THE USE OF SELECTED WASTE PRODUCTS FOR THE RECLAMATION OF EXISTING MSW LANDFILL SITES

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ABSTRACT

This paper presents an overview of a recently patented technology which defines the process of using selected waste products to assist in reclaiming existing municipal solid waste landfill sites [1]. The process involves the pressurized injection of these materials into the void spaces of existing landfill sites to both manage the waste product and assist in reclaiming the site. Depending on the waste type, the process could result in structural stabilization, accelerated biodegradation and/or enhanced gas recovery at the site. Waste-types that can be used in the process include fine-grained wastes and sludges. Fine-grained wastes included ash products from solid waste, wood, coal or sludge combustion facilities. Dredged spoils consisting of fine-grained sands, silts and clays can also be used in the process. Municipal wastewater treatment plant sludge used in the process offers the benefit of accelerated biodegradation and enhanced gas recovery due to the introduction of moisture, nutrients, and seed microorganisms (methanogenic bacteria) into the landfill site. The characteristics of landfills which make them suitable for the aforementioned process and methods of injection are reviewed along with the physical, biological and chemical effects on the landfill site. The paper focuses on the use of municipal wastewater treatment plant sludge and its effect on reclaiming the landfill site.

INTRODUCTION

Landfill sites, or portions of these sites that have exhausted their disposal capacity, are in many cases unesthetic landmarks, land areas that are unsuitable for development, and potential sources of both water and air pollution. Conventional landfill management techniques including capping of these landfills with impermeable geomembranes or low permeability soils (e.g., clay). Capping is designed to eliminate the percolation of rainwater through the landfill and the resulting leachate from contaminating groundwater. Although such an approach limits the amount of leachate produced in a landfill, it also effectively mummifies the landfill, reducing access to critical moisture required for microbial degradation. This management approach is a site maintenance strategy rather than a site reclamation strategy.

Recent interest concerning the final disposition of landfill sites has focused on new technologies that attempt to reclaim the site, rather than simply maintain the site. These technologies attempt to achieve this objective by either accelerating the rate of biodegradation of the landfill site, assisting in consolidating the materials within the site for volume reduction and/or structural stabilization, or by extracting and recycling materials from the site.

Controlled landfilling of municipal solid waste (MSW) is a method of landfilling that has been utilized to accelerate the rate of biodegradation of the organic matter in the waste and to increase the rate of production of methane gas [2]. The primary methodology consists of adding buffers, sewage sludge, and sewage treatment plant effluents to the municipal solid waste stream by premixing the refuse and these additives, prior to landfilling. Premixing of MSW with sludge assists in producing a landfill environment more suitable for biological activity. Other operations that have been proposed to provide a more suitable environment for biodegradation and methane generation have included the layered landfilling of refuse and sludge, and the recirculation of landfill leachate or other wastewater effluents onto the landfill.

Methods for consolidating landfill sites have been proposed to increase the volumetric capacity of the air space available at landfill sites. Consolidation also assists in structurally stabilizing the site by compacting and stiffening the landfill to provide a subsurface more suitable for supporting overlying structures. Landfill consolidation has been tried by imposing static surcharge loadings (e.g., stockpiles of soil) on the fill, by use of additional roller and bulldozer compaction [3], and by the process of dynamic compaction [4, 5]. Dynamic compaction consists of dropping a weight from a crane to consolidate the materials within the fill.

Landfill mining [6] has been proposed as a means to reclaim portions of the landfill site by excavating the landfill and processing materials through a processing plant that can segregate composted biodegradables, soils, and ferrous metal from the remaining materials (i.e., plastics, aluminum, wood, rubber, glass, etc.). Given available markets, composted waste and soils could be used as landfill cover and ferrous metal, plastics, aluminum, etc., could be diverted to recyclers.

Although each of the above technologies provide potential solutions, they are limited in their applicability due to the complex chemical, biological and geotechnical nature of municipal solid waste landfill sites, as well as the uncertainty of recycling markets (i.e., in landfill mining applications).

Controlled landfilling or layered landfilling concepts could conceivably enhance the degradation of a fill, however these processes are limited in practicality due to the difficulty of prehandling and mixing the refuse with additives prior to landfilling. In addition, these concepts do not offer options for enhancing biodegradation at existing landfill sites, where the refuse has already been deposited in the fill. Recirculation of landfill leachate or other effluents into the landfill could assist in increasing moisture content and perhaps nutrients in existing landfill sites; however, such measures provide little control over the distribution of liquids percolating through the landfill, and potential short circuiting, clogging and/or puddling of these liquids within the landfill.

Consolidation and stiffening of a landfill resulting from processes such as surcharge loadings, roller compaction and dynamic compaction are technically feasible; however, such processes cannot control expansion or rebound of the fill material, nor do they account for continued biodegradation and the subsequent physical deterioration and settling that will inevitably occur in the landfill environment.

The success of a landfill mining operation is in great part dependent on the relative degree of degradation at the landfill site and the ability to market materials recovered from the site. Recent evidence [7] indicates that degradation of organic matter within a landfill, due to the lack of suitable conditions for biological activity, is a slow and sometimes nonexistent process. A site which is only partially degraded is not a suitable candidate for landfill mining.

This paper describes a process that involves the pressurized injection of selected finegrained waste products and sludges into the void space that exists within municipal solid waste landfills. The selection of certain waste products for injection into the landfill environment is a process that offers the opportunity to accomplish several objectives: *(a)* to manage and beneficially use selected waste products; *(b)* to exploit the inherent porosity and waste management capacity that exists within MSW landfills; and *(c)* to structurally, chemically and/or biologically stabilize the landfill site. The process can be used on both active and inactive landfills, both before and after final capping.

Although the injection of materials, other than waste products, could conceivably produce the same stabilizing effects as selected waste products, such an approach using virgin products would be economically prohibitive. The costs associated with this approach, using waste products, is offset by the disposal cost associated with the selected waste.

The remainder of this paper presents a description of the geotechnical characteristics of landfills, the unused volumetric capacity that exists within MSW landfills, the process of landfill injection, enhanced physical and biological stabilization associated with the subject process, an overview of the economic issues, and potential physical impacts to the landfill site.

LANDFILL CHARACTERISTICS

The exact composition of materials that comprise a municipal solid waste landfill is a reflection of the past and present service area of the fill. In almost all cases, however, the composition can be expected to consist of a heterogeneous mix of residential, commercial and some industrial wastes. The behavior of this heterogeneous mix of materials in the landfill environment depends on several factors. These include the composition of the fill, the method of landfilling, and the meteorologic, hydrologic and geohydrologic environment of the fill. Together, the aforementioned factors produce a complex interaction of physical, chemical and biological processes that characterize the nature of the fill. To quantitatively express this complex system is a difficult task. Nonetheless, it is possible to make several simplifying generalizations about the character of MSW landfills, and from these generalizations it is possible to both qualitatively and quantitatively examine the nature of an MSW landfill site:

(a) Landfills will settle and consolidate.
(b) Landfills are highly permeable.
(c) Biodegradation can be expected to occur.
(d) Landfill gas will be generated.

Although quantitative geotechnical information on the character of landfills is limited, reported data are consistent with the aforementioned observations.

Landfilled Materials

Landfills settle and consolidate and are highly permeable because much of the material placed within the landfill is highly compressible and biodegradable. When these materials are stockpiled or landfilled in a random manner, they tend to produce a fill with high void spaces. Biodegradation of the organic matter continues to produce void spaces over the actively degrading life of the fill.

Table 1 provides an estimate of the types and relative quantities of materials which make up a typical municipal solid waste landfill [9, 11–13]. Table 1 also provides a qualitative assessment of the relative amount of void space, degree of compressibility, and biodegradability that each major material component is expected to exhibit in a stockpile or landfill cell.

Given the predominance, in terms of percentage by weight, of highly compressible materials, materials that produce high void spaces, and materials that degrade, it can be expected that a composite of these materials, even when compacted using conventional landfill compaction techniques and equipment, will produce a fill that will be highly porous, compressible, permeable and degradable.

Unit Weights

Sowers [8] reported a unit weight of uncompacted fills ranging from approximately 200 to 500 lb/cu yd depending on the amount of metal and debris in the fill. For compacted fills, he reported unit weights up to 1000 lb/cu yd. Landva [9] reported in-situ unit weights tested at a number of landfills in Canada to be in the range of approximately 200–450 lb/cu yd. Present day well operated landfills with compaction reportedly achieve unit weights ranging from 800 to 1400 lb/cu yd [10].

Moisture Content

The moisture content of the materials contained in municipal solid waste landfills are highly variable. Moisture contents (i.e., wet weight) ranging from approximately 10% to 50% have been reported [8]. Higher levels could be encountered in saturated zones where moisture is not free draining.

Porosity and Permeability

Sowers [8] reported typical void ratios[1] ranging from 15 in uncompacted fills to two in well compacted fills. These data suggest a highly porous fill. Landva [9] formulated an equation for calculating the unit weight of a landfill by assuming fractions of each material in the fill, the unit weight of each material, and their respective moisture contents. By using porosities[2] ranging from 30% to 60%, Landva [9] was able to fit his equation to observed field conditions. Landva also reported coefficients of permeability in test pits ranging from 1×10^{-3} to 4×10^{-2} cm/sec, reflecting a highly permeable and porous medium.

Penetration Tests

Sowers [14] and Mabry [15] presented the results of subsurface investigations of landfill sites using standard penetration tests (ASTM C1586). Standard penetration tests are field tests which measure the energy required to penetrate subsurface formations. Figures 1 and 2 provide profiles of boring logs, showing typical cross sections of landfills, and standard penetration test results [14]. Although standard penetration test values have not been correlated with the field behavior of an MSW landfill, when penetrating municipal solid waste, the results of these tests, as illustrated in Figs. 1 and 2,

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[1] Void ratio = volume of voids/volume of solids.

[2] Porosity = volume of voids/total volume.

TABLE 1 QUALITATIVE ASSESSMENT OF LANDFILL MATERIAL BEHAVIOR IN FILL ENVIRONMENT

Landfill Component	Typical % by Weight	Void Space[1]	Compressibility[2]	Degradability[3]
Garbage/food waste	10-40	High	High	High
Paper/cloth	20-60	High	Medium	Medium
Lawn/garden	10-20	High	High	High
Plastics	2-15	High	High	Low
Hollow and massive metal	5-15	High	Medium	Low
Rubber/tires	5-10	High	Low	Low
Lumber & demolition	1-5	High	Low	Medium
Rubble	1-10	High	Low	Low
Glass	5-15	Medium	Low	Low
Cover/soil	10-20	Medium	Low	Low

1. Anticipated porosity when randomly fitted and compacted in a landfill:
   - High: >40%
   - Medium: 20-40%
   - Low: <20%

2. Anticipated percent consolidation:
   - High: >20%
   - Medium: 10-20%
   - Low: <10%

3. Relative degree of degradability:
   - High: Readily degradable monomers and low resistant polymers
   - Medium: Slowly degradable and resistant polymers
   - Low: Inorganic corrodible and non-degradable materials

are always less than 10 blows per foot. Higher results were recorded when penetrating rubble sections (Fig. 2), or soil sections of the landfill. Standard penetration test values of less than 10 blows per foot are typical of loose, soft and compressible soil formations with low relative density and high void spaces.

Settlement

Landfill settlement is related to the initial void ratio and the loading applied to the fill [16]. Relationships between void ratio and applied pressure have been used to predict landfill settling rates [8, 17].[3] Gifford [2] summarized settlement data reported by others and attempted to compare the results by examining settlement in terms of strain (%)[4] versus time. Gifford's results indicate anticipated strains of 1–6% within 10 years. Much of this settlement could occur within the first year.

Biodegradation and Methane Generation

Given adequate moisture, nutrients and seed organisms, the anaerobic environment within MSW landfills will result in the biodegradation of organic waste materials and the corresponding production of landfill gas. Approximately 45–55% of this gas, by volume, will consist of methane, and the remainder primarily carbon dioxide [2]. Methane gas recovery is presently practiced at numerous landfills around the country for both safety reasons (to control the migration of this

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[3] $\blacktriangle e = C_c \log(1 + \blacktriangle P/P)$,
where $\blacktriangle e$ = change in void ratio, C_c = compression index, $\blacktriangle P$ = change in pressure, and P = total initial pressure.

[4] Strain (%) = (settlement/depth of fill) × 100.

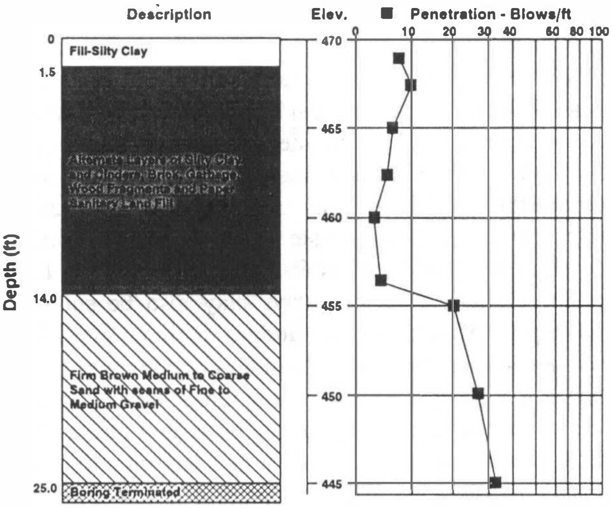

FIG. 1 TEST BORING IN REFUSE DISPOSAL ZONE OF SANITARY LANDFILL IN CENTRAL GEORGIA [14] (Courtesy of the American Society of Civil Engineers)

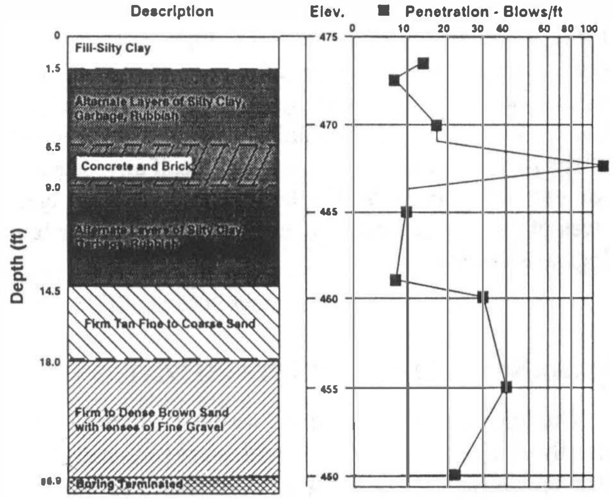

FIG. 2 TEST BORING IN RUBBLE ZONE OF SANITARY LANDFILL IN CENTRAL GEORGIA [14] (Courtesy of the American Society of Civil Engineers)

potentially explosive gas) and for methane utilization (energy recovery).

Theoretical methane generation from an MSW landfill is approximately 5 cu ft/lb of dry waste [18]. Actual production is generally one-third to one-half this amount, and recovery potential is 10% of that amount (i.e., 0.5 cu ft/lb). The lack of optimum conditions for methane generation undoubtedly plays a major role in the actual production of methane in the landfill environment. Optimum methanogenesis can be expected to occur at moisture contents of 60–80% [2, 18]. Another important factor for cell growth is the carbon to nitrogen (C/N) ratio and the nitrogen to phosphorus (N/P) ratio. For optimum anaerobic fermentation the C/N ratio should be in the range of 20–30. Since the C/N ratio in MSW can exceed 80, the large C/N ratio in MSW landfills can limit methane production [19]. The N/P ratio should be greater than 5 for optimum anaerobic activity. Buivid [19] demonstrated that the introduction of appropriate nutrients into a deficient environment could increase the rate of biodegradation and gas generation by more than two orders of magnitude.

UNUSED VOLUMETRIC CAPACITY OF EXISTING MSW LANDFILLS

The unused volumetric capacity (or pore space) in existing landfills is dependent on the age of the fill, the type of wastes in the fill and the method of landfilling. The effective porosity of the fill is the volumetric capacity of the landfill that is available for injection. It is estimated, based on a review of available information and experience of the authors in grouting landfill sites, that the volumetric capacity or the porosity of most landfills will range from 30% to in excess of 60%, well compacted fills being in the lower range of 30% and poorly compacted fills in the range of 60%.

These estimates suggest that there is significant untapped capacity available in existing MSW landfills to manage many suitable waste materials. Figure 3 illustrates the volume available in the landfills with 50- and 100-ft heights, respectively, as a function of landfill area. For example, a 125-acre, 100-ft high landfill, with an effective porosity of 30%, has an estimated unused capacity of approximately 6,000,000 cu yd.

LANDFILL INJECTION

Grouting is the injection of pumpable materials into a media such as soil or rock to change the physical properties of the formation. The injection of wastes into a landfill environment makes use of the same equipment and operations that are commonly used in subsurface grouting technology.

There are numerous methods of grouting, however the two methods most applicable to the subject process are slurry or permeation grouting, and compaction grouting.

Slurry or permeation grouting is the oldest method of grouting presently in use. It consists of injecting a liquid slurry into subsurface pore spaces to fill in the existing voids. Compaction grouting is the injection of

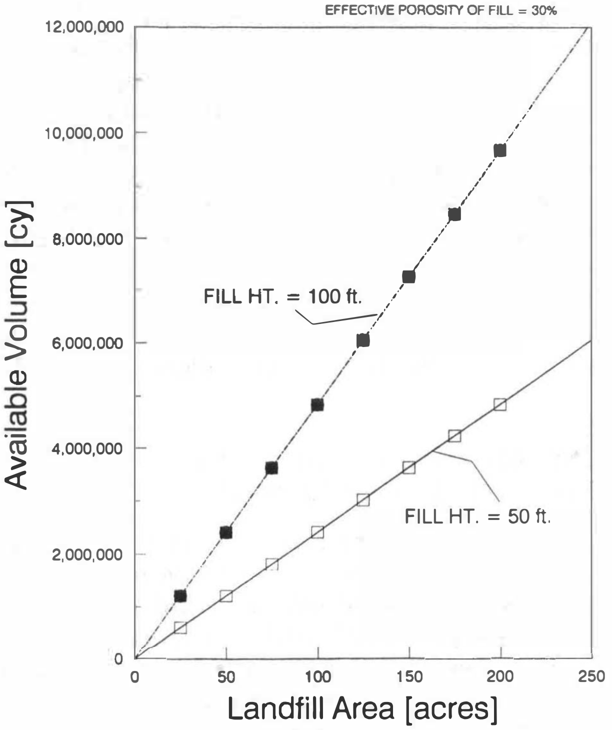

FIG. 3 LANDFILL INJECTION CAPACITY

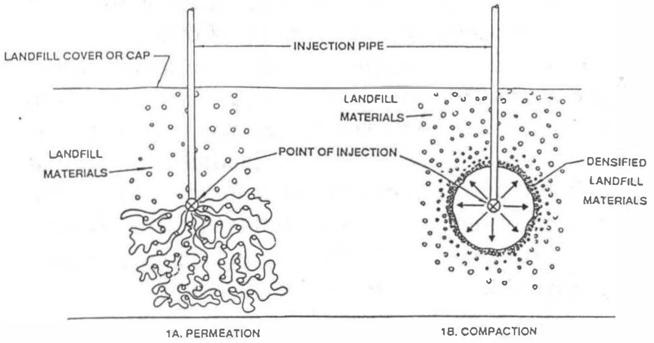

FIG. 4 SUBSURFACE INJECTION PROCESSES

very low slump material under high pressure for the densification and improvement of characterization of fills or soft soils. It has been used for remedial, new construction and karst terrains [20, 21]. Figure 4 provides a schematic that depicts the subsurface behavior of materials injected into a landfill environment for each respective method. A mix of slurry and compaction grouting is most applicable to the landfill injection processes.

Planning and implementation of a landfill injection scenario includes the development of a primary and secondary injection system to monitor the flow rate, pressure and extent of permeation of the waste within the landfill environment.

Wastes that are most suitable for injection are fine-grained wastes or wastes that have been preprocessed to a small grain size and liquified; or semi-liquid sludges. Examples of fine-grained waste are ash products from combustion facilities. This can include ash products from municipal solid waste, coal, wood, and sludge combustors. Dredged spoils, which consist of fine-grained sands, silts and clays may also be suitable. Examples of semi-liquid sludges include municipal wastewater treatment plant sludges and flue gas desulfurization sludges. These fine-grained wastes and/or sludges are in a form, or can be processed into a form that is a flowable and can be injected into the void spaces within a landfill. The types of waste products and additives that are preferable are those that can both exploit the volumetric capacity of the landfill and at the same time accelerate processes for reclaiming the landfill site by enhancing the physical and biological stabilization of the site.

Various materials can be added to the selected waste form, such as hydraulic cement, lime, coal fly ash, buffering agents, water and plasticizers. These additives can assist in adding strength to the waste form, adjust the permeability, pH, flowability and moisture content of the mix and fill. The type of additive, if any, selected for use will depend on the landfill reclamation objectives of the application (i.e., enhanced physical or biological stabilization).

ENHANCED PHYSICAL STABILIZATION

The injection of fine-grained wastes that consist primarily of inorganic materials, which are physically similar to aggregate materials such as sand, gravel and mineral filler, can be used to physically stabilize existing landfill sites. Injection of fine-grained wastes into the void spaces of landfills can be used as structural columns or foundations to transmit the weight of overlying structures to underlying formations capable of serving as the basic supporting medium. Mineral waste types that have specific applicability in physical stabilization processes are municipal solid waste combustion ash, dredged spoils, coal fly ash and flue gas desulfurization sludges.

The structural and environmentally-related properties of these wastes can be enhanced by mixing some of these waste products with hydraulic cement, lime, mixtures of coal ash and lime, or other stabilizing agents and water prior to injection to produce a concrete-like structure to be used as the structural sup-

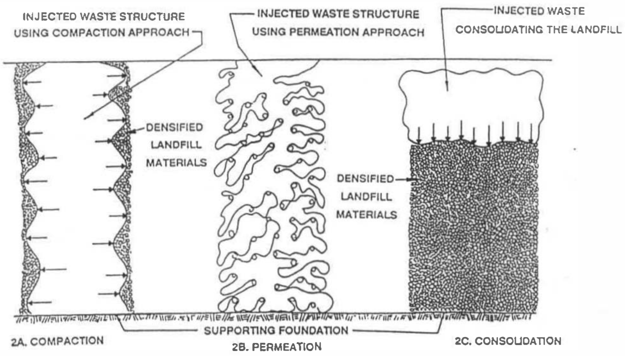

FIG. 5 STRUCTURAL RECLAMATION OPTIONS

porting material. The waste product can be introduced into localized areas in a manner that will produce vertical columns, similar to cast-in-place piles to support footings; or can be injected to permeate as much of the void space of selected sections of the fill as possible to increase the bearing capacity of the fill itself.

An alternative to the continuous injection of waste down to a firm, stable support, below the waste fill, is the injection of waste into the top of the fill to promote consolidation and more rapid subsidence of the fill. Injection of waste materials into the upper layers of the fill could be introduced in such a manner as to produce overburden pressures on the fill, thereby increasing the consolidation or settling rates of the fill. The end result of this activity would be the lowering of height of the landfill at a more rapid rate than that which would occur if the landfill were left to consolidate under natural conditions.

Figure 5 provides a schematic representation of these physical stabilization options.

ENHANCED BIOLOGICAL STABILIZATION

As previously outlined, the efficiency of methane gas production (quantity and rate), and the rate of degradation of the organic fraction of the wastes present in municipal solid waste landfills are dependent on an environment in which the moisture content, pH, population of anaerobic organisms, available organic materials, and nutrients are in proper balance. In municipal solid waste landfill environments, such a balance is rarely achieved. As a result, methane production and biodegradation rates are extremely slow, and in much of the landfill, biodegradation is virtually nonexistent. This is primarily due to the lack of adequate amounts of moisture and nutrients.

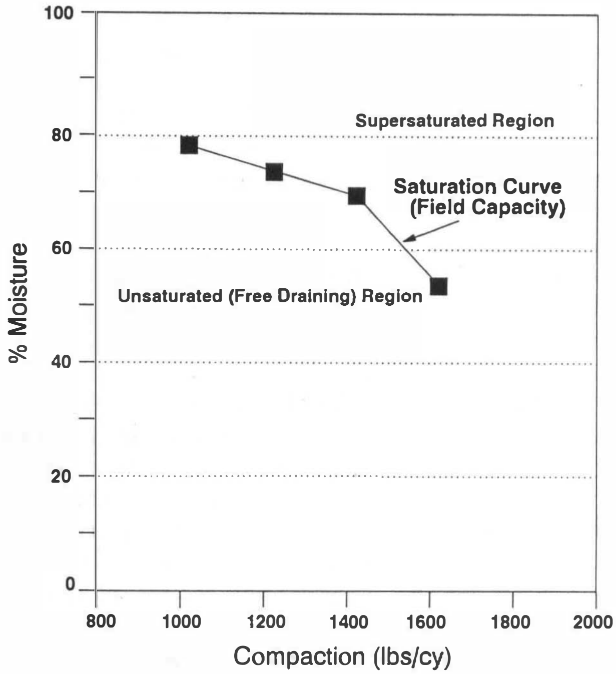

FIG. 6 FIELD WATER CAPACITY OF MSW (Courtesy of Elsevier Science Publishing Co., Inc., adapted from Ref. [19])

The introduction of sewage sludge and appropriate additives into a landfill site by means of controlled injection provides a means to produce an environment in which the moisture content of the solids within the landfill is as close to saturation as possible; to create an environment in which the carbon to nitrogen ratio is approximately 20 to 30; the nitrogen to phosphorus ratio is greater than 5; to ensure that sufficient buffer is available to maintain the pH of the environment between 6.7 and 7.2; and to ensure that the population of methanogenic bacteria are sufficient to metabolize the complex organic materials within the fill to methane and carbon dioxide.

Estimates of the quantity of waste required to saturate a given mass of municipal solid waste, along with the nitrogen and phosphorous content of the organic sludge to be injected, could be used to estimate the quantity of sludge which should be injected per unit volume of landfill, as well as additional additives which may be necessary to control the pH of the control volume for optimum methanogenesis. The result would be a more rapid degradation of the organic content in the landfill and the extraction of landfill gas at several times the rate of current landfill gas recovery systems.

Figure 6 shows an experimentally determined landfill saturation curve for compacted MSW, expressed as percent moisture versus pounds per cubic yard of MSW [19]. The results suggest that at a typical 800–1200 lb/cu yd landfills, 75–80% moisture content (by wet weight) represents approximate saturation levels. The goal of any injection process is to avoid supersaturation of the landfill environment. A high moisture content of 60–80% (wet weight) reportedly favors maximum methane production [18]. The introduction of municipal wastewater treatment plant sludge at a 10% solids content into a landfill in a ratio of one ton of wet sludge to one ton of MSW with a moisture content of 30%, and a unit weight of 1000 lb/cu yd will produce a moisture content of approximately 60% and a suitable environment for enhanced degradation.

In cases where additional moisture may need to be added to the waste form to achieve the proper moisture content for waste flow, landfill degradation, or structural stabilization (e.g., cement hydration), landfill leachate, if recoverable, can be used as the water source. This approach provides a means to manage the leachate and water balance of the fill without the addition of excess moisture.

Enhanced landfill degradation results in more favorable landfill gas recovery economics and a real potential for future reclamation of the landfill site due to the rapid and controlled degradation of the site. Whereas a site with poor environmental conditions may take several decades or even centuries to degrade (e.g., if capped), the use of controlled injection could assist in reclaiming the site in a fraction of the time.

Many biological reactions in which there are no rate limiting conditions (e.g., moisture, nutrients, toxic inhibitors) have been quantitatively defined using first order reaction rate models in which the rate of decomposition is directly proportional to the substrate concentrations. Ham et al. [22] suggested the use of first order reaction models in landfill degradation applications.

Assuming that biological decomposition in a landfill can be expressed by such a model, then

$$\frac{dC}{dt} = -kC$$

where

C = concentration of degradable material remaining after time t

$\frac{dC}{dt}$ = rate of decomposition

k = reaction rate

TABLE 2 PROJECTED BIODEGRADABLE DECAY RATES

	Fill Content (% Wt.)	Half-Lives (Years)	Decay Coef, k (1/yr)
Readily Degradable	15	1.5	0.46
Moderately Degradable	50	25	0.028
Non-Degradable	35	∞	--
		Weighted k	0.13

Integrating the above expression with respect to time yields the expression

$$C/C_0 = e^{-kt}$$

where

C_0 = initial concentration of degradable material at $t = 0$, and

C/C_0 = fraction of degradable material remaining after time t.

Ham [22] presented assumptions concerning the half-life of three categories of wastes in a landfill environment. These categories included readily decomposable waste products, moderately decomposable waste products and refractory or non-decomposable waste products. Ham [22] assumed half-lives of 1 year and 15 years, respectively, for the readily decomposable and moderately decomposable fractions, respectively. Using similar categories for wastes in New York State landfills, the New York State Energy Office reported half-lives of 1–1.5 years for readily degradable material and approximately 25–30 years for moderately degradable material [18].

Assuming that 15% of the waste stream consists of readily decomposable material, 50% moderately decomposable and the remaining refractory materials, weighted first order decay rates can be calculated based on the aforementioned half-lives. Table 2 presents the results of this calculation assuming half-lives for the readily decomposable fraction of 1.5 years and the moderately decomposable fraction of 25 years. The result is a composite decay rate, k, of 0.13/year.

A decay rate of 0.13/year is based on conditions in which the biodegradation is generally not inhibited by lack of moisture, toxic inhibitors, nutrients, etc. As previously discussed, this may not be the case in some landfills or in parts of others. In addition, capping of landfills will almost certainly create an environment that is moisture limiting.

Figure 7 is a semilog graph that illustrates the projected time frame required for degradation of a landfill under selected decay rates, k, of 0.06, 0.04, 0.2 and 0.01/year. These decay rates are intended to illustrate

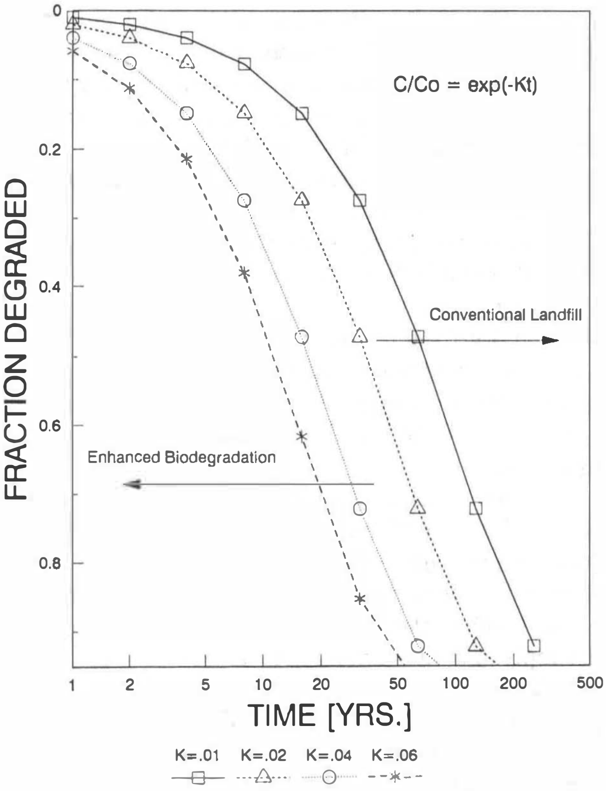

FIG. 7 LANDFILL DEGRADATION TIME SCALE

the anticipated longevity of most fills given present plans for capping. It is projected that conventional landfills could take from 50 to in excess of 250 years to biodegrade given present plans to cap MSW landfills. It is estimated that enhanced biodegradation would result in decay coefficients of at least one order of magnitude greater than this ratio, resulting in landfill degradation within a 5–25-year time frame.

ECONOMIC ISSUES

The management of municipal wastewater treatment plant sludge is a problem in many regions of the country. The State of New York generates approximately one million dry tons of sludge per day [23]. The State of New Jersey generates approximately 900,000 dry tons of sludge per day [24]. The Ocean Disposal Dumping Ban Act of 1988, which prohibits ocean disposal after December 31, 1991, coupled with the planned closure of many landfills in the Northeast portion of the U.S., has generated a need for the consideration of new innovative technologies for sludge management. The cost for disposal of sludge in many of these localities will range from $100 to over $200 per wet ton.

The economics of the landfill injection process are dependent on several factors:

(a) Transportation of the waste to the landfill and the landfill tip fee ($\$T$).

(b) The quantity of material available for injection, and the length of the negotiated injection contract ($\$I$).

(c) The increased rate of gas extraction (i.e., methane) and the monetary value of the energy recovered ($\$E$).

(d) The estimated value of landfill site, when reclaimed ($\$L$).

Given the above, the unit cost of managing municipal wastewater treatment plant sludge in a landfill using landfill injection technology can be estimated by means of the following equation:

$$\$C = (\$T + \$I) - (\$E + \$L)$$

where all costs are expressed in units of dollars per wet ton of sludge and,

$\$C$ = Unit cost
$\$T$ = Landfill tip fee
$\$I$ = Injection cost
$\$E$ = Energy revenues
$\$L$ = Land reclamation value

An economic analysis is presented below as an illustration. Assuming a 1-year operating contract for the injection of 100 wet tons per day, a landfill tip fee including transportation of $40/wet ton, an injection cost of $35/wet ton [25] and zero energy and land reclamation revenues, the cost of managing the sludge at the landfill site would be $75/wet ton. In equation form, $\$T = \$40$; $\$I = \$35$; $\$E = \$0$ and $\$R = \$0$, resulting in $\$C = \$75$. This cost is very competitive with present costs in many areas in the Northeast U.S.

In addition to the aforementioned economic and land reclamation benefits, the management of sludge or other wastes at existing MSW landfill sites, eliminates the need for siting new waste disposal facilities since disposal capacity is available within the sites which were previously thought to be unusable.

POTENTIAL IMPACTS OF LANDFILL INJECTION TO THE LANDFILL MASS

The injection of waste products into landfills on the scale proposed in this process is an activity that could potentially physically and chemically modify the solid waste mass in the landfill. There is little practical field experience to quantitatively define the exact impacts that this activity could have on the landfill environment.

Although the injection of grouting material into a landfill environment has been previously attempted and documented [21], the objectives of previous applications were primarily attempts to structurally stabilize the landfill to prevent settlement of the fill. As a result, the operating objectives of these applications included the goal to minimize the quantity of material (i.e., grout) injected into the landfill to keep injection costs as low as possible. The objectives of the subject process differ insofar as the application is intended to maximize the quantity of material (i.e., waste product) injected rather than minimize the injection quantity. It is noteworthy that the previously attempted applications experienced little economic success because of the relatively large void spaces and large quantities of expensive grouting material required to achieve the desired objectives.

Given the lack of field experience with the proposed process, there are a number of potential issues which need to be considered in the design and construction of landfill injection so that the treatment does not detrimentally affect the landfill environment. Some relevant issues include:

(a) Extra vertical loads on a leachate collection system and liner that exceed the bearing capacity of the system.

(b) Potential for clogging the leachate collection system with fines.

(c) Potential for impacting the bearing capacity and slope stability of the solid waste mass.

(d) Potential for side slope leakage.

(e) Odor problems.

The potential for adversely impacting the landfill environment in any one of the aforementioned ways is a waste and site specific issue. To ensure that these detrimental impacts do not occur requires an examination of the field conditions at the particular landfill site, the characteristics of the waste(s) in the fill, as well as the characteristics of the final waste form to be injected. In addition, close monitoring of field injection pressures and waste flow will be required to closely monitor the landfill response to the injection process.

Since there is little field experience with the implementation of the proposed activity as outlined, implementation of the technology will require field demonstrations to more fully assess some of the above issues and appropriate operating parameters.

SUMMARY

During the latter part of the 20th century, most communities relied heavily on landfills to manage their wastes. The result is a landscape dotted with mountains of covered refuse. Given present landfill management practices, these landfills, which will ultimately be capped will remain on our landscape into the twenty-first and perhaps twenty-second centuries.

In addition, as a society we continue to generate high volume, low toxicity-type wastes, such as municipal wastewater treatment plant sludge, MSW combustor ash and coal ash that will continue to require management. Although recycling of many of these wastes will assist in diverting a portion of these materials into usable products, it is unlikely that sufficient markets will be available to manage all of these materials. The result will be new landfills that will need to be sited in new locations.

The technology presented in this paper provides the potential means to integrate landfill reclamation and waste management technology in a manner that produces both beneficial environmental and economic impacts. It offers the potential means to reclaim instead of simply maintain landfill sites. It makes use of existing landfill sites, eliminating the need for new disposal capacity; and can be integrated into capping strategies to provide a means to manage and reclaim the landfill, even after capping has been completed.

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