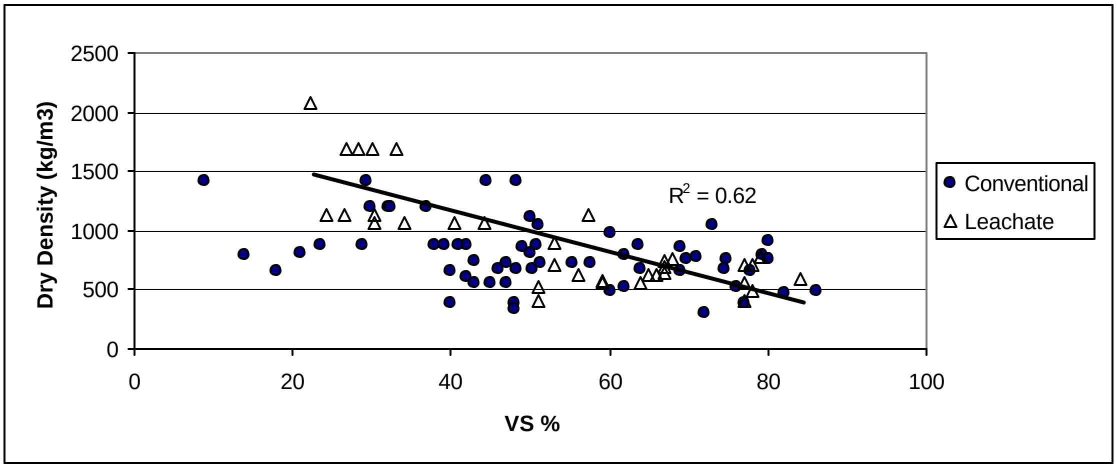

FIGURE 4-2. RELATIONSHIP BETWEEN DRY DENSITY AND VS IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

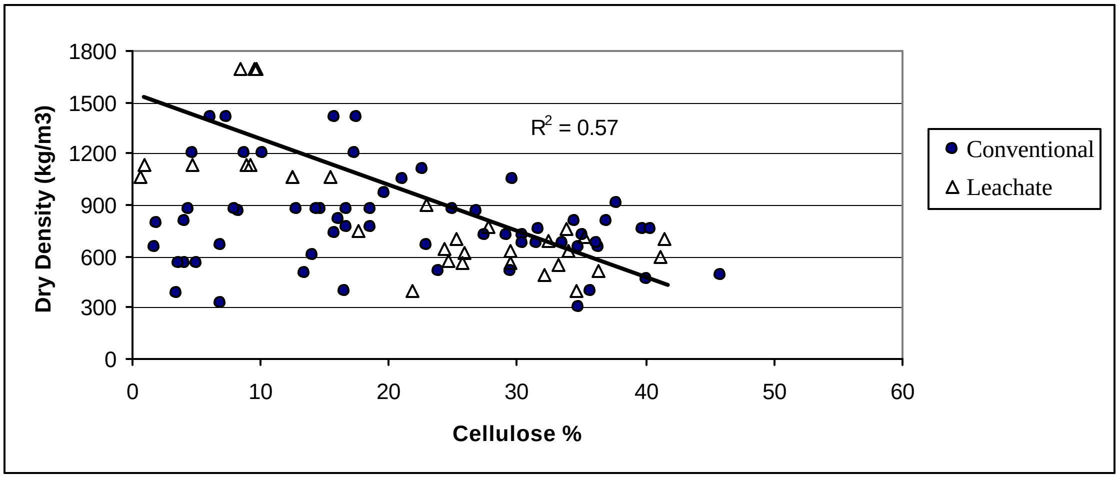

FIGURE 4-3. RELATIONSHIP BETWEEN DRY DENSITY AND CELLULOSE IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

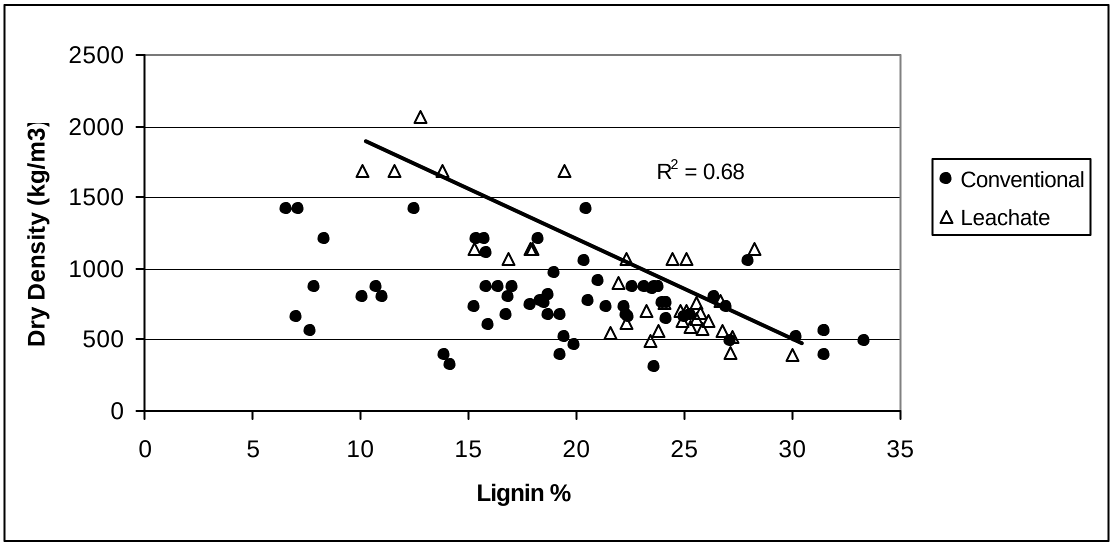

FIGURE 4-4. RELATIONSHIP BETWEEN DRY DENSITY AND LIGNIN IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

Figure 4-4 displays the relationship between lignin and dry density. The trend seen in the graph is the same as previously seen for VS and cellulose. In the leachate recycle landfill there is a strong relationship with a moderately high R^2 value (0.68).

All the figures indicate that in the leachate recycle landfills, the dry density and, therefore, the settlement can reach higher values. This indicates that the available room for further MSW is greater and potentially more MSW can be placed into the same landfill where leachate is recycled. Therefore, the applied operation can increase the volume of MSW placed into the landfill, and increase its lifetime before closure. The magnitude of the volume increase can reach 40 percent. When cellulose is gone and the lignin reaches 10- 15 % (just plastics remain) the dry density for leachate recycle is around 1500 kg/m^3, and for conventional it is just 900 (Figures 4-3 and 4-4). Therefore, by using a mass balance, the increase in volume would provide 40 percent more volume.

The decomposition of the waste can be affected by several factors such as temperature, pH, water content, nutrients, etc. (Park et al 2002). Figure 4-5a demonstrates the correlation between temperature and settlement of refuse based on the lab-scale study. The experiments were conducted by Ryan Kelly (2002.). In the figure, column points and a control point are distinguished. The control data point was taken from a column where neither temperature nor moisture was added, and it reached 2 inches settlement. The other column points in the figure indicates that temperature enhances the decomposition of MSW refuse, and that this relationship is very strong (R^2= 0.98). The higher the temperature, the bigger the settlement. In Figure 4-5b, the data from the conventional landfill shows the same phenomenon, however the data from the leachate recycle landfill shows opposite results. The reason for that behavior is shown in Figure 4-5c, where the relationship between temperature and cellulose are presented. It can be seen that in the leachate recycle landfills, the fresh MSW, high in cellulose, is warmer, than the decomposed refuse. Based on the phenomenon shown in Figure 4-5b, knowing the temperature at a given time may not provide enough information for accurate prediction of the settlement or dry density.

Figures 4-6 and 4-7 show the moisture effect on settlement and dry density. Figure 4-6a demonstrates the correlations between the moisture and the settlement in refuse based on the lab-scale study conducted by Ryan Kelly (Kelly 2002.). The figure indicates that moisture enhances the decomposition of the MSW refuse, even though the strength of the correlation is significantly lower (R^2=0.23) than for temperature. According to the lab-scale study, even though the correlation is not very strong, increase in moisture content caused an increase in settlement. The data from the landfills show a different result (Figure 4-7). Figure 6c indicates that the moisture content in the fresh refuse is higher than in the old decomposed MSW; and as the MSW refuse decomposes, it loses its moisture content and gets denser. This relationship can be seen in Figure 4-6b.

In contrast to Figure 4-6, the data from the seven landfills indicates that in a drier environment the density can be higher (Figure 4-7). Figure 4-7 shows the relationship between dry density and VS, cellulose and lignin with varying refuse moisture content. Landfills based on their moisture content were sorted into three main categories. In the dry moisture content category the average moisture content was 25 %. Into this group the control cells of Spruce Ridge and Evergreen were placed. The medium moisture content with an average of 38%, included samples from the bioreactor cells of Spruce Ridge, Middle Peninsula and from Maplewood landfills. The third category, the wet, had an average of 55 % moisture content. In this group Riverbend and Atlantic landfills were included. According to the figures, the drier the refuse the reachable dry density was higher. It is a very interesting phenomenon because elevated moisture contents are advised for higher degradation rates. However, too high a moisture content can have its draw backs; the density of the refuse cannot go beyond 800 kg/m^3. The dry density can be as high as 1500 kg/m^3 when the refuse considered is dry. It suggests that initial moisture addition to enhance biodegradation and initial compression can be undesirable for secondary settlement. The reason is that the pores of the MSW refuse are filled with water and it cannot reach as high a density as drier refuse. The water in the pores inhibits the pushing of refuse particles into the voids, so the density cannot reach its maximum value. It suggests that the ideal amount of moisture changes with the stage of landfill refuse degradation. Moisture content addition is important for degradation enhancement, but after it is completed the moisture should be taken out to enhance settlement, and secondary compression.

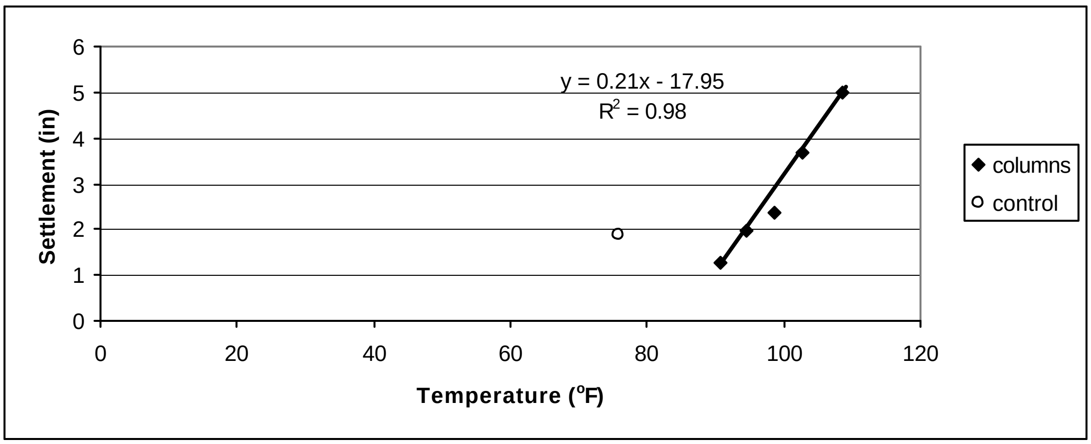

FIGURE 4-5A. EFFECT OF TEMPERATURE ON SETTLEMENT. DATA FROM KELLY, R. (2002)

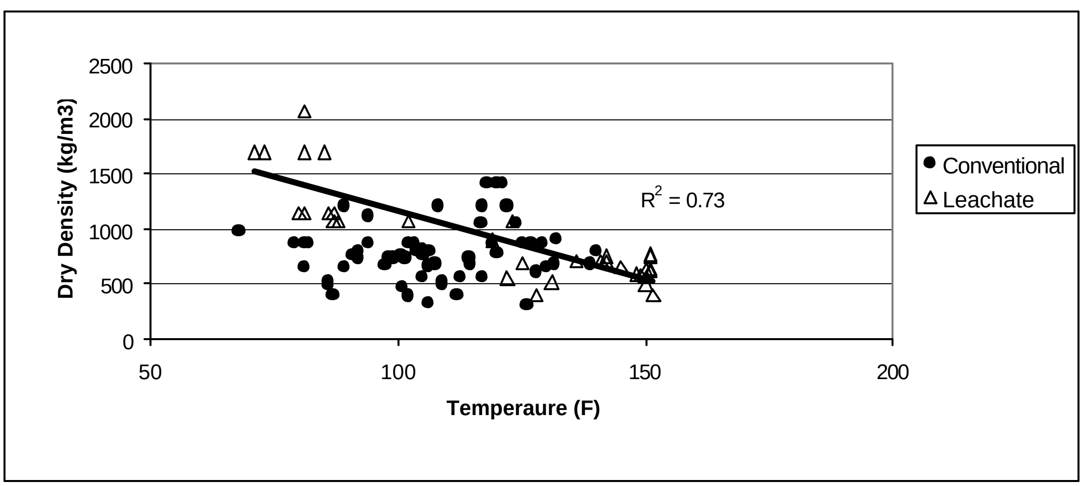

FIGURE 4-5B. EFFECT OF TEMPERATURE ON DRY DENSITY IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

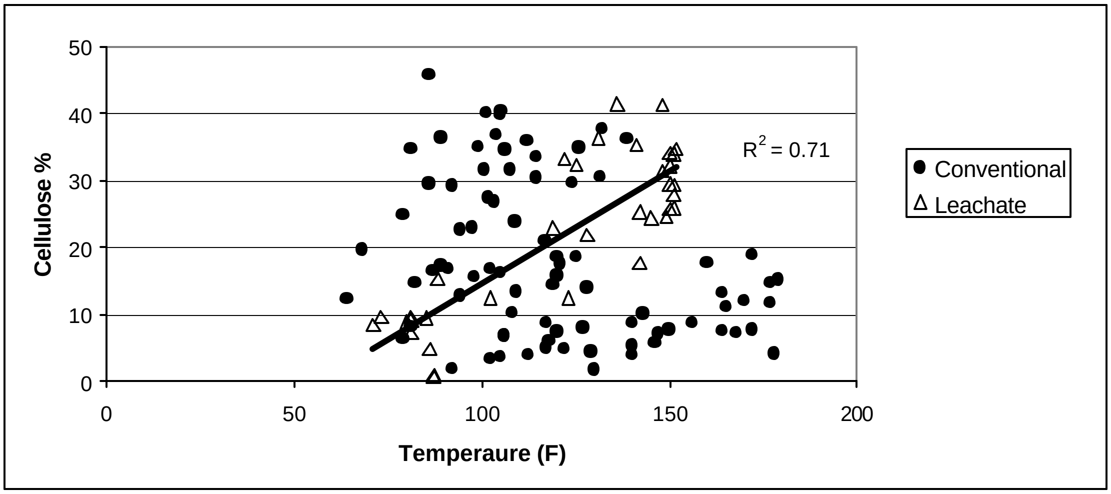

FIGURE 4-5C. RELATIONSHIP BETWEEN TEMPERATURE AND CELLULOSE IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

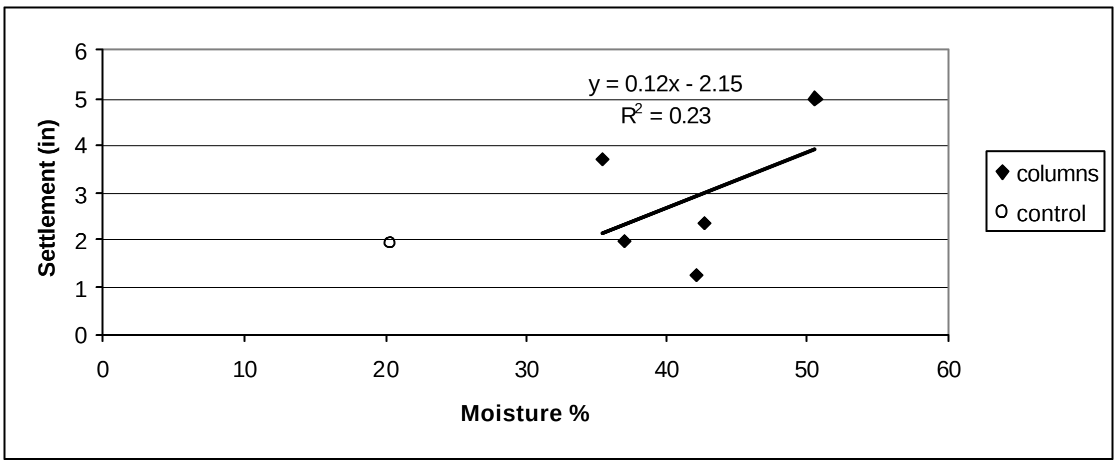

FIGURE 4-6A. EFFECT OF MOISTURE ON SETTLEMENT. DATA FROM KELLY, R. (2002)

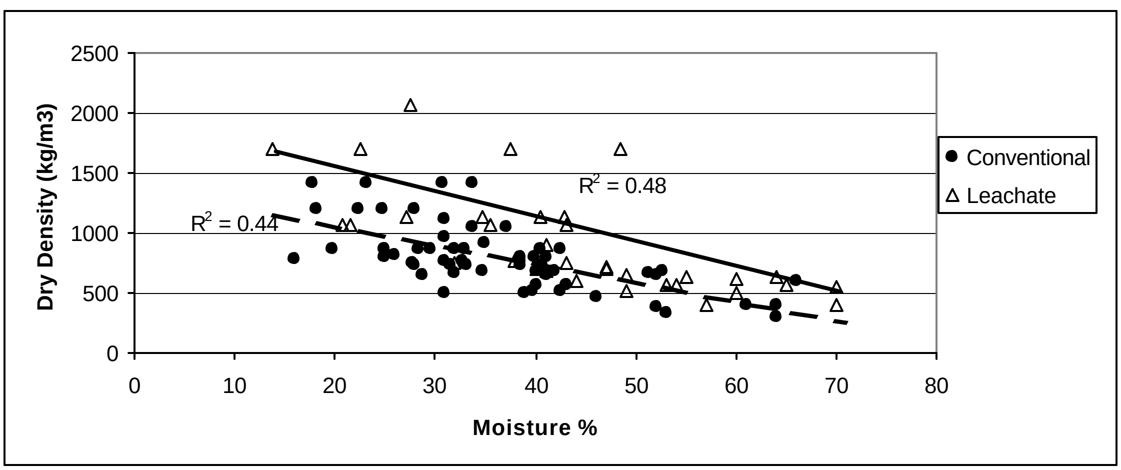

FIGURE 4-6B. EFFECT OF MOISTURE ON DRY DENSITY IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

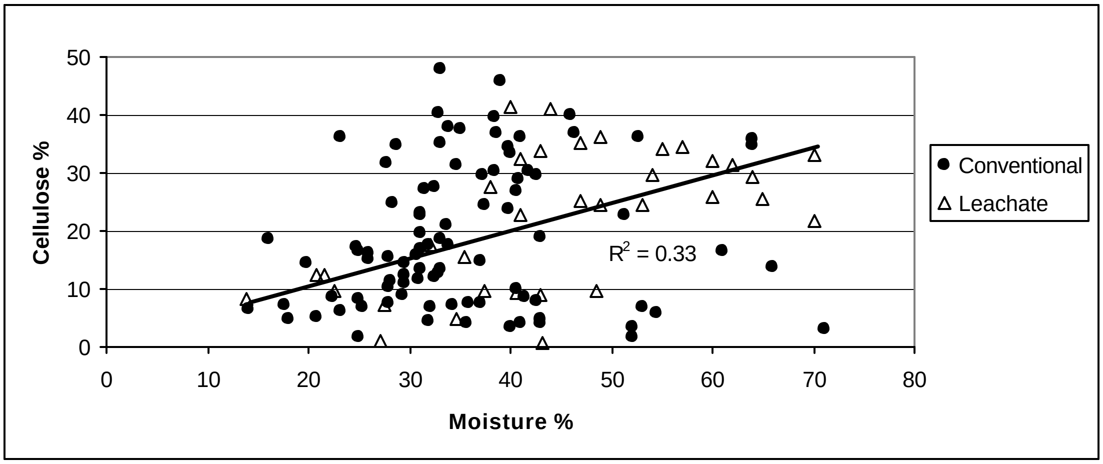

FIGURE 4-6C. RELATIONSHIP BETWEEN MOISTURE AND CELLULOSE IN BOTH CONVENTIONAL AND LEACHATE RECYCLE LANDFILLS

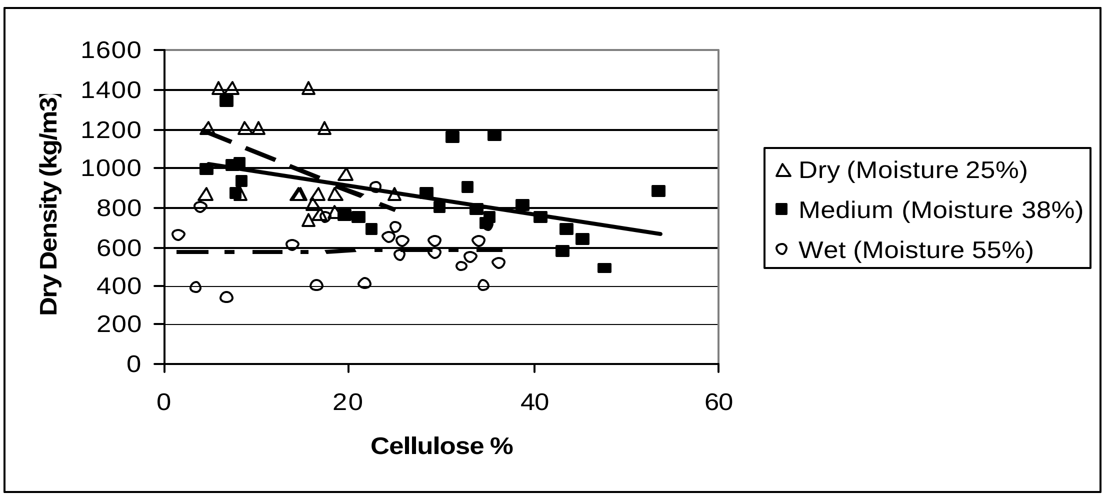

FIGURE 4-7A. RELATIONSHIP BETWEEN CELLULOSE AND DRY DENSITY IN THREE DIFFERENT MOISTURE CONTENT

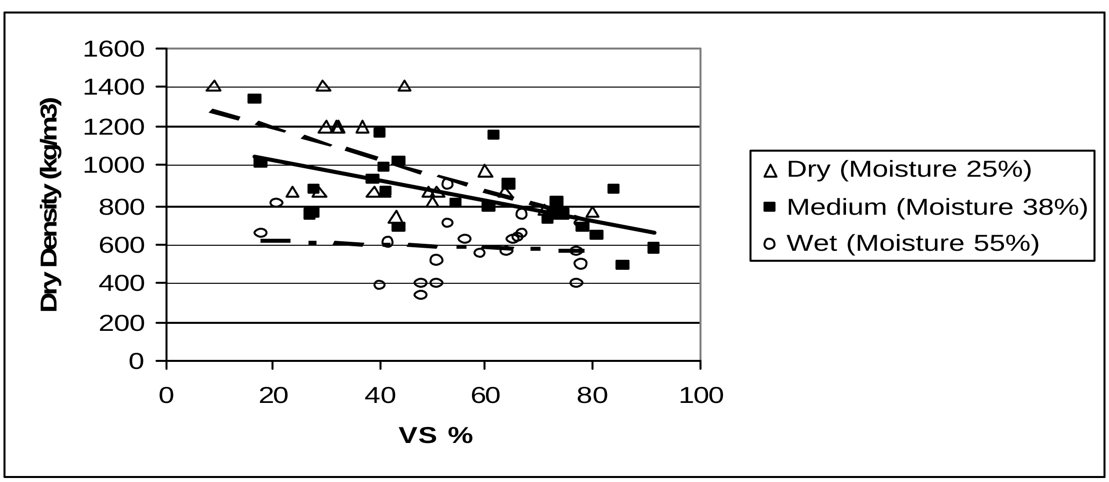

FIGURE 4-7B. RELATIONSHIP BETWEEN VOLATILE SOLIDS AND DRY DENSITY IN THREE DIFFERENT MOISTURE CONTENT

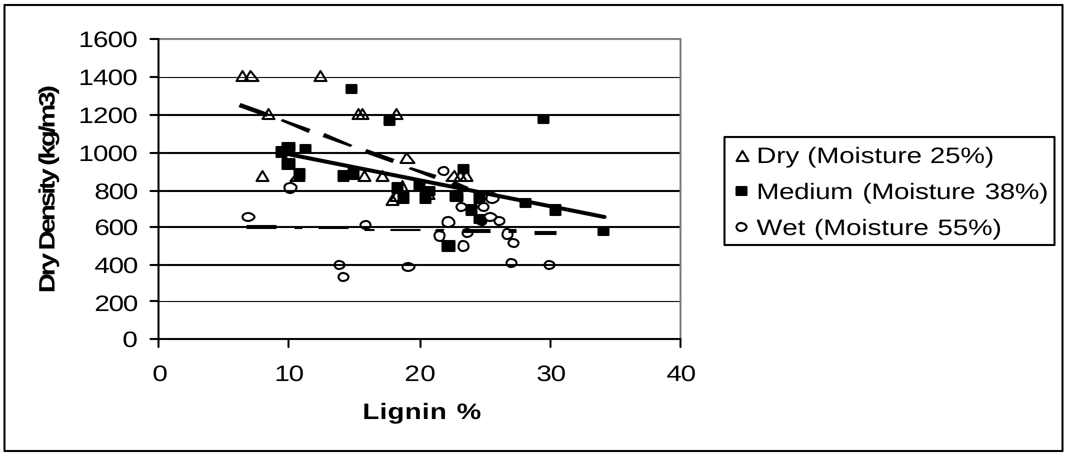

FIGURE 4-7C. RELATIONSHIP BETWEEN LIGNIN AND DRY DENSITY IN THREE DIFFERENT MOISTURE CONTENT

Conclusions

- There is an inverse relationship between dry density and VS, cellulose and lignin; as the MSW decomposes the dry density increases
- In leachate recycle landfills, the dry density is higher than in conventional landfills. There is more available room for further MSW load, and the lifetime of the landfill can increase before closure
- Measuring the temperature at any given time may not provide enough information for accurate prediction of the settlement or dry density
- Moisture addition is encouraged for MSW refuse degradation, but discouraged for settlement

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