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Landfilling of Water Treatment Plant Coagulant Sludges

Subject Area:
Water Treatment
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Water Treatment Plant
Coagulant Sludges

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Foreword

The AWWA Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of grass-roots consultation with subscribers, members, and working professionals. Under the umbrella of a Five-Year Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection.

This publication is a result of one of those sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the foundation staff and large cadre of volunteers who willingly contribute their time and expertise. The foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The foundation's trustees are pleased to offer this publication as a contribution toward that end.

Disposal of water treatment plant coagulant sludges is an issue facing utilities nationwide. Land disposal, or more specifically, placement of sludge in a dedicated monofill, is an alternative means of ultimate disposal that is generally technically feasible, economically competitive, and environmentally sound. This report explores regulatory constraints affecting sludge disposal as well as the chemical and physical sludge characterization necessary to ensure effective monofill design.

Duane L. Georgeson
Chair, Board of Trustees
AWWA Research Foundation

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Three utilities participated in this project and provided sludge samples, and their willingness to participate is appreciated:

City of Chesapeake, Virginia
City of Durham, North Carolina
Pennsylvania–American Water Company (Pittsburgh)

The comments and technical reviews by the project officer, Elizabeth Kawczynski, of AWWARF, and the Project Advisory Committee, composed of James Smith (USEPA), Gary Jardine (CH2M HILL), and Robert Croker (Pennsylvania–American Water Company), greatly assisted in the preparation of this report.

Executive Summary

Environmental Engineering & Technology, Inc. (EE&T), in conjunction with several utilities and The Pennsylvania State University, conducted this research project to better define the requirements for successful landfilling of coagulant sludges. The research focused on four primary issues:

- State and federal regulations or guidelines that affect the landfilling of water treatment plant sludges
- Studies to determine the type and amount of constituents that leach from coagulant sludges
- Studies to assess the physical properties of coagulant sludges as the properties relate to proper handling of sludges in a landfill
- Design considerations for coagulant sludge landfills

The regulatory environment regarding the disposal of water treatment plant (WTP) sludges has been in flux for many years. There are no federal regulations that specifically target landfilling of WTP sludges, and only a few states have regulations that specifically address these sludges. Therefore, regulations that were written to address other types of wastes are often utilized to regulate WTP sludges.

As a first step in regulatory landfilling of WTP sludge, most states are requiring that the sludge be proven nonhazardous by use of the toxicity characteristic leaching procedure (TCLP) test as defined by Resource Conservation and Recovery Act (RCRA) requirements. Once a sludge has been shown to be nonhazardous, many states apply municipal solid waste (MSW) regulations to the landfilling of WTP sludges. For landfilling sludge in an MSW landfill, requirements are generally that the sludge have no free water as determined by the paint filter test. Many states also require a minimum solids concentration, often in the 20 percent range. For creating a WTP sludge monofill, MSW requirements call for a liner and leachate collection system; groundwater monitoring; and specific siting, operating, and closure plans. As an alternative, the utility may be allowed to prove that the sludge will not impact groundwater or surface water and that the strict MSW requirements are not necessary.

In order to help assess the potential for contaminants to leach from coagulant sludges and thereby to impact water sources, a 6-month pilot evaluation was conducted. Two sludges from alum coagulation processes and one sludge from an iron coagulation process were put in 1-ft-square (0.093-m-square) columns to a 6-ft (1.83-m) depth. Simulated acid rain was then used as a leaching solution. Leachate was analyzed every other week for 6 months with the equivalent of 12 years of rainfall having been applied. The sludges were also analyzed by the TCLP test and were analyzed for total metals concentrations. The following was concluded:

- All the sludges were nonhazardous using the TCLP test. In fact, the researchers could not find any documentation in the literature of a coagulant sludge failing the TCLP test.
- It was found that the relatively expensive TCLP test could often be replaced with a total concentration test followed by a calculation procedure to classify the sludge as nonhazardous.
- No relationship was found between levels of contaminant concentrations detected in the TCLP extract and the amounts of metals that leached in the column tests.
- No relationship was found between total metals concentrations in the sludge and the amounts of metals that leached in the column tests.
- Some degree of leaching of arsenic, copper, iron, manganese, and zinc was found from all sludges; however, the percent of the total contaminant that leached was generally under 3 percent and often below 1 percent.
- None of the metal concentrations in the leachate exceeded drinking water maximum contaminant levels (MCLs), and therefore no groundwater impact was expected.

Physical characterization tests were conducted on the same three sludges used in the leachate study. Physical tests were designed to help determine the sludge solids concentration necessary for slope stability and to support earth-moving machinery. Tests used in geotechnical engineering were adapted for the evaluation of WTP sludge. Some limited field data were also collected. Conclusions from this portion of the research included the following:

- Conventional laboratory tests used in geotechnical engineering could be adapted to test WTP sludges.
- Solids concentration could not be used as an indicator of shear strength.
- The solids concentration required for slope stability and to support earth-moving equipment was different for each of the sludges. The solids concentration required to support landfill machinery ranged from 25 to 50 percent.
- Sludge age and disturbance affected the sludge's physical properties.
- Bulking agents could be used to increase the shear strength of the sludge.
- More research is needed to understand the sludge's physical properties and the relationship between test results and proper design.

Chapter 1

Introduction

Background Need

Water treatment plants across the United States are faced with the dilemma of how to dispose of their sludges in an economical and environmentally sound manner. The ever-changing regulatory environment poses new challenges to all involved in the drinking water industry. More stringent water quality regulations have made disposal of water treatment plant sludges a pressing issue for utilities nationwide. At the same time that greater quantities of sludge are being produced by advanced treatment processes, limitations are being imposed on disposal of sludge by regulations designed to protect the environment.

This report is designed to facilitate the determination of chemical and physical characteristics of specific water treatment plant (WTP) coagulant sludges, the assessment of regulatory impacts, and the associated determination of landfilling needs.

Disposal Options

Generally available WTP sludge disposal options include land application, long-term lagooning, manufacturing, composting, codisposal with municipal solid waste, and monofilling. Direct discharge into U.S. waters, once the predominant method of sludge disposal, has been severely restricted by the National Pollutant Discharge Elimination System (NPDES) permit system. Discharge to sanitary sewers is another viable disposal method (assuming capacity is available at the wastewater plant) generally subject to some type of pretreatment standards.

State interpretation of the regulations and guidelines established in or as a result of the Clean Water Act (NPDES system, in-stream water quality and pretreatment standards, discharge guidance documents) varies a great deal. In some states direct discharge of alum sludges to streams is allowed with or without the stipulation that certain pretreatment standards are met; in other states direct discharge is prohibited, generally through limitation on suspended solids discharge. For the most part, direct discharge into a stream is permitted only for settled backwash water or for overflow from a sludge solids separation process such as a lagoon or gravity thickener. Allowable pollutant concentrations are variable and can be based on in-stream water quality criteria guidelines established by the U.S. Environmental Protection Agency (USEPA), state-mandated enforceable in-stream standards, or other levels, such as maximum allowable concentrations, deemed appropriate by states. Example discharge requirements are shown in Table 1.1.

Table 1.1 Discharge requirements for overflow from solids separation processes

Parameter	Monthly average (mg/L)	Daily average (mg/L)
Suspended solids	30	60
Iron (total)	2	4
Aluminum (total)	4	8
Manganese (total)	1	2
Flow	Continuous monitoring	
pH	6–9 at all times	

Source: Dixon, Lee, and Moser 1988.

Land Application

Land disposal of WTP sludges by landfilling, lagooning, or beneficial land application for agricultural utilization or land reclamation is governed by a number of regulations, none of which were specifically written for WTP sludge. Elliott et al. (1990) explored the impacts and management aspects of land application of water treatment plant sludges. Land application guidelines for WTP sludge generally follow sewage sludge standards outlined in the Clean Water Act. Federal guidelines for maximum allowable cumulative metal loadings are presented in Table 1.2. Maximum allowable metal content limits for water treatment plant sludge to be land applied have been set by some individual states. Until an adequate data base exists for WTP sludges, however, regulatory agencies will continue to use the existing criteria established for sewage sludge.

A primary goal of land application of sludge is to allow sunlight and soil microorganisms to biodegrade the organic matter contained in the sludge while the soil binds up the metals, thereby utilizing land itself as a treatment system. Surface or subsurface application of WTP sludge to land as a means of ultimate disposal does, however, offer cause for concern, some of which stems from the tendency for alum sludge to fix the phosphorus in the soil, making it unavailable to plant roots for growth. In general, a maximum loading of 10 to 20 tons/acre (2.2 to 4.4 kg/m^2) of WTP sludge is required to prevent phosphorus deficiencies (Cornwell and Koppers 1990). Another concern is the potential leaching of nitrates through soil and into groundwater. Based on this criterion, nitrogen content in the sludge, the percentage of nitrogen available to crops and vegetation to be grown, and the nitrogen uptake level of the specific crop all must be considered in determining allowable annual sludge loading (application) rates. Physical sludge and soil characteristics and the particular crop to be grown dictate the appropriate method and proper rate of sludge application to agricultural land.

A number of states are applying sewage sludge land application guidelines to WTP sludge. In the state of Pennsylvania, land application of sludge associated with a beneficial effect on selected crop growth is regulated by various criteria. Rate of application is controlled by nitrogen loading, trace metals, or hydraulic loading limit, and site life is calculated based on a maximum accumulation of trace metals. A soil pH of less than 6.5 and saturated, snow-covered, or frozen ground both preclude land application.

Partially dewatered sewage sludge applied to stabilize and rejuvenate nonagricultural land is commonly sprayed from mobile equipment. Where land availability poses no constraint, application of liquid alum sludge to forested land

Table 1.2 Recommended cumulative limits for metals of major concern applied to agricultural cropland

Metal	Soil cation exchange capacity (meq/100 g) Less than 5	 5–15	 Greater than 15
	Maximum amount of metal, lb/acre (kg/ha)		
Cadmium	4.4 (5)	8.9 (10)	17.8 (20)
Copper	125 (140)	250 (280)	500 (560)
Lead	500 (560)	1,000 (1,120)	2,000 (2,240)
Nickel	125 (140)	260 (280)	500 (560)
Zinc	250 (280)	500 (560)	1,000 (1,120)

Source: USEPA 1983.

could prove to be a viable, cost-effective means of sludge disposal. More research is required, however, to ascertain long-term effects. Although land application is often a feasible sludge disposal alternative and one that is likely to be used more frequently in the future, land and transportation requirements can sometimes render it cost prohibitive.

Long-Term Lagooning

Large earthen basins termed lagoons have been used as a method of sludge treatment as well as a means of ultimate disposal. In lagoons, sludge solids settle and supernatant is normally discharged (in accord with NPDES permit requirements) or recycled to the head of the plant for treatment. Many existing lagoons would not be able to meet the requirements for new construction, such as those for liners, that have been imposed as a result of the concern regarding groundwater contamination associated with sludge disposal in lagoons.

Groundwater monitoring is often required to detect any degradation of ambient groundwater quality. Specific requirements regarding liners and leachate collection systems vary from state to state. In some cases, an underlying collection system is required in addition to a leachate collection system to ensure that the soil zone beneath the liner remains dry.

Manufacturing

Although large-scale applications have been inhibited due to a number of factors (economics, logistics, etc.), utilization of WTP sludge in or resulting from various manufacturing operations has shown promise in the areas of brickmaking, cement making, and recovery of steel. Rapidly decreasing capacity of landfills and associated increasing tipping fees coupled with more stringent solid waste disposal regulatory criteria will necessitate further exploration of these and other innovative sludge disposal options.

The concept of using alum sludge for brickmaking was determined to be technically feasible by the City of Durham, N.C. (Rolan 1976). Although the addition of sludge as an ingredient in the brickmaking process did not adversely impact the structural integrity of the product or hinder its marketability, costs associated with handling and hauling sludge from the city's water treatment plants to the local brick company rendered the disposal option cost prohibitive. On the other hand, a combined belt press–brickmaking sludge-handling alternative implemented in the Santa Clara Valley Water District in San Jose, Calif., resulted in considerable savings to the district (Migneault 1988).

Composting

Composting of alum sludge in conjunction with another highly organic waste material is another possible sludge disposal option. In composting, partially dewatered sludge is typically mixed with some type of bulking agent and allowed to decompose aerobically. Little documentation regarding composting trials with WTP coagulant sludge can be found in the literature; most sludge composting to date has involved sewage sludge. However, cocomposting studies that have been conducted using WTP sludge along with sewage sludge have indicated that the addition of WTP sludge has no detrimental effect on compost quality (Potter and Vandermeyden 1991). Compost can be marketed as a substitute for topsoil and peat.

Codisposal With Municipal and Industrial Solid Waste

Although codisposal of WTP sludge in a municipal or industrial solid waste landfill remains a widely practiced sludge disposal option, a number of factors are making it less attractive. First of all, landfill tipping fees continue to rise sharply as available landfill capacity dwindles. Second, solid waste disposal criteria, particularly with regard to liner and leachate collection requirements and groundwater monitoring, will continue to be made more stringent. Finally, placing WTP waste in an industrial or municipal waste landfill containing wastes potentially more toxic or of questionable quality carries with it a substantial assumption of liability.

In spite of the negative aspects of codisposal, this method of sludge disposal is currently cited as the option chosen by more individual states than any other alternative (AWWA Water Treatment Waste Disposal Committee 1991). Particularly where municipal solid waste or industrial waste landfills are located in close proximity to small water treatment plants that generate relatively small amounts of sludge, codisposal would appear to be a viable option.

Monofilling

Monofills, or sludge-only landfills, are for the most part governed by the same regulations that address codisposal of sludge in municipal solid waste landfills (MSWLFs). Although types of monofill construction vary, as does MSWLF construction, trenching is the most widespread method. With this type of construction, dewatered sludge is deposited in trenches and subsequently covered with soil. In alternate design methods such as area fill and diked containment, space is better utilized, but a drier cake is required (USEPA 1978).

Even if the disposal criteria for a sludge monofill are the same as those for an MSW landfill, costs associated with a monofill are often much less than those for the development of an MSW landfill. In addition, a monofill is free of the potential liability associated with disposing of sludge in landfills that may have received wastes from a number of unknown sources.

Project Purpose and Objectives

The overall purpose of this research project is to provide guidance to be used by utilities and other regulatory authorities in characterization and ultimately landfilling of WTP coagulant sludges. More specifically, the purpose of the project is defined by the following principal objectives:

- An assessment of regulations that currently affect WTP sludge disposal
- The development of sludge characterization procedures in terms of physical requirements and chemical limitations for landfilling imposed by applicable regulations
- An evaluation of landfill siting and design criteria

Physical and chemical characterization of sludge has a direct bearing on its disposal in landfills. Assessment of applicable regulations and their impacts is also critical to the development of disposal strategies. Chapter 2 of this research report is designed to provide an overview of the current regulatory framework surrounding disposal of WTP sludges in landfills. An overview of the generally available alternative sludge disposal options is presented in the preceding chapter.

Chapter 3 of this report addresses leaching from WTP coagulant sludges. A description of extraction tests and other chemical analyses is presented, and the landfill leachate research conducted for this project is discussed.

Physical characteristics of sludge required for landfilling are the subject of Chapter 4. New physical parameters resulting from this and other research are presented, along with physical characterization techniques historically employed in assessing acceptability for disposal.

Landfill siting and design criteria are outlined in the last two chapters of this report. A lengthy, involved process, landfill siting involves a number of technical considerations that are detailed therein. General landfill design criteria are presented, and criteria specific to sludge monofills are highlighted in the final chapter.

Chapter 2

Regulatory Framework for Landfilling

Classification of Water Treatment Plant Sludge for Land Disposal

Initial classification of a water treatment plant (WTP) sludge as hazardous or nonhazardous dictates the possible disposal alternatives. Means of disposal currently practiced include direct stream discharge, permanent lagoons, land application, and land disposal (landfilling). For all options, existing fragmented networks of regulations to which disposers of WTP wastes must adhere are undergoing changes that will potentially toughen and consolidate them. The focus of this report, landfilling of WTP sludge, falls into one of three basic categories:

- Sludge monofills
- Codisposal of WTP sludge in municipal or industrial waste landfills
- Hazardous waste landfills

Although there are no federal laws in place that directly govern the handling and disposal of water treatment plant sludges in the United States, applicable regulations can be found in the following bodies of legislation: the Clean Water Act (CWA), the Resource Conservation and Recovery Act (RCRA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The CWA deals with water quality by placing limits on direct discharge. The RCRA and CERCLA affect land disposal of solid wastes. Additional regulations apply in cases where the sludge contains radioactivity.

No federal mandates are currently in place that would prohibit the disposal of WTP residuals deemed nonhazardous in a municipal solid waste landfill (MSWLF). Disposal of nonhazardous wastes in MSWLFs is governed at the federal level by RCRA regulations. It should be noted, however, that more stringent individual state regulations disallowing disposal of WTP sludge in MSWLFs would override RCRA rules.

The toxicity characteristics used to identify hazardous wastes, those subject to regulation under Subtitle C of RCRA, were revised in a rule promulgated by the USEPA in March of 1990. For all practical purposes, the extraction procedure (EP) toxicity test was replaced by the more rigorous and comprehensive toxicity characteristic leaching procedure (TCLP) test. If a sludge fails the TCLP test, it must be treated as a hazardous waste as specified under Subtitle C of RCRA. A number of specific constituents that could be present and potentially leach from WTP sludge are quantified in the TCLP. The procedure essentially expands the list of constituents tested for in the EP toxicity test and lowers the acceptable concentrations. The list of measured constituents along with corresponding regulatory threshold levels is shown in Table 2.1. In addition to serving to determine whether a waste is hazardous, the TCLP test is used in regulating the land disposal of wastes.

The three other indicators of a hazardous material according to RCRA are ignitability, reactivity, and corrosivity. Hazardous wastes that are capable of causing a fire during transport, storage, or disposal are defined as ignitable. A number of properties indicate reactivity in a waste, including violent reaction with water leading to the formation of potentially explosive mixtures. Corrosivity as indicated by pH or capability to corrode steel is another identifying characteristic of a hazardous waste. In addition to the four extrinsic characteristics used in RCRA to classify a waste as hazardous, official lists of designated hazardous wastes have been published by USEPA in the Code of Federal Regulations, Section 40 (40 CFR), Part 261, Subpart D (*Federal Register* 1990).

Table 2.1 Toxicity characteristic contaminants and regulatory levels

Contaminant	Regulatory threshold level (mg/L)
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0
Endrin	0.02
Lindane	0.4
Methoxychlor	10.0
Toxaphene	0.5
2,4-D	10.0
2,4,5-TP	1.0
Chlordane	0.03
Heptachlor (and its epoxide)	0.008
Benzene	0.5
Carbon tetrachloride	0.5
Chlorobenzene	100.0
Chloroform	6.0
1,2-Dichloroethane	0.5
1,1-Dichloroethylene	0.7
Methyl ethyl ketone	200.0
Tetrachloroethylene	0.7
Trichloroethylene	0.5
Vinyl chloride	0.2
1,4-Dichlorobenzene	7.5
Hexachlorobenzene	0.13
Hexachlorobutadiene	0.5
2,4-Dinitrotoluene	0.13
Hexachloroethane	3.0
Nitrobenzene	2.0
Pyridine	5.0
o-Cresol	200.0
m-Cresol	200.0
p-Cresol	200.0
Pentachlorophenol	100.0
2,4,5-Trichlorophenol	400.0
2,4,6-Trichlorophenol	2.0

Source: Federal Register 1990. 40 CFR 261, 55:61:11805.

The primary concern regarding land disposal of radioactive wastes is the potential release of radon gas. Moisture content of both the waste and the cover material would affect the flux of this gas. Although the Nuclear Regulatory Commission, the USEPA, and the Department of Transportation are involved with various aspects of wastes containing radium, the ultimate regulatory authority lies with individual states rather than with one of these federal agencies.

Federal Regulatory Framework

Existing Regulations

Clean Water Act (CWA)

Federal efforts began to focus on eliminating the discharge of pollutants into waterways with the 1972 amendments to the Federal Water Pollution Control Act, which introduced the concept of National Pollutant Discharge Elimination System (NPDES) permits and established the first national water quality goals. Additionally, amendments to Section 405 of the Clean Water Act of 1977, which was amended from the Federal Water Pollution Control Act of 1972, served to establish guidelines for the use and disposal of sewage sludge. Maintenance and restoration of the chemical, physical, and biological integrity of U.S. waters were the principal goals of the act. Limits were placed on the quantities of numerous pollutants that may be discharged into the nation's surface water. The scope of state and local regulatory programs was subsequently expanded to include groundwater and lake water quality, and the focus of the act was broadened to include nonpoint sources of pollution and toxic pollutants from point and nonpoint sources. The required NPDES permit, which must be renewed every 5 years, defines monitoring and recording requirements and records effluent limits.

Leaching of metals into groundwater from land-disposed waste is a prime health and environmental concern and is addressed in Section 405 of the Clean Water Act. Sections 405(d) through (f) establish a comprehensive framework for regulating the use and disposal of sewage sludge. The thrust of these regulations deals with the determination of total metals concentrations and equilibrium modeling to evaluate potential groundwater impact rather than toxicity as defined by RCRA regulations.

Resource Conservation and Recovery Act (RCRA)

Although the establishment of governing criteria for the land application of WTP sludges was authorized under the CWA, the landfilling of dewatered residuals produced at water treatment plants is regulated by RCRA and other solid waste disposal requirements. The RCRA focuses on the following five elements:

- Classification of hazardous wastes
- Cradle-to-grave manifest system
- Standards to be followed by generators, treaters, disposers, and storers of hazardous wastes
- Enforcement of established standards
- Authorization of states to obtain primacy for implementation of the regulations

Subtitle C of RCRA concerns the disposal of hazardous wastes, and Subtitle D establishes a framework in which all levels of government can work cooperatively to effectively control the management of nonhazardous solid wastes. The protection of land, water (both surface and ground supplies), and air from contamination by solid waste was the original goal of RCRA.

Under RCRA, the basic criteria for determining whether a waste should be classified as hazardous or nonhazardous are ignitability, corrosivity, reactivity, and toxicity. Sludge determined to be hazardous or that which contains polychlorinated biphenyls (PCBs) in concentrations greater than 50 ppm is regulated under Subtitle C of RCRA and the Toxic Substances Control Act. The uniform hazardous waste manifest system developed by the USEPA makes possible the tracking of hazardous waste from its generation to the point of ultimate disposal. If manifests are correctly processed, the generator of the hazardous waste, who is ultimately responsible for the waste disposal, can reliably track the waste from the "cradle" to the "grave." To ensure that a hazardous waste can be monitored from its generation to its disposal, each RCRA hazardous waste generator must obtain an identification number from the USEPA.

Subtitle D of RCRA governs the management of nonhazardous solid waste, the category under which the bulk of WTP wastes falls. The USEPA does not have the authority to directly enforce the criteria set forth therein, except where facilities are involved in the handling or disposal of sewage sludge; states are given the primary authority to enforce the criteria through their regulatory programs. The USEPA is required, however, to assess the adequacy of state permit programs, which must be implemented within 18 months after promulgation of the revised rules (40 CFR, Parts 257 and 258 [*Federal Register* 1991]). In Part 257, "Criteria for Classification of Solid Waste Disposal Facilities and Practices," specific criteria are enumerated and the conditions are described under which violation of these criteria would pose a potential threat of adverse impacts on health or the environment. The following rules regarding floodplains, endangered species, surface water, groundwater, application to land used for the production of food chain crops, disease, air, and safety must be adhered to in order to ensure that the potential for adverse effects on health and the environment is minimized.

Restricting the flow of the base flood, reducing the storage capacity of the floodplain, or causing a washout of solid waste would constitute a violation of the floodplain criteria established in the regulations. In addition, facilities are prohibited from causing or contributing to the demise of any endangered or threatened species or the critical habitat thereof. Causing a discharge of pollutants that is in violation of the CWA's National Pollutant Discharge Elimination System or of a federally approved areawide or statewide water quality management plan would be accompanied by a reasonable probability of adverse effects on health or the environment and hence would breach the rules. Contamination of an underground drinking water source beyond the solid waste boundary or an alternative boundary specified by the state would constitute a violation of the rules as well. Contaminants under Part 257 of the CFR include the 10 inorganics, 4 chlorinated hydrocarbons, and 2 chlorophenoxyls that appear in the National Primary Drinking Water Regulations.

To remain in compliance with the regulations, the population of disease vectors on site must be minimized through the periodic application of cover material or some equally effective technique. Protection of air quality is ensured through prohibition of open burning of waste. Safety standards that limit explosive gases (methane) and address fires, bird hazards to aircraft, and site access are contained in the regulations as well.

Specific constraints are placed on the application of solid waste to land used for the production of food chain crops with regard to cadmium and polychlorinated biphenyls. In general, minimum pH requirements must be satisfied. The maximum allowable application rate of sludge with respect to cadmium as of January 1, 1987, was 0.4 lb/acre (0.5 kg/ha). Maximum cumulative application rates are set according to the pH of background soil coupled with soil cation exchange capacity, with the stipulation that the pH (if below 6.5) must be adjusted to and maintained at 6.5 or greater wherever food chain crops are grown. Sludge having PCB concentrations greater than or equal to 10 mg/kg applied to land used for producing animal feed must be incorporated into the soil, and sludge having a PCB concentration in excess of 50 mg/kg must be disposed of in a hazardous waste landfill.

Revisions to the Criteria for Classification of Solid Waste, set forth in final form in 40 CFR, Parts 257 and 258 (*Federal Register* 1991), were proposed in response to the 1984 Hazardous and Solid Waste Amendments to RCRA. Reorganization of Part 257 to exclude MSWLFs resulted in the creation of Part 258. Only MSWLFs that will be receiving waste on or after October 9, 1993, are subject to all of Part 258 requirements. Although WTP sludge is defined as a solid waste in the regulations, the focus of the rules is the location, design, operation, cleanup, and closure of municipal solid waste landfills. However, because disposal of WTP wastes in MSWLFs and construction of sludge monofills are viable ultimate disposal options and there are no federal regulations in place that directly apply to WTP waste disposal, Parts 257 and 258 currently offer the best federal guidelines.

Siting restrictions regarding wetlands, fault areas, unstable areas, and seismic impact zones are included in Part 258. According to the regulations, placement of an MSWLF in a wetland must not result in "significant degradation" as defined in Section 404(b) of the Clean Water Act. A ban on locating new landfills within 200 ft (61 m) of certain faults, along with design specifications to ensure resistance of horizontal acceleration in seismic impact zones and structural stability in unstable areas, is also included in the proposed regulations. A more detailed discussion of siting criteria can be found in Chapter 5.

Subpart C of 40 CFR, Part 258 (*Federal Register* 1991), addresses required daily operating criteria with regard to cover material requirements, disease vector control, explosive gas control, air quality, access restrictions, run-on/runoff control systems, surface water, liquids restrictions, recordkeeping requirements, closure and postclosure criteria, financial assurance, and the exclusion of receipt of hazardous wastes. Although procedures to detect and prevent disposal of hazardous wastes and wastes containing PCBs are outlined in this section, the Toxic Substances Control Act makes provisions for the disposal of limited categories of PCB materials in MSWLFs.

Design criteria for liner and leachate collection systems, based on such considerations as hydrogeology, climate, leachate characteristics, groundwater quality, proximity of groundwater users, final cover requirements, and overall groundwater carcinogenic risk levels are detailed in Subpart D of 40 CFR, Part 258 (*Federal Register* 1991). Two basic design options are outlined in the rules, one required only in states without USEPA-approved programs and the other available in states with approved programs. The latter is site specific and subject to state approval and must ensure that drinking water MCLs will not be exceeded in the uppermost groundwater aquifer at the point of compliance (often the solid waste disposal area boundary). The former is required in states without USEPA approval and involves the installation of a protective composite liner system consisting of a flexible membrane liner and a compacted soil component. The flexible membrane liner component provides a highly impermeable layer to maximize leachate collection and removal, and the lower soil component serves as a backup in the event of liner failure (40 CFR, Part 258 [*Federal Register* 1991]). A provision in the regulations does allow states without approved programs to petition to use the performance standard approach instead of the composite liner approach.

Groundwater monitoring procedures and corrective action measures are covered in Subpart E of 40 CFR, Part 258 (*Federal Register* 1991). These requirements may be suspended, however, upon demonstration to the state that no potential exists through the postclosure period for migration of hazardous constituents to the uppermost aquifer. In addition to requiring the installation of a network of monitoring wells at new and existing MSWLFs, the proposed rules outline sampling and analysis requirements. A two-phased monitoring approach has been proposed, in which initiation of Phase II monitoring is triggered by a change in groundwater chemistry or detection of certain Phase I parameters at statistically significant levels above background. Phase I monitoring includes sampling semiannually for the following parameters: antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, nickel, selenium, silver, thallium, vanadium, zinc, and a number of volatile organic compounds. Phase II monitoring consists of an expanded list of hazardous contaminants (40 CFR, Part 258 [*Federal Register* 1991]). In the event that any of the Phase II parameters is detected at statistically significant levels, the regulations dictate that the measured level be compared to the state-specified groundwater protection level, either a Safe Drinking Water Act MCL or some health-based concentration limit that triggers the assessment of corrective measures.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as the Superfund Act, was established to deal with the numerous existing abandoned or uncontrolled hazardous waste disposal sites that pose a real threat to public health and safety as well as to the environment. Prior to the act's passage, USEPA was only authorized to regulate hazardous waste management at active and properly closed sites. Superfund, essentially a pool of money derived from special taxes, forms the core of CERCLA. Establishment of this fund fulfilled the primary focus of CERCLA. An expansion of the Superfund pool that serves to continue cleanup efforts begun under CERCLA is provided by SARA, the Superfund Amendments and Reauthorization Act of 1986. The funds thereof are used to remediate defunct sites in accord with RCRA requirements.

The USEPA is authorized under CERCLA to take necessary short-term actions to deal with sites posing some immediate threat to human health or the environment as well as to implement long-term plans to clean up complex sites, which are selected on the basis of risk assessments. The identification of responsible parties is an important part of the remediation process. Possibly the most noteworthy aspect of these regulations, however, is that they employ a volume use basis in assessing cleanup costs, which potentially places liability with a utility whose sludge did not cause the problem.

State Regulatory Framework

As determined in a survey conducted during the first quarter (1989) of this research project, common classifications of WTP sludge by states include special or solid waste (majority of states), industrial waste, municipal waste, commercial waste, and waste by-product of a water treatment plant. As in classification, there is considerable variability among states regarding disposal practices. At the time of the survey, nearly all states were using the extraction procedure toxicity test to determine whether a sludge is hazardous. As of September 25, 1990, however, a toxicity characteristic leaching procedure test as defined in 40 CFR, Part 261 (*Federal Register* 1990), is required to determine whether a waste is hazardous..

Summary of Individual State Surveys

During the first quarter of this research project a telephone survey was conducted to determine what state regulations were being applied to WTP wastes. In general, it is apparent that state regulations vary tremendously. Some states have few regulations and limited knowledge regarding how and where their water treatment plant wastes are disposed of, whereas others are much more highly regulated, with clear procedures in place for dealing with WTP wastes.

Several clear divisions emerge among the various state regulations. Possibly the most prevalent dividing line occurs between states that have large numbers of water treatment plants producing sludge and those that have only a few. States that have experienced problems with WTP sludge have procedures in place to deal with the waste, whereas those generating small amounts of waste, such as those whose main supply is from groundwater aquifers, seem to have little concern about it and consequently have few regulations governing its disposal. States having small or few water treatment plants that are able to discharge wastes to large receiving waters within their borders with little discernible impact usually have little regulation of WTP disposal practices.

State responses to survey questions dealing with landfilling of sludges in MSWLFs and sludge monofilling are tabulated in the appendix. A sample questionnaire form (Figure A.1) is also included therein. Tables A.1 and A.2 were compiled based on responses to a survey conducted for this research. Table 2.2 presents a summary of the results. Landfill requirements vary from state to state, and sludge-only landfills are often permitted on a case-by-case basis. For example, although New Jersey regulations do not prohibit the disposal of WTP wastes in MSWLFs, there are no MSWLFs in the state.

Solids content of a sludge is the criterion most widely used to determine whether it will be accepted for disposal in an MSWLF. Another commonly used gauge is the amount of free water contained in a sludge, normally measured using the paint filter liquids test. Specific mixing ratios of sludge to refuse are also required in some states. No states prohibit the use of sludge monofills. Requirements were reported to be the same as or similar to those for a new MSWLF in the majority of states.

Among states requiring a minimum percent solids content, Nebraska and California requirements were found to be the most stringent at 70 and 50 percent, respectively. In a number of other states, such as New York and South Carolina, sludge having a solids content greater than 20 percent was found to be acceptable for

Table 2.2 Summary of state requirements for landfilling of water treatment plant sludge

Standard	Percentage of states where standard was in place at time of survey
Solids content	
2–20 percent	8
20–30 percent	18
30–40 percent	4
>40 percent	6
Numerical limit not specified	60
Free water	
No free water	56
Paint filter test specified	34
Minimum sludge to refuse ratio (applies to codisposal only)	18
Monofill requirements essentially the same as codisposal (often case by case as well)	76

Note: All 50 states were surveyed.

disposal. At the other end of the spectrum, a number of states were found to have no minimum sludge solids concentration criteria. Found throughout various USEPA regions scattered across the country, states falling into this category included Rhode Island, Maryland, Florida, Michigan, and Colorado. A majority of states prohibit the deposit of WTP sludge containing free liquid; a number of these specify the paint filter liquids test. Most states require no specific mixing ratio of WTP sludge to refuse, although some suggest a 1:3 or 1:4 ratio to maintain workability. A ratio of 1:10 is required by West Virginia.

Common threads in the regulatory framework for WTP sludge disposal at the state level emerged through comparison of responses to a number of survey questions. In addition to categorization of WTP sludge and methods of determining whether a waste is hazardous, the formality of each state's current regulatory structure, in terms of the procedures in place and their enforcement, was given a relative ranking by the interviewer. At the time of the survey the degree of formality exhibited by most in-place state regulatory structures was low. With regard to this parameter, for only 7 out of 50 states (Pennsylvania, Michigan, Minnesota, Iowa, New York, New Jersey, and California) were the systems in place deemed very formal. At the other end of the spectrum, the regulatory structures of Georgia, Maine, and Hawaii were labeled informal.

Another survey regarding state regulatory approaches for WTP wastes was documented in the paper titled "State Regulatory Approaches for Water Plant Wastes" (AWWA Water Treatment Waste Disposal Committee 1991). The committee found that codisposal in MSWLFs, in spite of rapidly diminishing available capacity, currently remains the most frequently employed disposal alternative. Next to codisposal, land application and direct discharge were found to be most prevalent. Although most states regulate WTP wastes based on NPDES standards and solid waste and sewage sludge regulations, these wastes are not necessarily a major concern to state regulatory agencies, many of which are waiting for the development of USEPA regulations for WTP sludges before developing their own. In general, water treatment plant wastes are considered to be chemically inert with relatively low concentrations of pollutants.

Chapter 3

Leaching From Water Treatment Plant Coagulant Sludges

Introduction

The serious threat posed to vital groundwater sources as evidenced by reported instances of contamination has made groundwater protection a priority for the USEPA. Protection of groundwater is critical, as it provides 50 percent of the nation's drinking water, 40 percent of the water used for irrigation, and about 6 percent of the water used for industry. Evolving through inclusion in various regulations, the issue of groundwater protection has provided the impetus for research in the area of leaching. Studies have been conducted in which the potential leaching of various constituents has been investigated through leaching contaminant identification and quantification. Behavior of trace metals found in WTP sludge applied to land was investigated by Elliott et al. (1990). A thorough discussion of leaching studies that have been routinely conducted in Germany and the Netherlands is presented by Cornwell and Koppers (1990). Some research has progressed to the point of attempting to determine the relative mobility of various constituents (mostly metals) and to compare the effects of various factors that appear to have some particular influence on the release of pollutants. An understanding of these factors could potentially lead to development of pretreatment techniques that could minimize or eliminate the concern over metals release (Cornwell and Koppers 1990).

Congress directed USEPA to determine if landfill leachate poses a serious threat to groundwater, and if so, to develop environmental constraints on all types of landfills. Additionally, USEPA was directed to develop a data base on landfill leachate quality. Notably, most landfills surveyed by USEPA do not monitor for groundwater protection. According to USEPA data, only 18 percent of industrial landfills and 5 percent of construction debris landfills are monitoring for groundwater quality. Of those industrial landfills that do monitor, 25 percent were cited in 1984 for violating state standards to protect groundwater (USGAO 1990). Most of the contamination incidents were attributable to small amounts of hazardous waste that were codisposed with nonhazardous material.

Extraction tests are one means of predicting the contaminants that will leach from a waste and the amount of each that will leach. A waste that fails the current regulatory toxicity characteristic leaching procedure is classified as hazardous, making it subject to the stringent rules that govern the disposal of hazardous substances. Groundwater monitoring wells and sampling from leachate collection systems can also be employed to gauge leachate quality.

Leaching from WTP coagulant sludges is the focus of this chapter. The aforementioned extraction procedures are described and test data are provided for comparison. Also, a summary of a 6-month pilot-scale landfill leaching study conducted as a part of this research, including a description of the testing apparatus and procedures, presentation and comparative analysis of data, and conclusions reached, is detailed herein. In this study, chemical characterization of the sludge and evaluation of the simulated monofill leachate were accomplished to assess regulatory impacts and to help establish WTP sludge monofill design parameters.

In the following sections, information on the methods of evaluating metals content of sludge is presented. In each case, examples of data presented in the literature and data collected in this research are presented. Potential regulatory implications are explored. First is a discussion of total metals analysis, which, of course, indicates the worst-case potential for contamination of soil or groundwater. Second is a discussion of the extraction tests that are designed to predict leaching and used to classify sludge. Finally, a presentation is made on actual leaching studies, which are difficult and expensive to conduct but are the best indicators of contamination potential.

Total Metals Analysis

Total metals analyses are performed to determine concentrations at which various metals are present in a particular medium. These background levels are important for a number of reasons. First, the absence of a particular constituent or its presence in very low amounts may eliminate the need for additional costly testing. This circumstance is explored further under the heading "Landfill Leaching Study" later in this chapter. Second, background concentrations are essential in quantification of leaching of constituents. Finally, in reference to sludge, background levels of specific constituents can be compared to existing or proposed regulatory limits that govern certain disposal options. Because approximately 20 to 90 percent of the waste solids generated at surface water treatment plants are composed of water treatment chemicals, contaminants in these chemicals may significantly affect the quality of sludge generated (Cornwell and Koppers 1990).

In the pilot-scale evaluation of sludge landfill leachate quality conducted by Environmental Engineering & Technology, Inc., which is detailed in a subsequent section of this chapter, each of three sludge samples was analyzed for total metals. The total metals analysis resulted in data consistent with those found earlier by Cornwell et al. (1987), American Water Works Service Company (Cornwell and Koppers 1990), and Dempsey (Cornwell and Koppers 1990). Results of the analysis for sludge used in this research are shown in Table 3.1. As expected, aluminum concentrations in the two alum sludges were substantially (roughly 4 times) higher than the aluminum content of the ferric sludge. The reverse was true for iron. The initial arsenic and chromium contents of the alum sludges were higher than the amounts present in the ferric sludge. Manganese, nickel, lead, barium, and zinc concentrations, however, were greater in the ferric sludge. High aluminum and iron levels can be linked directly to the coagulant employed in water treatment. The substantial manganese concentrations can likely be attributed to the raw water source. Mercury concentrations were quite low in all sludges; silver and selenium were not detectable.

Table 3.1 Total metals analysis for sludges used in leaching research

Metal	Alum sludge 1 (mg/kg dry weight)	Alum sludge 2 (mg/kg dry weight)	Ferric sludge 3 (mg/kg dry weight)
Aluminum	107,000	123,000	28,600
Arsenic	25.0	32.0	9.2
Barium	30	<30	230
Cadmium	1	1	2
Chromium	120	130	50
Copper	168	16	52
Iron	48,500	15,200	79,500
Lead	11	9	40
Manganese	1,180	233	4,800
Mercury	0.1	<0.1	0.2
Nickel	24	23	131
Selenium	<2	<2	<2
Silver	<2	<2	<2
Zinc	91.7	393	781

Total metals concentrations in three alum sludges are provided in Tables 3.2 through 3.4 for comparison. (These sludges were subjects of independent sludge studies unrelated to this research.) None of the constituents analyzed was present in inordinately high concentrations. A graphical depiction of example metals concentrations found in WTP sludges is presented in Figures 3.1 through 3.5. Note that in reporting total metals concentrations, the sludge should be dried before analysis so that the results are presented in mg /kg, dry weight. This was the case with the three test sludges used in this research. However, whether the sludges shown in Tables 3.2 through 3.4 had been dried could be neither confirmed nor negated due to insufficient information.

Extraction Tests

Extraction tests are designated by USEPA in the *Federal Register* as the method to be used in identifying in a solid waste the characteristic of toxicity, one of the four extrinsic characteristics that define a waste as hazardous. The presence in the extract from a representative waste sample of any number of contaminants at or above a specified regulatory level constitutes failure of the test and furthermore makes the waste subject to regulation as a hazardous waste per Subtitle C of RCRA. The toxicity characteristic leaching procedure (TCLP) officially replaced the extraction procedure (EP) toxicity test in May 1990 as the indicator of toxicity in a waste. Although more comprehensive and stringent because of its expanded list of potential contaminants and lower regulatory threshold limits, the TCLP may not significantly impact WTP coagulation sludges, which are generally found to be chemically inert and free of toxins at a level of regulatory concern.

Extraction Procedure Toxicity Test

The initial step in an EP toxicity test involves separation of a representative sample of the waste to be tested (minimum 100-g sample) into its component solid and liquid phases (40 CFR, Part 261 [*Federal Register* 1990]). Typically, separation

Table 3.2 Metals concentrations in Tampa, Fla., alum sludge

Metal	Amount present (mg/kg)
Aluminum	170,000
Barium	—
Cadmium	—
Chromium	70
Cobalt	16
Copper	90
Iron	62,400
Lead	100
Magnesium	2,360
Manganese	68
Silver	—
Zinc	22

Source: Cornwell 1981.

— indicates that a metal was not analyzed.

Table 3.3 Elemental analysis of alum sludge from Oak Ridge, Tenn.

Metal	Amount present (mg/kg)
Aluminum	13,500
Arsenic	13
Barium	333
Cadmium	<1
Chromium	200
Copper	7
Iron*	—
Lead	47
Manganese	983
Mercury	<2
Nickel	140
Selenium	1
Silver†	—
Zinc	167

Source: Schmitt and Hall 1975.

* The amount of iron was too high for a reliable quantitative analysis.

† Silver was used as a carrier in analysis.

is achieved through pressure or vacuum filtration or filtration coupled with centrifugation. The solid material obtained through separation is adjusted to a pH of 5.0, modified if necessary to conform to particle size requirements (able to pass through a 0.375-in. [9.5-mm] standard sieve), and placed in an extractor along with deionized water for a period of 24 hours. After the extraction period, more fluid is added and the material in the extractor is separated into solid and liquid components. Liquid components from the two separations are combined to become the extract to be analyzed for the presence of specific contaminants. For wastes containing less than 0.5 percent solids, the waste itself serves as the extract.

EP toxicity test results for sludge from three different water treatment plants and data collected during an American Water Works Service Company survey are presented in Table 3.5, along with threshold limits for each constituent of concern.

Table 3.4 Inorganic contaminants present in a California water treatment plant alum sludge

Metal	Amount present (mg/kg)
Aluminum	10,000–57,000
Antimony	nd–3.6
Arsenic	5.7–36
Barium	40–140
Beryllium	nd–0.6
Cadmium	nd–12
Chromium	<10–40
Cobalt	5.2–10
Copper	140–400
Lead	1.0–26
Mercury	nd–0.41
Molybdenum	<0.5–4
Nickel	nd–84
Selenium	nd–36
Silver	nd–1
Thallium	nd–14
Vanadium	39–64
Zinc	6.2–64
Hexavalent chromium	nd–<10
Fluoride	<0.5–30

Source: Contra Costa Water District, Concord, Calif., personal communication, 1990.

Note: Results presented were revealed through several total threshold limit concentration tests performed over a 4-year period on sludge under the authority of the Contra Costa Water District in Concord, Calif.

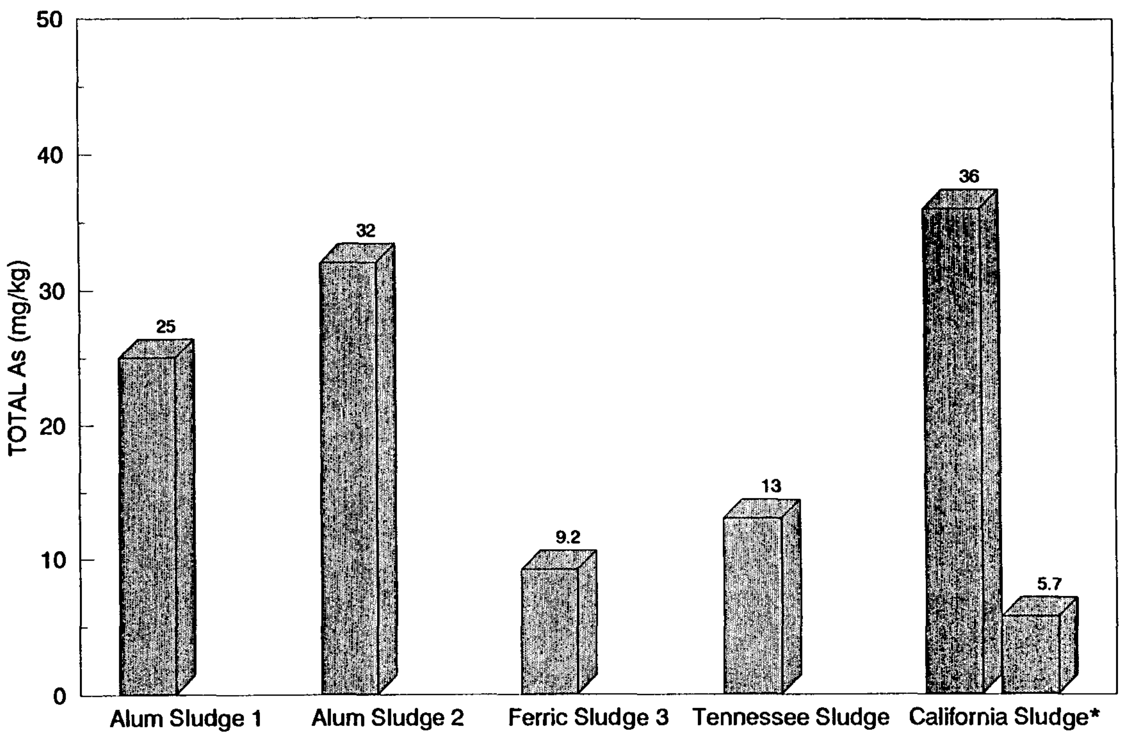
nd: nondetectable.

As shown, all regulated constituents, if detected at all, fell well within allowable limits.

Toxicity Characteristic Leaching Procedure

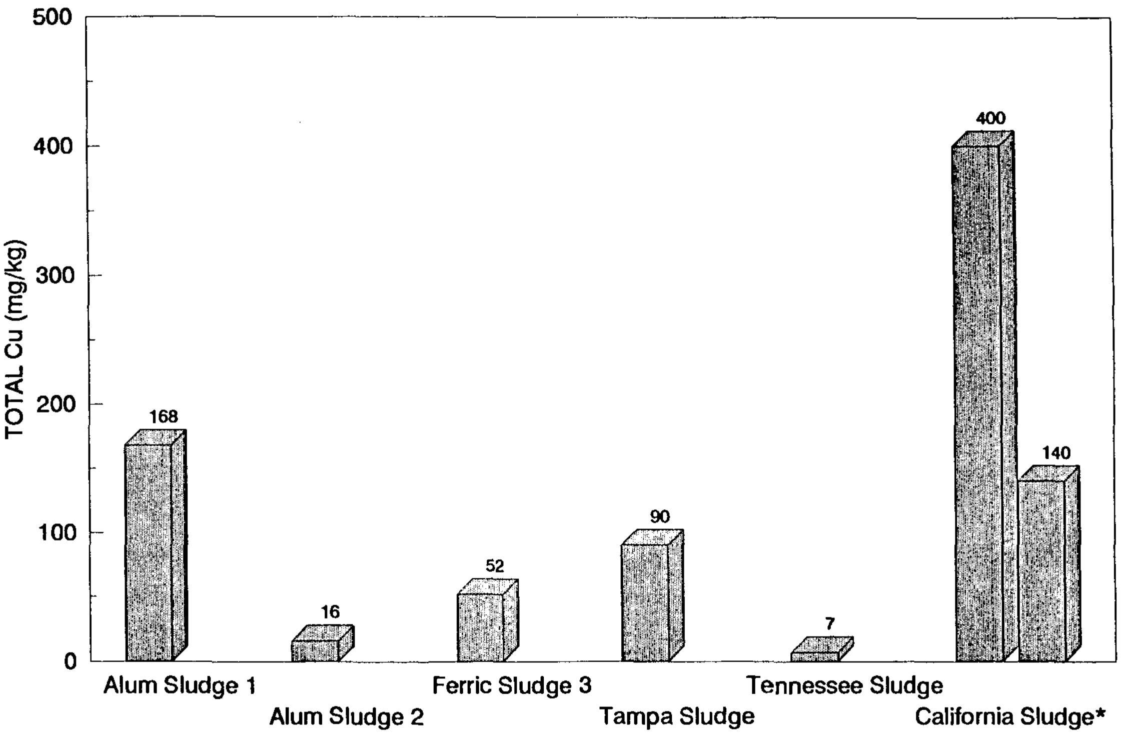
The TCLP is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes (40 CFR, Part 261 [*Federal Register* 1990]). The intent of the procedure is to identify and quantify contaminants that leach from a solid waste. If a total analysis of the waste reveals that individual analytes are not present, or that they are present at such low concentrations that regulatory levels could not possibly be exceeded, the TCLP need not be run (40 CFR, Part 261 [*Federal Register* 1990]). As in the EP toxicity test, a representative waste sample having a solids content of at least 0.5 percent is first separated into solid and liquid (if any) phases by subjecting it to pressure filtration. If a waste sample contains less than 0.5 percent solids, the waste itself is used as the extract in the procedure, after being filtered through a glass-fiber filter.

Extraction of the solid phase, which involves the addition to the solid of an amount of extraction fluid equal to 20 times its weight followed by their combination in an extraction vessel, is preceded by a reduction in solid particle size (if necessary to conform to standard requirements). When obtaining an extract to be used for analysis of nonvolatiles (metals, etc.) only, a minimum waste amount of 100 g is specified, primarily to ensure that an adequate volume of extract is obtained for analysis. However, when an extract is to be used to evaluate the mobility of volatiles,



*The two values indicate the high and low concentrations of a range compiled from tests performed over a 4-year period.

Figure 3.1 Arsenic concentrations in example water treatment plant sludges



*The two values indicate the high and low concentrations of a range compiled from tests performed over a 4-year period.

Figure 3.2 Copper concentrations in example water treatment plant sludges

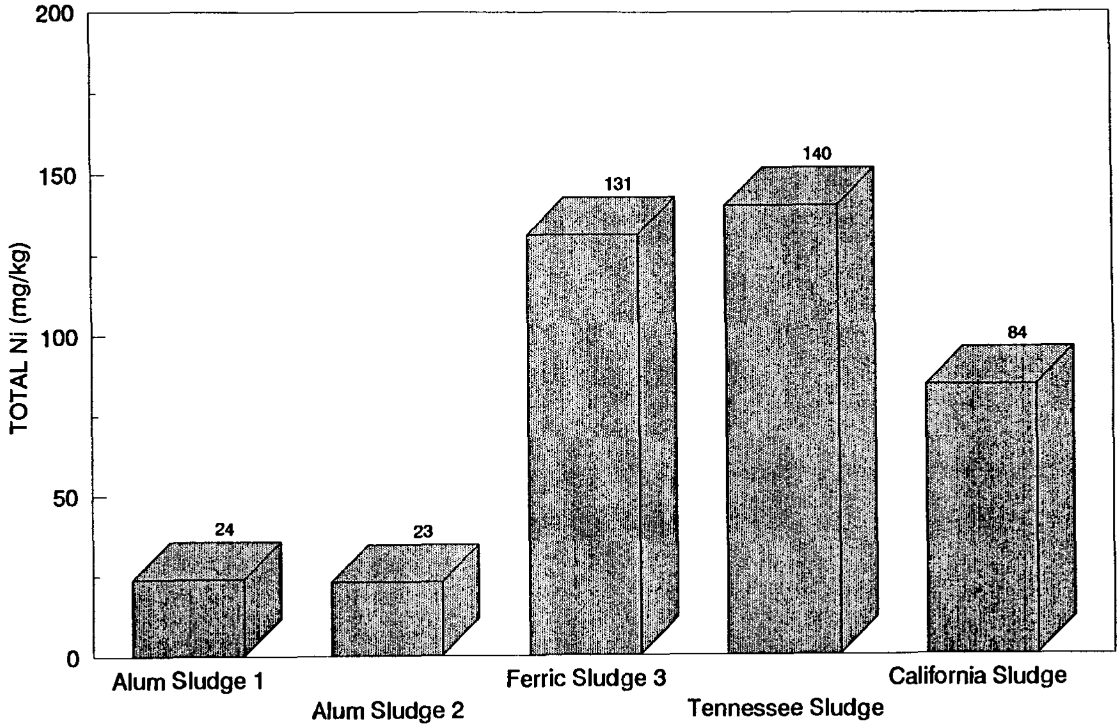
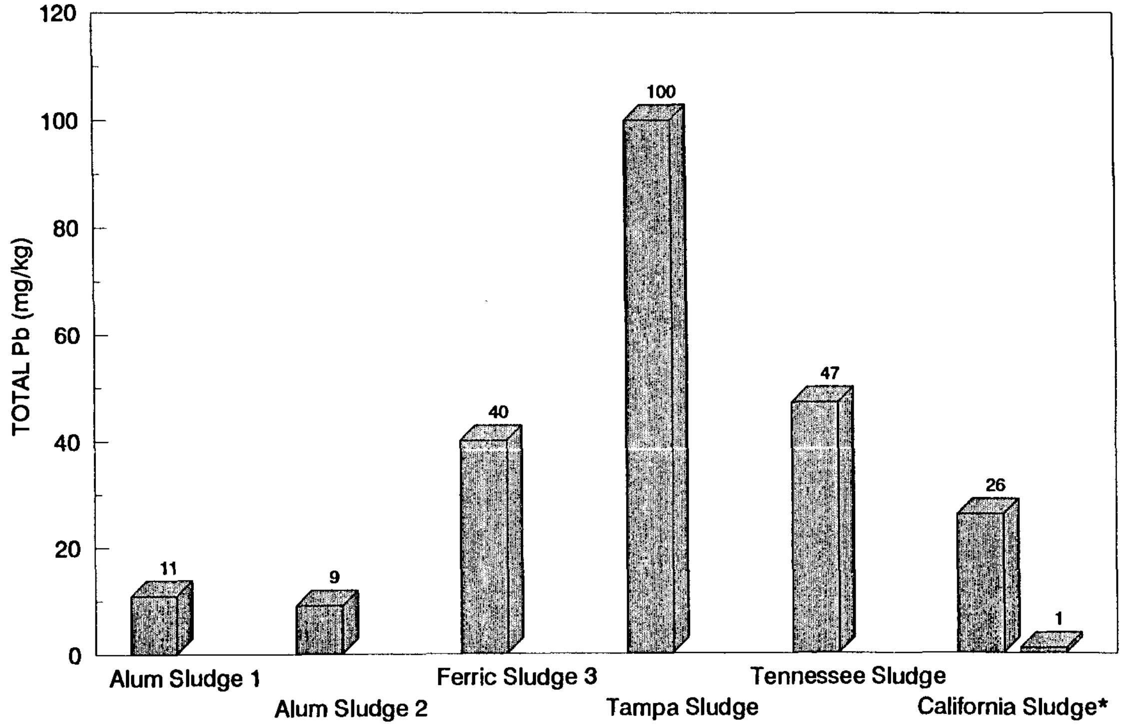
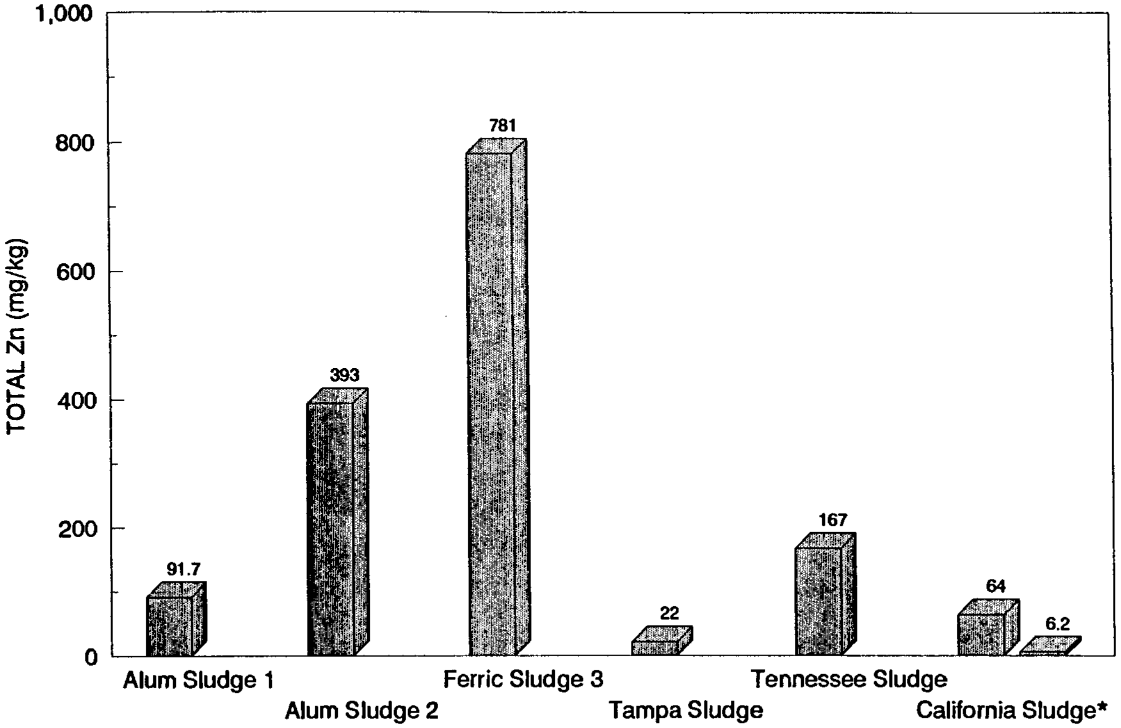


Figure 3.3 Nickel concentrations in example water treatment plant sludges



*The two values indicate the high and low concentrations of a range compiled from tests performed over a 4-year period.

Figure 3.4 Lead concentrations in example water treatment plant sludges



*The two values indicate the high and low concentrations of a range compiled from tests performed over a 4-year period.

Figure 3.5 Zinc concentrations in example water treatment plant sludges

Table 3.5 EP toxicity test results for alum sludge

Contaminant	Regulatory threshold (mg/L)	Saltonstall, Conn.* (mg/L)	West River, Conn.* (mg/L)	Chesapeake, Va.† (mg/L)	American Water Works Service Co. 66-plant survey‡ (mg/L)
Arsenic	5.0	<0.01	<0.01	<0.003	<0.2–0.4
Barium	100.0	0.21	0.1	<0.1	<0.1–34.0
Cadmium	1.0	<0.005	<0.005	0.005	<0.005–0.06
Chromium	5.0	<0.01	<0.01	<0.05	<0.1–3.8
Lead	5.0	<0.01	<0.01	<0.05	<0.03–4.1
Mercury	0.2	<0.001	<0.001	<0.001	<0.0004–0.003
Selenium	1.0	0.09	<0.01	<0.007	<0.001–0.08
Endrin	0.02	<0.01	0.01	<0.01	<0.001
Lindane	0.4	<0.0002	<0.0002	<0.0002	<0.00005
Methoxychlor	10.0	<0.004	<0.004	<0.0001	<0.0005
Toxaphene	0.5	<0.1	<0.1	<0.002	<0.001
2,4-D	10.0	<0.005	<0.005	<0.001	<0.005
2,4,5-TP Silvex	1.0	<0.01	<0.01	<0.001	<0.0005

Source: * Bugbee and Frink 1985.
† City of Chesapeake, Va., personal communication, 1985.
‡ Lowther 1988.

the maximum amount of solid that can be accommodated by the zero-headspace extraction (ZHE) vessel is 25 g, because of the volume of the vessel and the amount of extraction fluid required. After an 18-hour extraction period, the liquid extract is separated from the solid material through filtration using a glass-fiber filter. Assuming compatibility (i.e., combination will not result in formation of multiple phases), the liquid extract is added to the liquid (if any) from the original separation for analysis; otherwise, liquid fractions are analyzed separately and a volume-weighted average concentration is determined (40 CFR, Part 261 [*Federal Register* 1990]).

Some notable details regarding the extraction procedure include the specification that a ZHE vessel be employed when testing for the mobility of volatiles (zero headspace in the vessel precludes the escape of volatiles into the air) and the selection of the type of extraction fluid based on waste alkalinity in analysis of nonvolatile compounds. Two different extraction fluids, one having a pH of approximately 5 and the other with a pH of about 3, are used in the TCLP test. In TCLP extractions to be used to analyze for volatile constituents, and in extractions for nonvolatile analytes in which the pH of the sample after being mixed with water and stirred vigorously is less than 5, extraction fluid no. 1 (pH 4.93 ± 0.05) is specified. If the pH of the waste sample after being stirred is greater than 5, hydrochloric acid is added to the mixture, which is subsequently heated to 50°C, held at that temperature for 10 minutes, and allowed to cool. Only if the pH is less than 5 after completion of this test should fluid no. 1 be used for the extraction; otherwise extraction fluid no. 2 (pH 2.88 ± 0.05) should be used. Along with the difference in extraction time (18 hours for the TCLP and 24 hours for the EP toxicity test) and the type of filter used for the separation into solid and liquid phases, these requirements comprise the more significant differences in the TCLP and EP toxicity tests.

The results of TCLP tests performed on alum sludge from two different sources are shown in Table 3.6 along with the threshold level for each constituent regulated. None of the regulatory limits were exceeded. Although detection limits for each constituent varied from test to test, results were similar; the vast majority of regulated constituents were not detectable in either of the sludge samples. Constituents that were detected were present in amounts well below regulatory levels.

Landfill Leaching Study

As part of a research project funded by AWWARF, a study concerning the chemical characterization of WTP coagulant sludges was conducted by Environmental Engineering & Technology, Inc. (EE&T), at its process laboratory in Newport News, Va. The focus of the study was to simulate conditions found in a dedicated sludge landfill and to analyze the quality of leachate produced in order to assess its potential as a groundwater contaminant. Determination of total metals concentrations in the sludge along with leachate monitoring made possible the quantification of leaching constituents. In addition, the sludge itself was tested for toxicity in accordance with RCRA requirements, in order to verify its nonhazardous nature.

The concept of the lysimeter model used in the test was based on wastewater and refuse studies done by USEPA Cincinnati with SCS Engineers, as reported by Stamm and Walsch (1988). The models and monitoring were altered to reflect the nature of WTP sludge as well as the specific intent of the research. Figure 3.6

Table 3.6 TCLP results for two water treatment plant coagulant sludges

Contaminant	Regulatory threshold level (mg/L)	Contra Costa Water District alum sludge (mg/L)	Phoenix, Ariz., alum sludge (mg/L)
Arsenic	5.0	0.04	<0.3
Barium	100.0	1.1	1.1
Cadmium	1.0	<0.05	<0.02
Chromium	5.0	0.06	<0.04
Lead	5.0	<0.2	<0.5
Mercury	0.2	<0.001	<0.01
Selenium	1.0	<0.02	<1
Silver	5.0	<0.05	<0.01
Endrin	0.02	*	<0.00007
Lindane	0.4	*	<0.00004
Methoxychlor	10	*	<0.0002
Toxaphene	0.5	*	<0.0005
2,4-D	10	*	<3
2,4,5-TP	1.0	*	<0.5
Chlordane	0.03	*	<0.0003
Heptachlor (and its epoxide)	0.008	*	<0.00004
Benzene	0.5	<0.001	<0.003
Carbon tetrachloride	0.5	<0.001	<0.001
Chlorobenzene	100	<0.001	<0.001
Chloroform	6.0	<0.001	0.004
1,2-Dichloroethane	0.5	<0.001	<0.001
1,1-Dichloroethylene	0.7	<0.001	<0.001
Methyl ethyl ketone	200	0.37	<0.01
Tetrachloroethylene	0.7	<0.001	<0.001
Trichloroethylene	0.5	<0.001	<0.001
Vinyl chloride	0.2	<0.001	<0.001
1,4-Dichlorobenzene	7.5	<0.02	<0.001
Hexachlorobenzene	0.13		<0.01
Hexachlorobutadiene	0.5	<0.05	<0.01
2,4-Dinitrotoluene	0.13	<0.2	<0.01
Hexachloroethane	3.0	<0.1	<0.01
Nitrobenzene	2.0	<0.02	<0.01
Pyridine	5.0	*	<0.05
o-Cresol	200	<0.05	<0.01
m-Cresol	200	*	*
p-Cresol	200	<0.1	<0.01
Cresol	200	*	*
Pentachlorophenol	100	<0.2	<0.01
2,4,5-Trichlorophenol	400	<0.1	<0.01
2,4,6-Trichlorophenol	2.0	<0.1	<0.01

Source: Phoenix data: Environmental Engineering & Technology 1990. Contra Costa data: Contra Costa County, personal communication.

* Results for these constituents were not available for review.

schematically illustrates the lysimeter columns utilized during the pilot testing. The 1-ft-square (0.093-m-square) PVC columns were fitted with drains for leachate collection. Approximately 6 ft (1.83 m) of sludge were placed in each column over a base of gravel and sand. Rainfall was simulated by the application through a perforated plate at the top of each column of water having the chemical characteristics of Virginia rainwater. Rainwater having a pH of 4.5 was "made" in the laboratory with the composition shown in Table 3.7.

The pilot scale evaluation of landfill leachate quality was begun in November 1990 and was continued for a period of 24 weeks from that date. Sludges from each

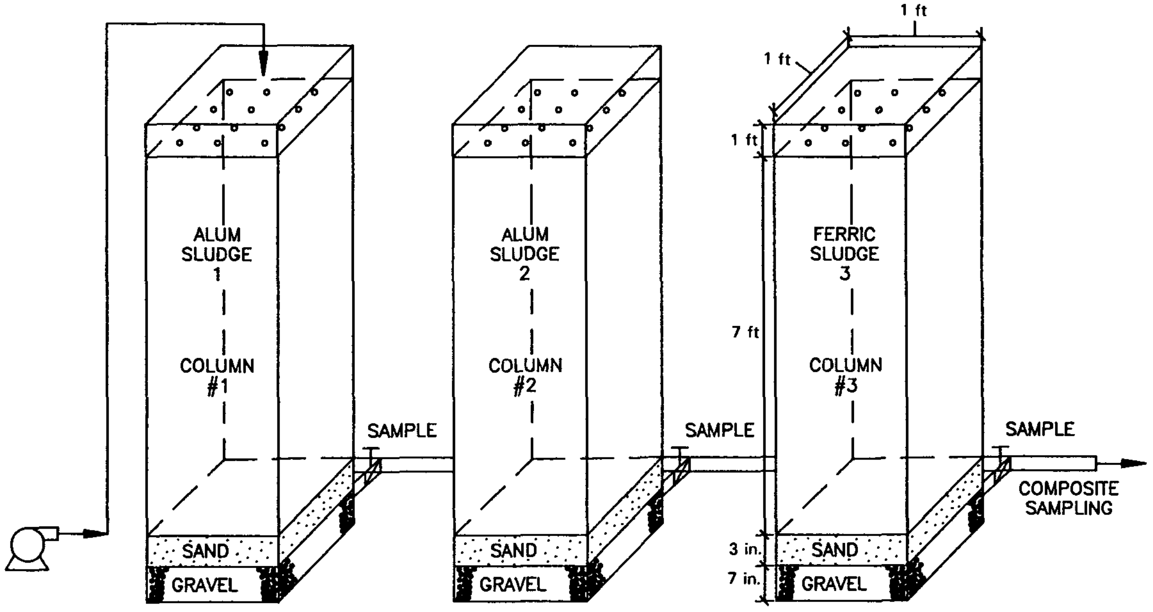


Figure 3.6 Lysimeter pilot testing

Table 3.7 Chemical constituents of synthetic rainwater

Constituent	Concentration (mg/L)
NH^3	0.045
CA^{2+}	0.14
Mg^{2+}	0.073
Na^+	0.46
K^+	0.078
Cl^-	1.63
N^{3-5}	0.036
SO_4^{2-}	1.54
pH	4.5

of three different water treatment plants were placed in lysimeter columns 1, 2, and 3 after being dried to solids contents of approximately 35 percent. Sludge sources are detailed below.

Column 1, alum sludge 1:	Alum sludge from Williams Water Treatment Plant located in Durham, N.C., derived from a water having medium turbidity and medium color
Column 2, alum sludge 2:	Alum sludge from Chesapeake Water Treatment Plant located in Chesapeake, Va., derived from a water having low turbidity and high color
Column 3, ferric sludge 3:	Ferric sludge from Aldrich Treatment Plant (a Pennsylvania–American Water Company plant), derived from a water having medium turbidity and medium color

Typical raw water quality data for the three sludge sources are provided in Table 3.8. The same sludges were used in the physical characterization work, which is the focus of Chapter 4 of this report.

In each column, rainfall was applied at an instantaneous hydraulic loading rate of 44.1 L/d for a 24-hour period. This rate corresponds to a flow rate of about 31 mL/min. This flow was applied at the top of the column to a perforated plate that created a head of water and resulted in a "dripping" from the plate across the sludge surface area. The sludge was placed very loosely in the column so as to allow the rain to percolate through. Had the sludge been compacted, the rain would have ponded because of the low permeability. After a period of 1 week, during which the rainwater remained in each column, the columns were drained and composite samples of leachate were collected for subsequent analysis. After the first 3 weeks, analyses were conducted on samples drawn approximately every fourth week. The total amount of water applied to the columns was equal to about 450 in. (1,143 cm) of rain. This is equal to the amount of rain that falls in Virginia over a period of about 12 years.

Dissolved metals analyses performed (using Standard Methods 303A, 303C, and 304 [APHA, AWWA, and WPCF 1980] on leachate that drained from the lysimeter columns indicated some degree of leaching of the following metals: arsenic, cadmium, copper, iron, manganese, nickel, and zinc. Concentrations of all constituents monitored over the 24-week period of the landfill study are shown in Tables 3.9 through 3.11. Slight amounts of selenium (below primary drinking water MCLs) were detected in leachate collected from columns 2 and 3 during the first week of the study only. Because the background selenium concentrations for all three sludges were below the detection limits used in the total metals analyses (performed in accordance with Standard Methods 303A, 303C, 303F, and 304 [APHA, AWWA, and WPCF 1980]), however, the percentage leached could not be calculated. For all metals that leached measurably, data showing the amount of leaching along with the rain applied during each test period (test periods ranged from 1 to 6 weeks) are presented in the appendix.

Table 3.8 Typical raw water quality of sludge sources and required coagulant addition

	Alum sludge 1 Williams WTP Durham, N.C.		Alum sludge 2 Chesapeake WTP Chesapeake, Va.		Ferric sludge 3 Aldrich Treatment Plant Pa.–American Water Co.	
Parameter	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Turbidity (ntu)	43.0	8–140	5	2–20	14	3–400
Color (cu)	41.0	20–60	250	100–400	Data not available	
pH	6.7	6.3–6.8	6.5	5.0–6.8	7.4	7.1–8.0
Total alkalinity (mg/L as $CaCO_3$)	15.2	6–25	30	10–35	41	26–60
Total hardness (mg/L as $CaCO_3$)	20.0	10–26	50	45–55	157	85–290
Total organic carbon (mg/L)		3–6	25	20–40		1–8
Coagulant type	Alum		Alum		Ferric	
Coagulant dose (mg/L)	30.0		140	90–220	2.4*	
Polymer type	None used		Nonionic		Cationic/Nonionic	
Polymer dose (mg/L)	0		0.4	0.3–0.5	0.7/0.02	

* Coagulant dose is expressed on a dry weight basis.

Table 3.9 Lysimeter leachate dissolved metals concentrations (mg/L), alum sludge 1

Parameter	Week 1	Week 2	Week 3	Week 6	Week 10	Week 14	Week 18	Week 24
Aluminum	<1.0	<1.0	<1.0	<0.5	<0.5	<0.5	<0.5	<0.6
Arsenic	0.0025	0.001	0.0035	0.0027	<0.0005	<0.0005	<0.0005	<0.0005
Barium	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.3
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chromium	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.1
Copper	0.10	0.12	0.06	<0.03	<0.03	<0.03	<0.03	<0.03
Iron	<0.01	<0.01	0.21	2.0	0.5	0.3	0.3	1.42
Lead	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.08
Manganese	8.30	8.50	7.50	8.70	6.70	7.60	8.7	9.5
Nickel	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Selenium	0.008	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Silver	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Zinc	0.036	<0.005	0.016	0.010	0.011	0.008	<0.005	<0.006

Note: Standard Methods procedures 303A, 303C, and 304 were used in the analysis.

Table 3.10 Lysimeter leachate dissolved metals concentrations (mg/L), alum sludge 2

Parameter	Week 1	Week 2	Week 3	Week 6	Week 10	Week 14	Week 18	Week 24
Aluminum	<1.0	<1.0	<1.0	<0.5	<0.5	<0.5	<0.5	<0.6
Arsenic	<0.0005	<0.0005	0.0019	0.0005	0.0010	<0.0005	<0.0005	<0.0005
Barium	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.3
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chromium	<0.2	<0.2	<0.2	<0.2	0.0046	<0.2	<0.2	<0.0002
Copper	<0.03	0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Iron	<0.01	<0.01	0.03	<0.10	0.2	<0.1	0.1	0.30
Lead	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.08
Manganese	0.36	0.27	0.20	0.11	0.06	0.03	0.06	0.29
Nickel	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Selenium	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Silver	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Zinc	<0.005	<0.005	0.009	0.017	<0.005	0.006	<0.005	<0.006

Note: Standard Methods procedures 303A, 303C, and 304 were used in the analysis.

Table 3.11 Lysimeter leachate dissolved metals concentrations (mg/L), ferric sludge 3

Parameter	Week 1	Week 2	Week 3	Week 6	Week 10	Week 14	Week 18	Week 24
Aluminum	<1.0	<1.0	<1.0	<1.0	<0.5	<0.5	<0.5	<0.6
Arsenic	0.011	0.011	0.0146	0.0366	0.0153	0.0195	0.0048	0.0139
Barium	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.3
Cadmium	0.01	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Chromium	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.1
Copper	0.06	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Iron	<0.01	<0.01	0.03	1.0	0.2	0.1	0.1	0.52
Lead	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.08
Manganese	22.8	21.3	13.0	8.9	7.30	5.00	5.14	4.32
Nickel	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Selenium	0.005	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.002
Silver	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Zinc	0.373	0.123	0.055	0.037	0.024	0.027	0.021	0.008

Note: Standard Methods procedures 303A, 303C, and 304 were used in the analysis.

The TCLP analyses were conducted using each of the three test sludges. All three would "obviously yield no liquid when subjected to pressure filtration" (40 CFR, Part 261 [*Federal Register* 1990]) and were deemed 100 percent solid as defined in the CFR. The solid wastes were prepared for extraction by crushing to ensure that particles were no larger than 1 cm in their narrowest dimension. Subsequently, because analysis of nonvolatiles was to be involved, the appropriate extraction fluid to be used was determined. After the sludge was mixed vigorously with a specified volume of water, sludge pH values were measured to be greater than 5. The procedure of adding acid to the mixture, heating it, maintaining a constant temperature for a 10-minute period, and then cooling it was thereby necessitated according to the regulations. Resulting pH values of less than 5 (pH dropped below 3) dictated that fluid no. 1 be utilized in the extraction of nonvolatiles as well as volatiles. Fluid no. 1 is used unconditionally in obtaining extracts to be used for analysis of volatile compounds.

A ZHE device was used to obtain TCLP extract for analysis of both volatile and nonvolatile compounds. The TCLP procedure states that zero headspace is required in extraction vessels only when the extract is to be used for analysis of volatile analytes. The procedure further indicates that the ZHE vessel should not be used in obtaining extract to be used for the analysis of nonvolatiles. It is the authors' belief that use of the ZHE vessel instead of an extraction bottle for extraction of nonvolatiles would not yield an extract unsuitable for subsequent analysis; however, the limited volume of the ZHE vessel (0.5 L) could preclude obtaining an adequate volume of extract for analysis. It is also worth noting that a ZHE device is quite expensive and more cumbersome to operate than a bottle extractor.

The maximum amount of each TCLP-regulated metal present in each of the three sludges evaluated in this leaching research, determined through a total metals analysis, was compared to the TCLP regulatory threshold level. As shown in Table 3.12, no constituent is out of compliance with the limit. It should be noted that the data in the first three columns of the table indicate the total amounts of metals present, rather than the amount that would be extracted from the waste in an 18-hour extraction as performed in the TCLP. The formula used to estimate the maximum amount of a particular constituent that could be extracted from the sludge is presented below, along with a sample calculation for arsenic.

$$\frac{\begin{pmatrix}\text{sludge total metal}\\ \text{concentration}\\ \text{(mg/kg)}\end{pmatrix}\begin{pmatrix}\text{TCLP sample}\\ \text{size}\\ \text{(g)}\end{pmatrix}\begin{pmatrix}\text{solids content}\\ \text{of sludge}\\ \text{(\%)}\end{pmatrix}}{\text{extraction fluid volume (L)}} = \begin{matrix}\text{maximum leachable}\\ \text{quantity (mg/L)}\end{matrix}$$

$$\frac{\text{Arsenic}}{\text{Alum sludge 1}}: \frac{(25\ \text{mg/kg})(1\ \text{kg/1,000 g})(25\ \text{g})(0.57)}{0.5\ \text{L}} = 0.72\ \text{mg/L}$$

Performing such a calculation along with a total metals analysis could eliminate the need for further, more expensive analysis according to the federal TCLP procedure.

A direct comparison of potential and actual leaching serves to indicate metals that could not possibly exceed TCLP allowable limits (all in this case); only if 100 percent of the metals were to be extracted from the waste during the extraction procedure would the concentrations shown be reached. The potential significance of this comparison from the standpoint of economics is derived from the following statement: "If a total analysis of the waste demonstrates that individual analytes are not present, or that they are present at such low concentrations that appropriate regulatory levels could not possibly be exceeded, the TCLP need not be run" (40 CFR, Part 261 [*Federal Register* 1990]). It appears that a relatively inexpensive standard metals analysis would be sufficient for a typical WTP coagulant sludge to prove that regulatory TCLP metals limits could not be exceeded. Table 3.13 indicates the total metal concentration (for each regulated metal) that would have to be present in sludges with solids contents of 57 and 22 percent to reach threshold levels (assuming 100 percent of the total is extracted), along with actual concentrations determined analytically through total metals analyses performed on alum sludges 1 and 2. In the examples shown, the regulatory limits could not be reached.

Actual TCLP results obtained in an analysis performed on alum sludges 1 and 2 and ferric sludge 3 show the amounts of each constituent that were extracted from the waste. These numbers are presented in the last three columns of Table 3.12

Table 3.12 Total analysis versus TCLP analysis for sludges used in landfill leaching research

	Maximum concentration in waste based on total metals analysis (mg/L)			TCLP regulatory limit (mg/L)	TCLP analysis results (mg/L)		
Metal	**Alum sludge 1**	**Alum sludge 2**	**Ferric sludge 3**		**Alum sludge 1**	**Alum sludge 2**	**Ferric sludge 3**
Arsenic	0.72	0.35	0.27	5.0	0.0088	0.0023	0.0006
Barium	0.86	0.33	6.60	100.0	1.0	<1.0	2.0
Cadmium	0.03	0.011	0.06	1.0	<0.02	<0.02	0.02
Chromium	3.43	1.43	1.44	5.0	<0.1	<0.1	<0.1
Lead	0.32	0.10	1.15	5.0	<0.1	<0.1	<0.1
Mercury	0.0029	0.0006	0.0057	0.2	<0.002	<0.002	<0.002
Selenium	<0.1	<0.1	<0.1	1.0	<0.002	<0.002	<0.002
Silver	<0.1	<0.1	<0.1	5.0	<0.1	<0.1	<0.1

Table 3.13 Total sludge metal concentrations required to fail TCLP test compared to actual data

	Minimum concentration to exceed TCLP limit* (mg/kg)		Total concentrations determined through total metals analyses (mg/kg)	
Constituent	**22 percent solids**	**57 percent solids**	**Alum sludge 2 (22 percent solids)**	**Alum sludge 1 (57 percent solids)**
Arsenic	455	175	32	25
Barium	9,090	3,510	<30	30
Cadmium	90	35	1	1
Chromium	455	175	130	120
Lead	455	175	9	11
Mercury	18	7	<0.1	0.1
Selenium	90	35	<2	<2
Silver	455	175	<2	<2

* TCLP limit would only be exceeded if 100 percent of the constituent were to be extracted during the test. Quantities are shown on a dry weight basis.

for purposes of comparison. None of the regulatory limits set forth in the TCLP were violated. Only three metals were detected in the TCLP extract: arsenic, barium, and cadmium. The percentage of arsenic that actually leached ranged from 0.2 to 1.2 percent. One-third of the cadmium present in the ferric sludge was extracted in the TCLP test; however, the amount of cadmium initially present was low enough to render this insignificant. From one-third to 100 percent of the barium present was extracted in the TCLP. Again, however, quantities were far below allowable limits. The remaining constituents on the TCLP list (pesticides, volatile organics) were not detected and were eliminated from further consideration. Complete results are shown in Table 3.14.

Table 3.14 TCLP test results for landfill leaching study sludges

Contaminants	Regulatory threshold level (mg/L)	Alum sludge 1	Alum sludge 2	Ferric sludge 3
Arsenic	5.0	0.0088	0.0023	0.0006
Barium	100.0	1	<1	<2
Cadmium	1.0	<0.02	<0.02	0.02
Chromium	5.0	<0.1	<0.1	<0.1
Lead	5.0	<0.1	<0.1	<0.1
Mercury	0.2	<0.002	<0.002	<0.002
Selenium	1.0	<1	<0.002	<0.002
Silver	5.0	<0.1	<0.1	<0.1
Endrin	0.02	<0.005	<0.005	<0.005
Lindane	0.4	<0.005	<0.005	<0.005
Methoxychlor	10	<0.005	<0.005	<0.005
Toxaphene	0.5	<0.005	<0.005	<0.005
2,4-D*	10	—	—	—
2,4,5-TP*	1.0	—	—	—
Chlordane	0.03	<0.005	<0.005	<0.005
Heptachlor (and its epoxide)	0.008	<0.005	<0.005	<0.005
Benzene	0.5	<0.005	<0.005	<0.005
Carbon tetrachloride	0.5	<0.005	<0.005	<0.005
Chlorobenzene	100	<0.005	<0.005	<0.005
Chloroform	6.0	<0.005	<0.005	<0.005
1,2-Dichloroethane	0.5	<0.005	<0.005	<0.005
1,1-Dichloroethylene	0.7	<0.005	<0.005	<0.005
Methyl ethyl ketone	200	<0.100	<0.100	<0.100
Tetrachloroethylene	0.7	<0.005	<0.005	<0.005
Trichloroethylene	0.5	<0.005	0.005	<0.005
Vinyl chloride	0.2	<0.01	<0.01	<0.01
1,4-Dichlorobenzene	7.5	<0.005	<0.005	<0.005
Hexachlorobenzene	0.13	<0.005	<0.005	<0.005
Hexachlorobutadiene	0.5	<0.005	<0.005	<0.005
2,4-Dinitrotoluene	0.13	<0.01	<0.01	<0.01
Hexachloroethane	3.0	<0.01	<0.01	<0.01
Nitrobenzene	2.0	<0.005	<0.005	<0.005
Pyridine	5.0	<0.500	<0.500	<0.500
o-Cresol	200	<0.500	<0.500	<0.500
m-Cresol	200	<0.500	<0.500	<0.500
p-Cresol	200	<0.500	<0.500	<0.500
Cresol	200	<0.500	<0.500	<0.500
Pentachlorophenol	100	<0.005	<0.005	<0.005
2,4,5-Trichlorophenol	400	<0.01	<0.01	<0.01
2,4,6-Trichlorophenol	2.0	<0.01	<0.01	<0.01

* Due to the extremely low probability that these pesticides would be present in a WTP sludge, they were omitted from the TCLP extract analysis.

The total percentage of each constituent that had leached from each column over the period of study is presented in Table 3.15, along with a ratio of predicted (according to the TCLP) to actual percentage leached. A value of 1 indicates a perfect correlation between observed and predicted values. For example, the TCLP test in which no cadmium was extracted indicated that no cadmium would leach from the alum sludges, and no cadmium was detected in the leachate from these sludges. Overprediction by the TCLP is indicated by numbers higher than 1, and numbers lower than 1 indicate that more of a constituent actually leached from the sludge than was predicted in the test. Arsenic leaching from the alum sludges was overestimated by a factor of 12 to 27, whereas for the ferric sludge the TCLP analysis indicated that the amount of arsenic leaching would be just 8 percent of the actual amount that leached. Limited data appear to indicate a tendency for the TCLP to err on the conservative side. However, most of the metals that exhibited significant leaching are not TCLP parameters, and such a comparison could not be made.

The percentage of each leached constituent as a function of cumulative rainfall is represented graphically in Figures 3.7 through 3.12. Although zinc, copper, and cadmium leaching seemed to reach a definitive plateau (zinc and cadmium after approximately 250 cumulative inches of rainfall had been applied and copper almost immediately), manganese, iron, and arsenic levels present in the leachate were still exhibiting increasing trends toward the conclusion of the testing period.

None of the primary drinking MCLs for the metals monitored over the course of the study were exceeded in any of the leachate samples analyzed. And of the metals that exhibited any leaching, only arsenic and cadmium appear on the Primary Drinking Water Standards list. Elevated levels (above the secondary maximum contaminant level [SMCL]) of iron were found in leachate from alum

Table 3.15 Actual and predicted leaching of metals for landfill leaching research

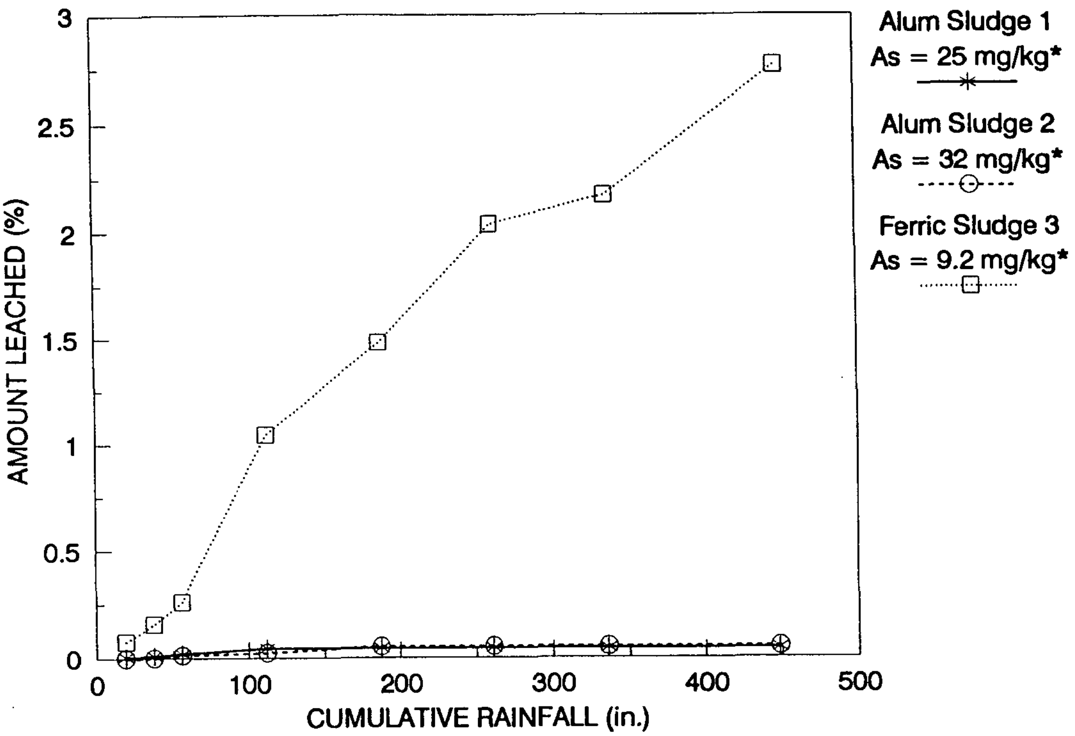
	Percent of total metal present that actually leached			Ratio of leaching percentage predicted by TCLP to percentage of metal that actually leached		
Metal	**Alum sludge 1**	**Alum sludge 2**	**Ferric sludge 3**	**Alum sludge 1**	**Alum sludge 2**	**Ferric sludge 3**
Aluminum*	0.00	0.00	0.00	—	—	—
Arsenic	0.05	0.05	2.77	27.16	12.64	0.08
Barium	0.00	0.00	0.00	0	1	0
Cadmium	0.00	0.00	2.03	1	1	16.42
Chromium	0.00	0.00	0.00	1	1	1
Copper*	0.12	0.42	0.08	—	—	—
Iron*	0.03	0.05	0.01	—	—	—
Lead	0.00	0.00	0.00	1	1	1
Manganese*	12.48	3.38	2.45	—	—	—
Nickel*	0.00	0.00	0.03	—	—	—
Selenium†	†	0.00	†	†	1	†
Silver	0.00	0.00	0.00	1	1	1
Zinc*	0.13	0.05	0.08	—	—	—

* These metals are not analyzed in a standard TCLP test.

† Selenium leaching could not be quantified.

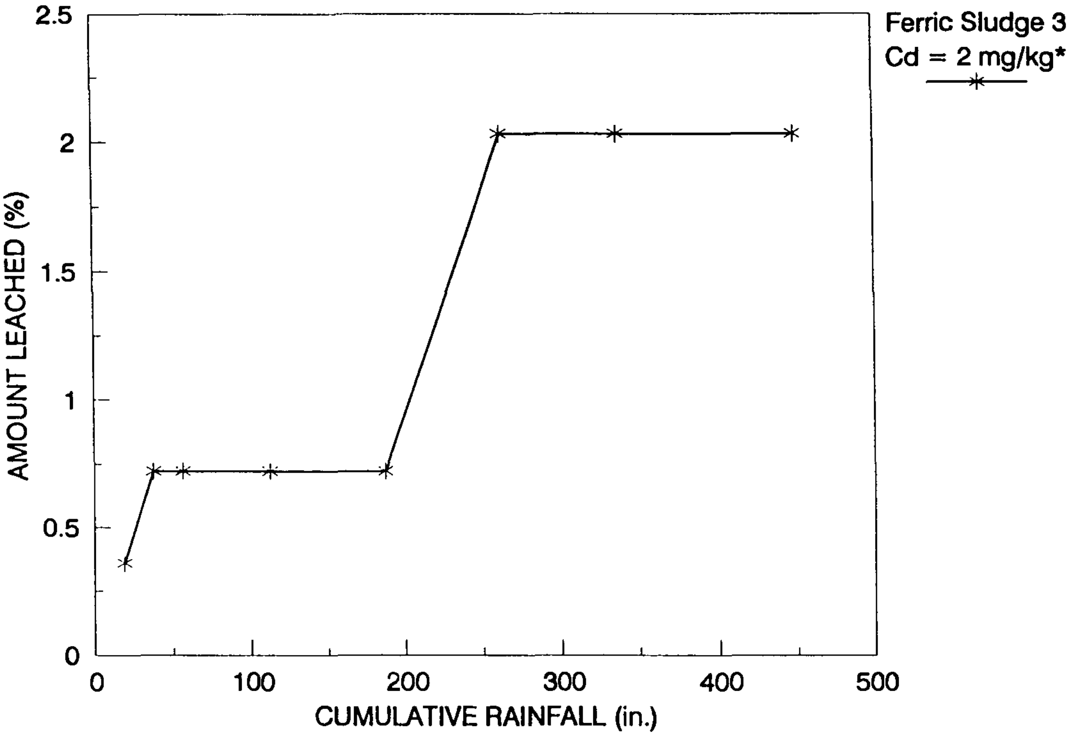
— indicates that no comparison could be made because the constituent is not a regulated parameter in the TCLP.

0 (zero) indicates that none of the constituent was detected in the leachate, although some degree of leaching was predicted in the TCLP.



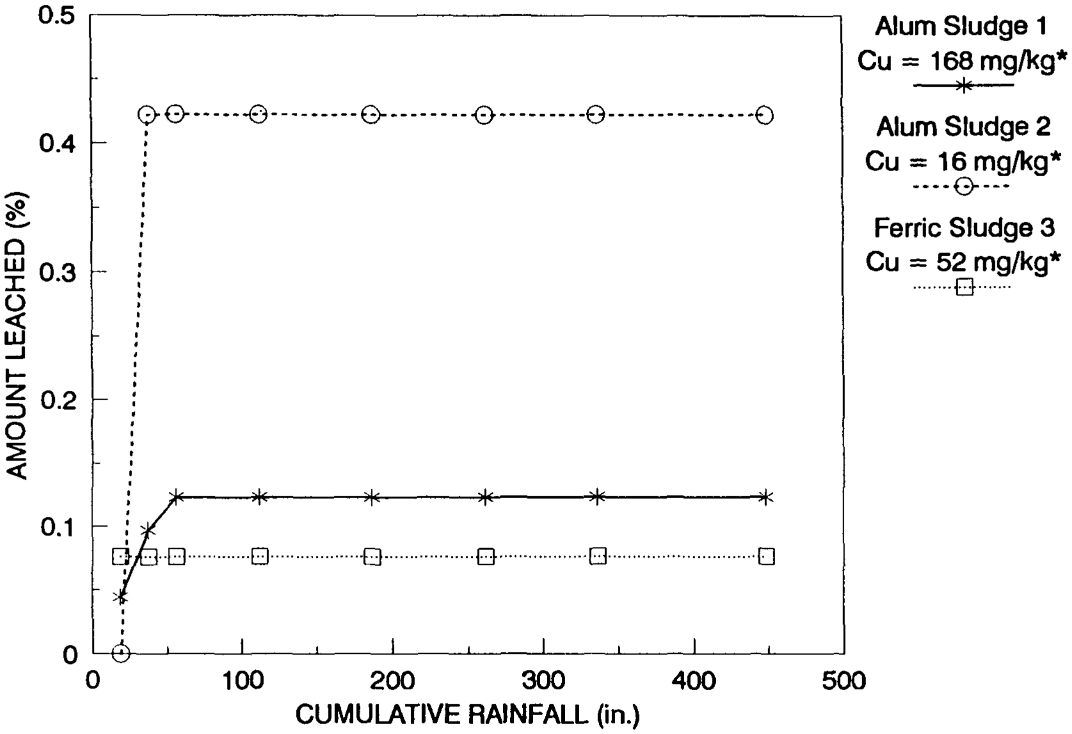
*Concentrations are total concentrations in sludge as received.

Figure 3.7 Arsenic leaching from lysimeter columns



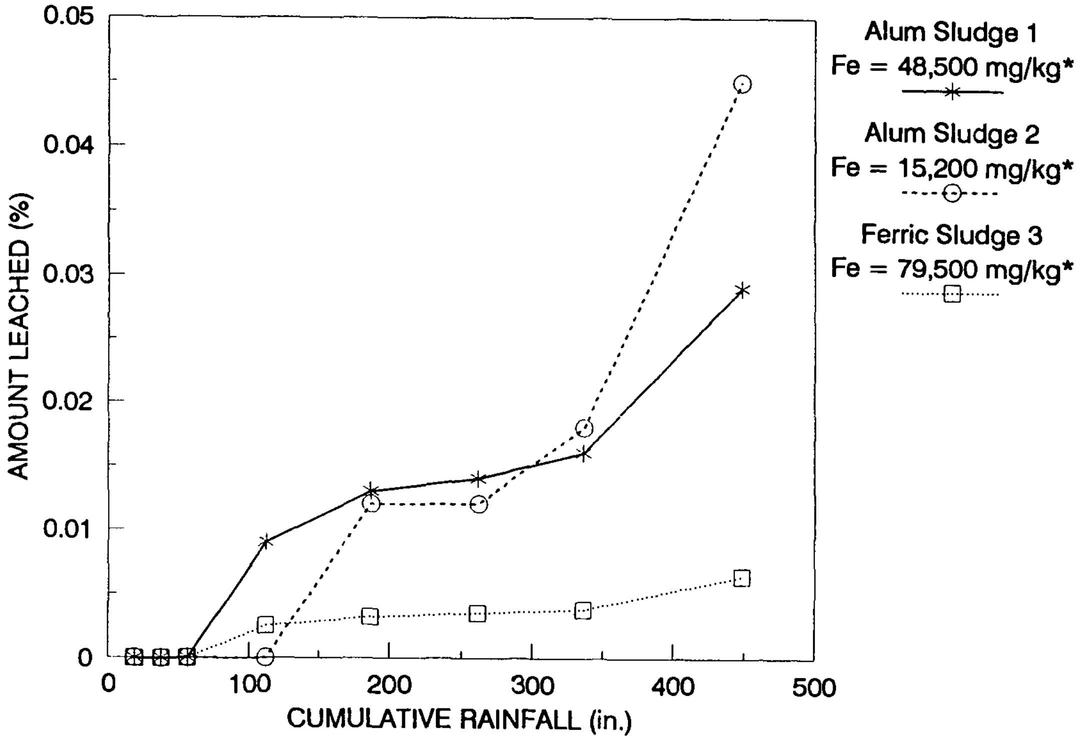
*Concentrations are total concentrations in sludge as received.

Figure 3.8 Cadmium leaching from lysimeter columns



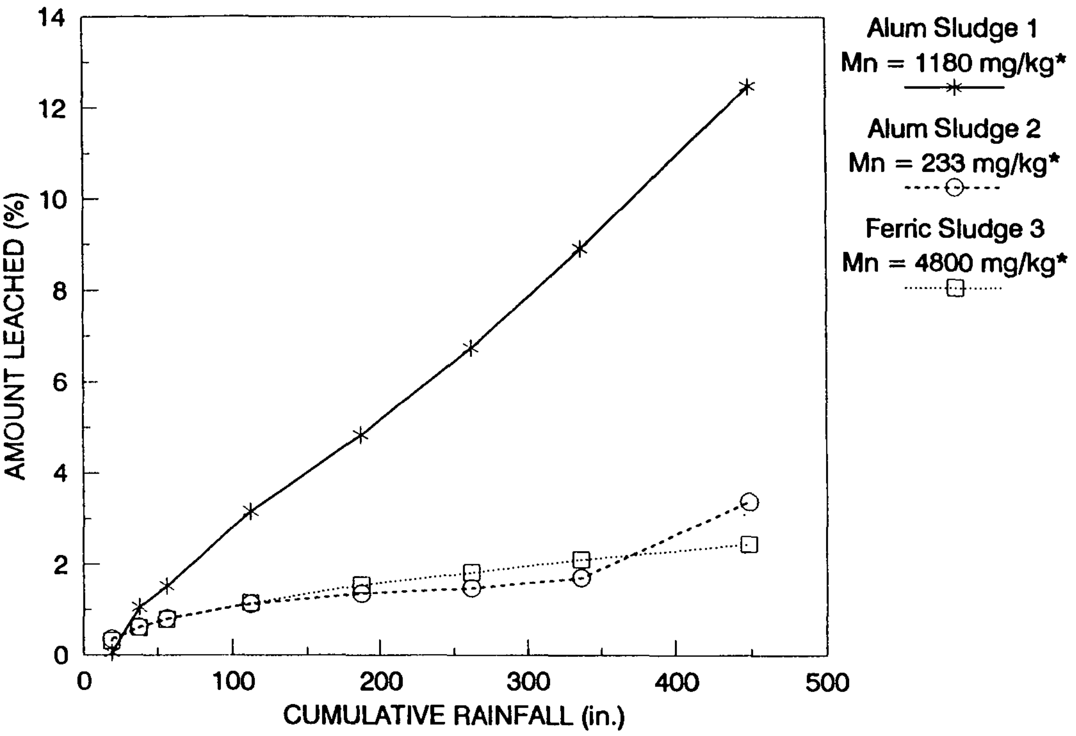
*Concentrations are total concentrations in sludge as received.

Figure 3.9 Copper leaching from lysimeter columns



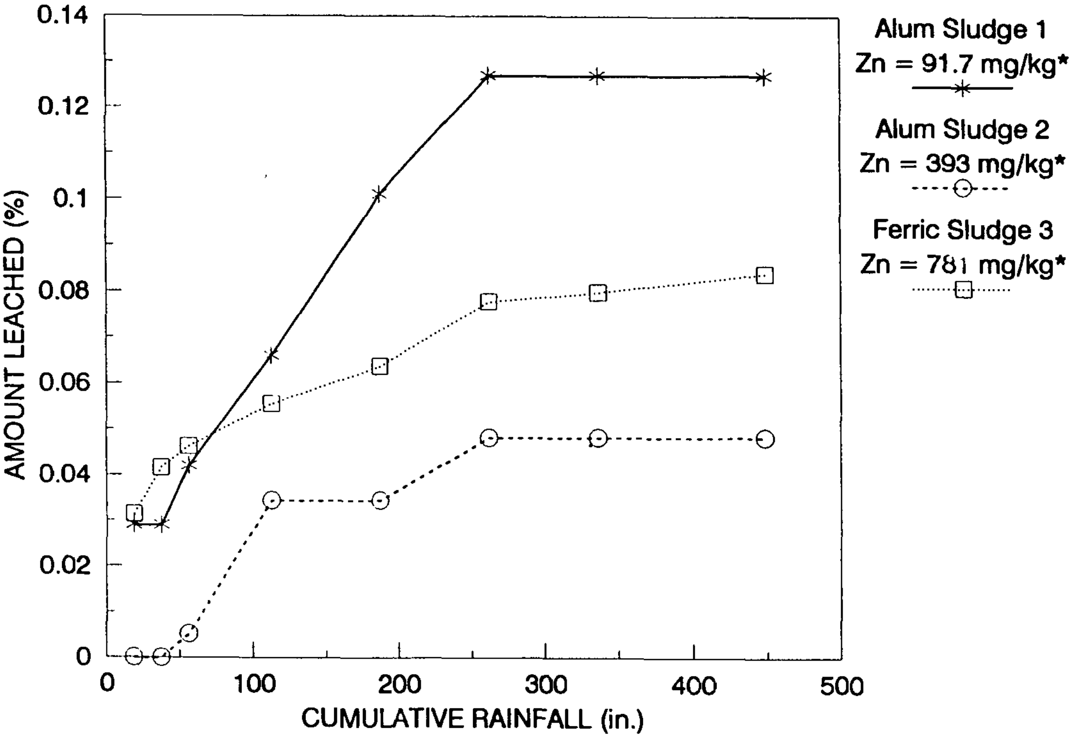
*Concentrations are total concentrations in sludge as received.

Figure 3.10 Iron leaching from lysimeter columns



*Concentrations are total concentrations in sludge as received.

Figure 3.11 Manganese leaching from lysimeter columns



*Concentrations are total concentrations in sludge as received.

Figure 3.12 Zinc leaching from lysimeter columns

sludge 1 and ferric sludge 3, and analysis of leachate from all three of the sludges revealed the presence of manganese well in excess of SMCLs. The SMCLs for iron and manganese are 0.3 and 0.05 mg/L, respectively. It should be noted that these inorganics do not appear in the revised federal regulations for waste disposal in municipal solid waste landfills on the list of groundwater protection monitoring indicator parameters, although they were included in the proposed rule. (See Chapter 2 for information regarding regulations.)

Although primary drinking water standards were not violated by any of the metals that leached, the USEPA's often more stringent in-stream water quality guidelines were exceeded in a few instances. In some cases copper, iron, and zinc levels in the leachate were found in concentrations that exceeded USEPA's in-stream guidelines. For comparative purposes, threshold concentrations for both sets of standards are indicated in Table 3.16. Figures 3.13 through 3.15 illustrate leachate concentrations in relation to these drinking water and in-stream contaminant limits.

In addition to metals, pH, alkalinity, and hardness of leachate from each of the columns were monitored over the course of the study. As noted earlier in this chapter, pH is believed to have particular influence on the leaching of various constituents from WTP residuals. For the most part, pH of the leachate remained at about 6.5 to 7 for the duration of the study, indicating that the sludge had a buffering effect on the rainwater. The pH of the leachate from alum sludge 1 was closer to 6 and actually fell into the 5.5 range for several weeks during the middle of the testing. Nevertheless, it was well above the pH of 4.5 of the rainwater applied. The drop in pH did not appear to precipitate any increased leaching. Figure 3.16 shows pH variations over the course of the test.

The hardness and alkalinity of the leachate were also determined on a weekly basis. Leachate from ferric sludge 3 had the highest initial hardness at 1,544 mg/L as $CaCO_3$. Just a couple of weeks into the study, however, the hardness dropped to approximately 500 mg/L as $CaCO_3$, where it leveled off. The hardness of the leachate from the two alum sludges was much lower initially and exhibited a less pronounced reduction, as depicted in Figure 3.17. Alkalinity is plotted as a function of time in Figure 3.18. Although alkalinity showed a definitive overall increase in leachate from ferric sludge 3, only a slight increasing trend in alkalinity was exhibited by the alum sludges.

Table 3.16 Drinking water maximum contaminant levels (MCLs) and fresh water in-stream standards for various metals

Metal	Drinking water MCLs* (mg/L)	Fresh water in-stream guidelines (mg/L)†
Arsenic	0.05	0.072
Cadmium	0.01	0.002§
Copper	1‡	0.002
Iron	0.3‡	1
Manganese	0.05‡	—
Nickel	—	0.056§
Zinc	5‡	0.047

Sources: * *Federal Register* 1980a. 45 CFR 168 (primary MCLs); and *Federal Register* 1979. 44 CFR 140 (secondary MCLs).
† *Federal Register* 1980b. 45 CFR 231.

‡ These numbers are secondary maximum contaminant levels.

§ These limits are a function of a water's hardness. The values shown are for a water with a hardness of 50 mg/L as $CaCO_3$.

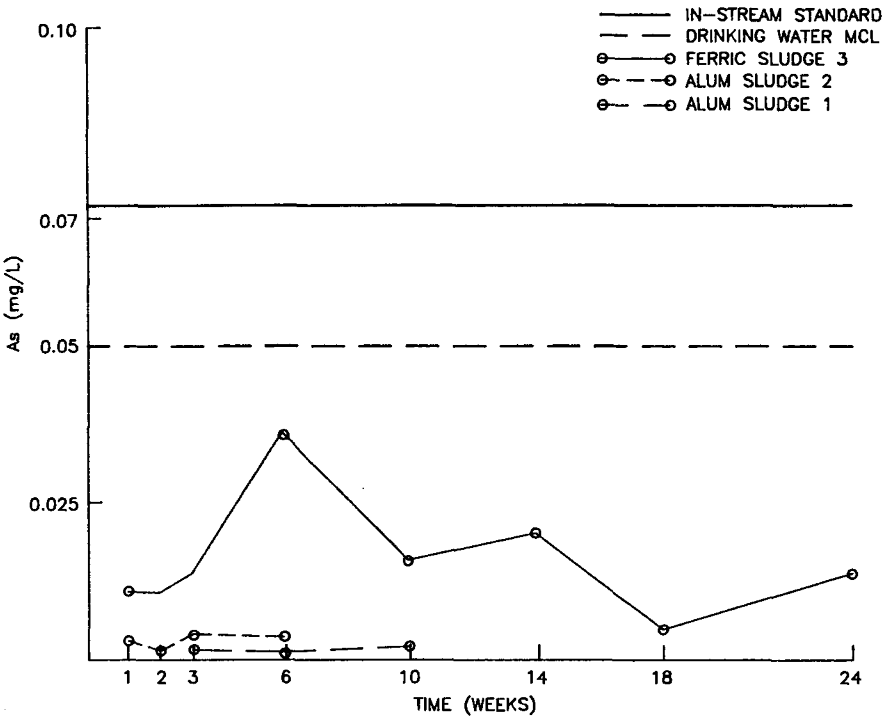


Figure 3.13 **Arsenic leaching in relation to drinking water and in-stream water quality standards**

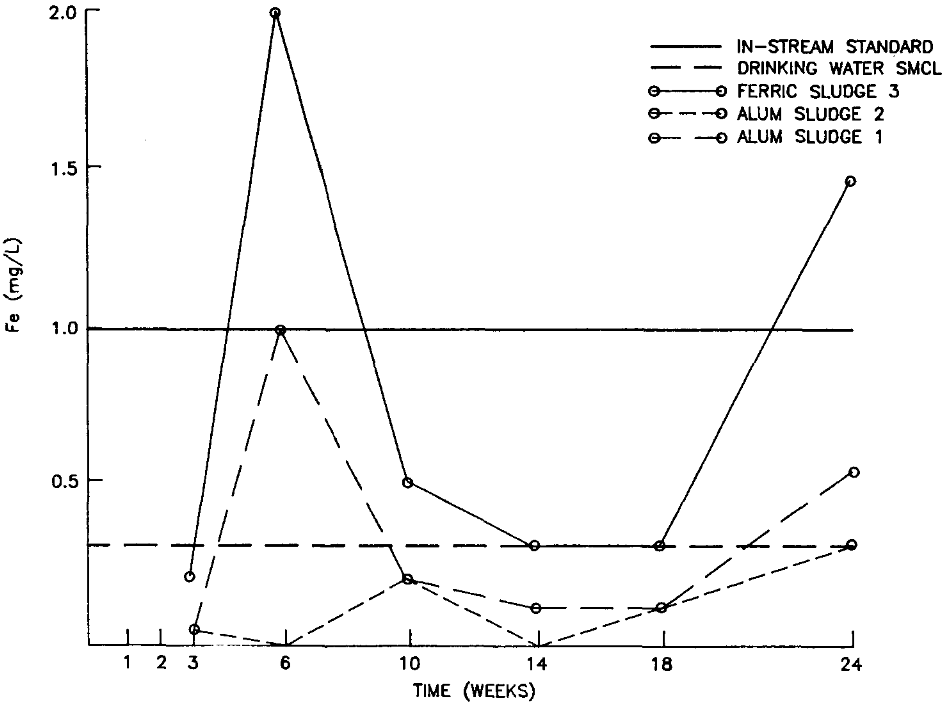


Figure 3.14 **Iron leaching in relation to drinking water and in-stream water quality standards**

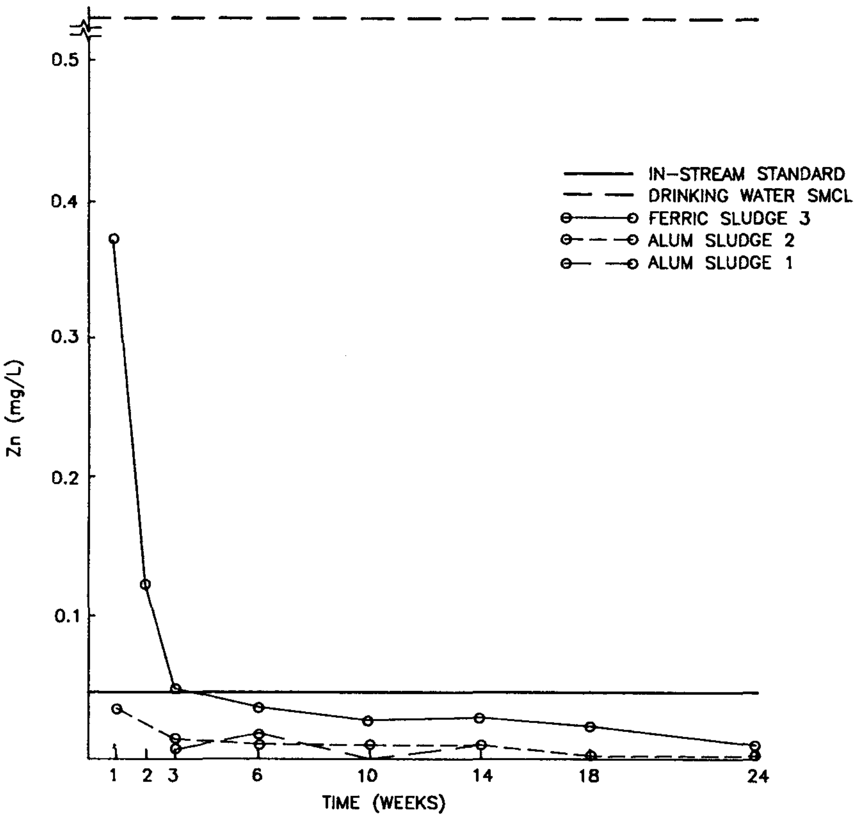


Figure 3.15 Zinc leaching in relation to drinking water and in-stream water quality standards

It is interesting to note that aluminum did not leach from any of the sludges, considering the substantial background concentrations, particularly in the alum sludges, and in view of the fact that concerns regarding aluminum toxicity prompted the USEPA to mandate an allowable "in-stream" aluminum limit. Although leaching patterns among the three sludges were by no means identical, certain similarities were evident.

With the exceptions of nickel and cadmium, which leached from ferric sludge 3 only, the same metals leached from all three of the sludges. More manganese leached from the alum sludges than any other constituent, and leaching of manganese from ferric sludge 3 was surpassed only slightly by that of arsenic. Iron, however, although it was initially present in greater amounts on a weight-to-weight basis in all sludges than any of the other metals that leached, leached less from each sludge source (on a percentage basis) than all of the other identified leachate metals. The percentages of copper and zinc leaching from alum sludge 1 and ferric sludge 3 were comparable. Presented below are the three different observed leaching sequences (in terms of percentage leached):

Alum sludge 1	Mn>Zn, Cu>As>Fe
Alum sludge 2	Mn>Cu>As, Zn, Fe
Ferric sludge 3	Mn, As>Cd>Zn, Cu>Ni>Fe

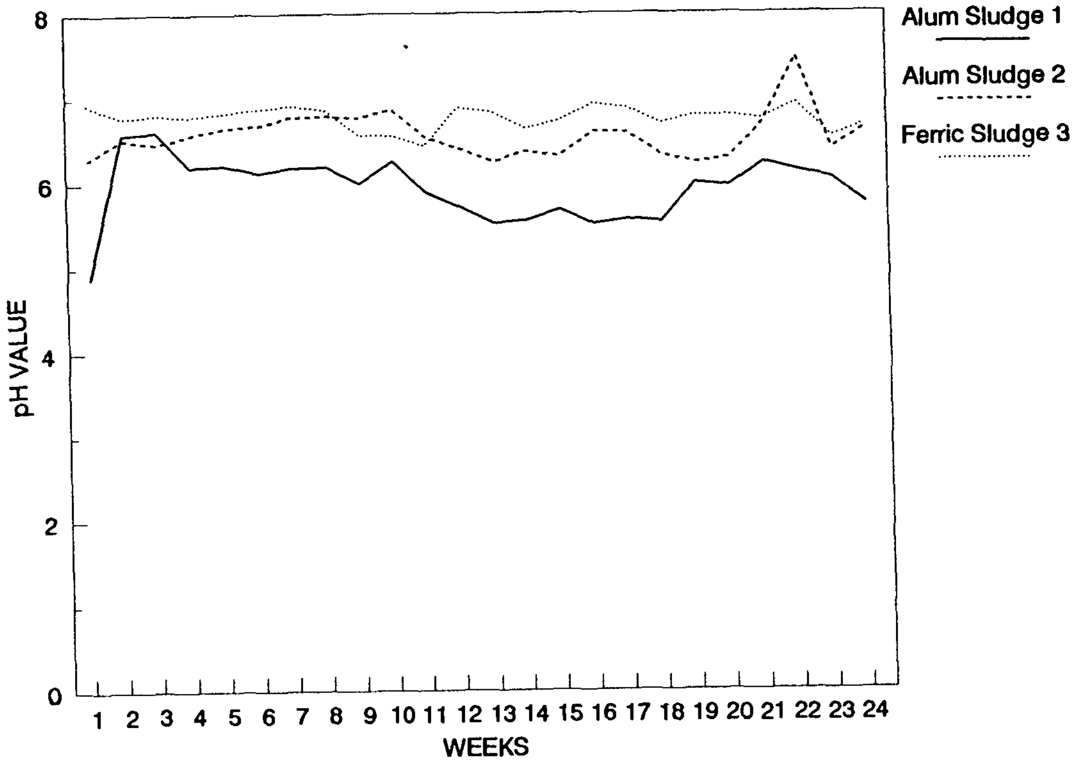


Figure 3.16 pH versus time

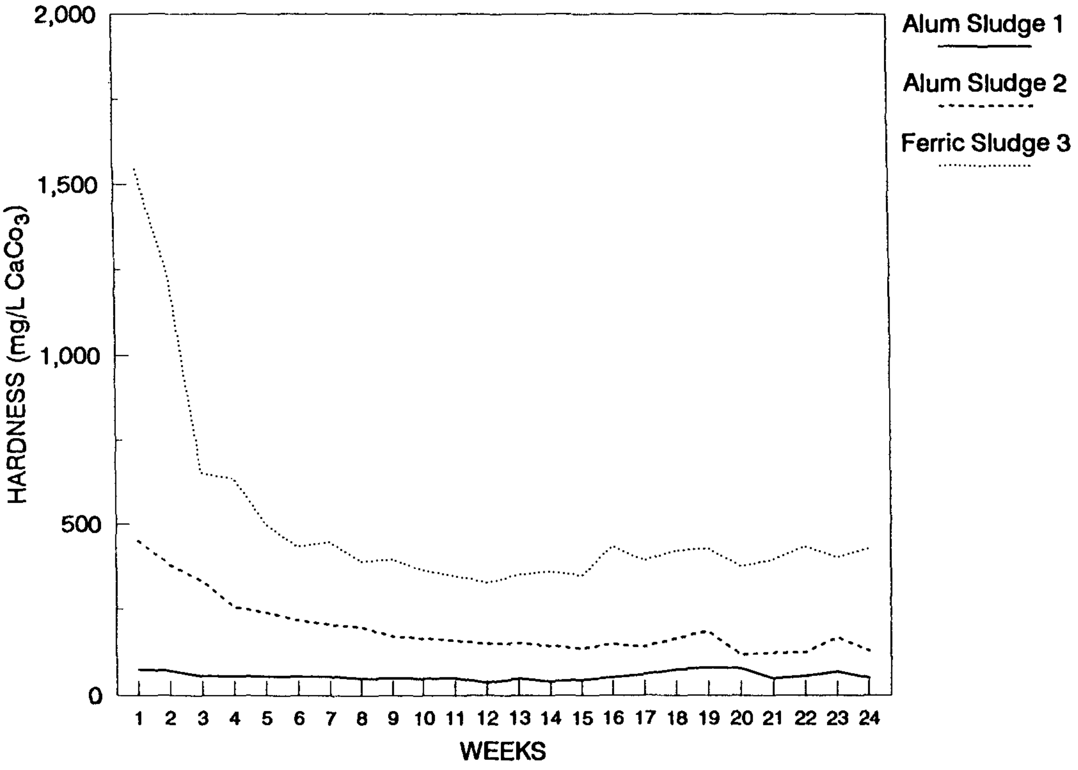


Figure 3.17 Hardness versus time

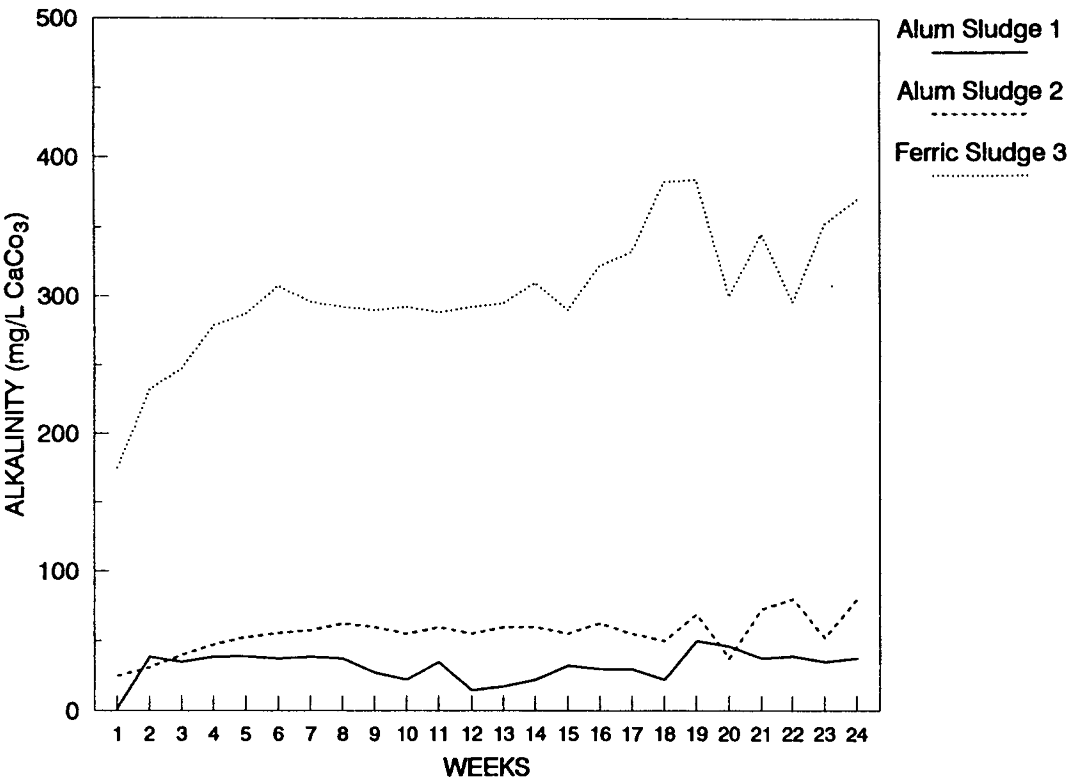


Figure 3.18 Alkalinity versus time

The highest percentages of arsenic, copper, and zinc leached from the sludge containing the lowest background level of each of these elements (ferric sludge 3, alum sludge 2, and ferric sludge 3, respectively) determined in a total metals analysis. Similarly, the lowest percentage of iron and manganese leached from ferric sludge 3, which initially contained more of these metals than either of the alum sludges. Nickel and cadmium, on the other hand, leached only from the sludge in which background concentrations were approximately 5 and 2 times higher than those measured in the other two. These results indicate that leaching of trace metals from WTP sludges is not directly related to the amount of the metal originally present in the sludge. To the contrary, with two exceptions the highest degree of leaching determined for each metal among the three leachates did not come from the sludge containing the highest background levels.

Of the constituents that actually leached from the waste at detectable concentrations as determined in dissolved metals analyses performed on the leachate over time, only arsenic and cadmium are regulated in the TCLP. For the alum sludges, the actual percentage of arsenic that leached was less than that predicted by the TCLP test. This also was the case for cadmium, which leached from the ferric sludge only. The reverse was true for the arsenic that leached from ferric sludge 3.

Conclusions

Becoming more and more attractive as regulations tighten and commercial landfilling costs increase, dedicated sludge monofilling offers utilities a competitive option for ultimate disposal of their WTP coagulant residuals. Monofilling, however, is not free of constraints regarding protection of groundwater from contamination by leached pollutants. This pilot-scale landfill leachate study focused on identification and subsequent quantification of contaminants leaching from WTP coagulant sludges. Chemical characterization of the sludge used in the study determined through TCLP analysis eliminated concern regarding its suitability for handling and disposal as a nonhazardous waste. Synthetic rainfall was applied to the lysimeter columns at rates determined to yield a cumulative amount of precipitation equivalent to the amount of rain that falls in Virginia over a period of about 12 years.

Pertinent findings from this research, some of which may be helpful in the development of landfill design criteria and the assessment of regulatory impacts, are summarized below.

- Arsenic, copper, iron, manganese, and zinc all leached to a certain degree from all three sludges. A slight degree of leaching was exhibited by nickel from the ferric sludge only. Cadmium leached only from the ferric sludge. Selenium leached from the ferric sludge and one of the alum sludges during the first week of the study.
- Higher background concentrations (as determined through a total analysis) of a particular metal in a sludge did not result in a greater percentage of leaching of the metal.
- All sludges were found to be nonhazardous based on TCLP analyses.
- Aluminum did not leach in detectable quantities from any of the sludges.
- No primary drinking water MCLs were exceeded in any of the leachate samples analyzed during the study.
- Only copper, iron, and zinc levels in the leachate occasionally exceeded in-stream water quality criteria.
- Sludge had a buffering effect on leachate. This finding is particularly significant in view of the potential effect of pH reduction on pollutant release cited repeatedly in the literature.
- A total metals analysis indicated that none of the TCLP-regulated metals were present in high enough concentrations to exceed TCLP limits.

Summary

Leaching of contaminants from WTP coagulant residuals has been the focus of an increasing number of studies and will continue to be scrutinized in view of the mounting concern and regulatory impositions regarding protection of irreplaceable groundwater resources. Mobility of trace metals is of particular concern and has been the focus of most leaching research to date. Research that specifically targets leaching from WTP sludge, including a simulated monofill leaching study conducted for AWWARF, is summarized in this chapter.

In addition to chemical characterization of landfill leachate in terms of identification and quantification of leachable constituents, characterization of the sludge itself constitutes an essential part of the landfilling process. The TCLP establishes national criteria for classifying a solid waste as hazardous on the basis of toxicity and predicts the mobility of a number of potential groundwater contaminants. Although the list of constituents is longer and threshold levels are more stringent than those of the test it replaced, the TCLP test has not created the stumbling block for WTP coagulant sludges anticipated by some; TCLP results reviewed in this research did not reveal any instances of WTP sludges failing the test.

The factor that appears throughout the literature as one of the most influential with regard to release of contaminants from WTP sludge is pH. Reductions in pH accompanied by increases in mobility of a number of trace metals have been measured and documented. In the pilot-scale monofill leaching study mentioned above, however, significant reductions in pH could not be duplicated through application of simulated acid rainfall to the sludge due to its buffering capacity. The buffering capacity exhibited by the sludge may be attributable to its substantial $CaCO_3$ concentration (Cornwell and Koppers 1990).

None of the metals monitored throughout the sludge monofill leachate study were found in quantities that exceeded established primary drinking water MCLs, although both iron and manganese were present in greater amounts than their respective SMCLs. It is interesting to note that although recently published federal regulations governing municipal solid waste landfills originally included the secondary maximum contaminants iron and manganese on the list of indicator groundwater parameters to be monitored, these constituents were omitted from the finalized list. Although there are no federal regulations in place that specifically regulate the disposal of WTP residuals (as explained in Chapter 2, their niche in the current regulatory framework is tenuous), it seems reasonable to consider existing guidelines until such regulations are developed.

Chapter 4

Sludge Physical Characterization

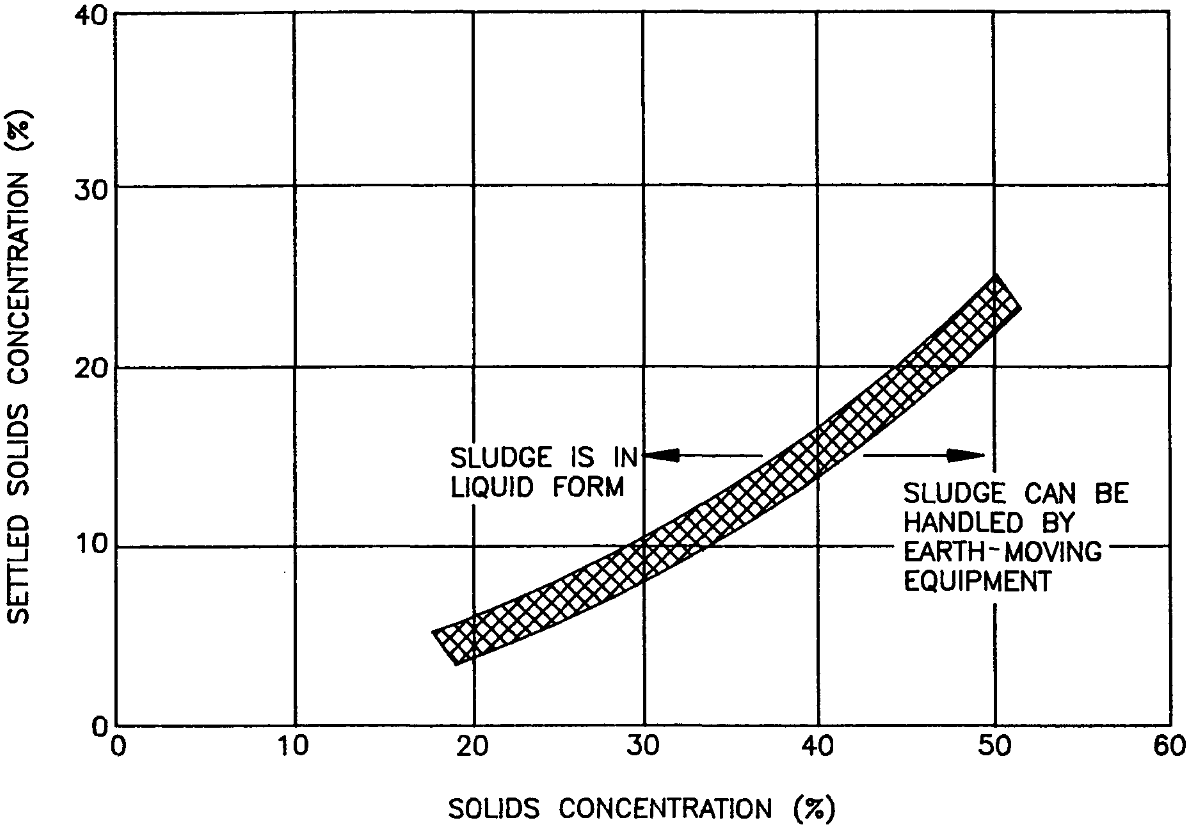
Historical Aspects

Historically, physical sludge characteristics have not been a major concern with respect to ultimate disposal. This was because ultimate disposal practices such as direct discharge, lagooning, on-site stockpiling, and municipal landfills did not have stringent regulatory requirements or specific needs to establish minimum sludge strength requirements. Disposal of dewatered sludge was typically governed by a handleability criterion related to solids concentration. Minimum solids concentrations for a sludge to be handleable were documented in work by Calkins and Novak (1973), as shown in Figure 4.1. They correlated a relationship between the solids concentration to which a sludge would gravity settle and the concentration at which the sludge becomes handleable. Coagulant sludges typically gravity thicken to 2 to 4 percent solids concentration and therefore, according to Figure 4.1, may be handleable at a 20 to 25 percent solids concentration. Lime sludges, on the other hand, may gravity thicken to a 40 percent solids concentration but will not be handleable until a 60 to 70 percent solids concentration is reached.

Since the late 1970s, the issue of sludge disposal has become increasingly difficult. Direct discharge of residuals to surface waters became regulated under the National Pollutant Discharge Elimination System (NPDES) following the 1972 amendments to the Federal Water Pollution Control Act and the 1977 Clean Water Act. Typical discharge limitations include an average total suspended solids concentration of 30 mg/L and a maximum level of 60 mg/L. In certain states, a nondetectable residual chlorine standard also exists. It should be noted, however, that there is no nationwide ban on discharge of WTP sludge to surface waters. In some instances, direct discharging is still being permitted but involves considerations of flow and quality of the receiving stream (Frey 1991).

Not only has disposal of WTP sludges in municipal landfills become increasingly difficult from a regulatory point of view, but landfill availability has notably decreased and sharp increases in disposal costs are typically seen across the country. In terms of minimum sludge solids concentrations, disposal of WTP sludges is currently being regulated by the paint filter liquid test and individual state standards.

For disposal of a sludge in a sanitary landfill, federal regulations require that the sludge is adequately dewatered and does not contain free-flowing liquids. To determine if a dewatered sludge contains free-flowing liquids, a paint filter liquid test is performed in the laboratory. This test involves placement of a 100-g or 100-mL sample in a funnel that holds a conical paint filter (mesh no. 60, fine-mesh size). If any liquid passes through the filter during a 5-minute test period, the sludge is



Source: Calkins and Novak 1973.

Figure 4.1 Handleability of water treatment plant sludges

considered to contain free liquids and its disposal into a sanitary landfill is prohibited. For a coagulant sludge to pass the paint filter liquid test, the sludge must generally be dewatered to about a 20 to 25 percent dry solids concentration. It is interesting to note that this range is comparable with the data shown in Figure 4.1. Some landfills that accepted sludges prior to this regulation already followed such requirements, and others utilized mixing of poorly dewatered sludge and municipal solid waste as a disposal method. Federal regulations do not allow the latter method and require utilities to improve their dewatering technique or utilize an alternative disposal method. Individual landfills, however, may continue to mix solid waste with sludges that have passed the paint filter test in order to increase the overall stability of the sludge.

Physical Characterization Research

Because federal and state regulations make the ultimate disposal of residual solids increasingly difficult and costly for utilities, the need arises to develop data on physical sludge characteristics to assess ultimate disposal in dedicated sludge landfills that could be controlled by a utility. Dedicated or monofill disposal of dewatered sludge could be accomplished in a variety of operations such as trenching and area filling. Within the framework of dedicated disposal, however, the handleability of the residual solids should be carefully considered in terms of transportation, placement, and overall stability of the disposal area. These criteria would also apply to disposal of sludges in a municipal landfill if the landfill operator elects to dedicate certain areas for sludge disposal, as is often done.

Physical characteristics of dewatered WTP residuals were researched herein to determine if these techniques are useful for establishing design guidelines and criteria for sludge handling and disposal. The laboratory work was conducted at The Pennsylvania State University and adopted tests commonly employed in geotechnical engineering. Key objectives of the physical characterization research were to:

1. Determine general physical sludge properties relevant to handleability and disposal operations
2. Develop data on sludge shear strength properties that relate to bearing capacity and slope stability
3. Establish minimum design guidelines and laboratory tests for utilities to follow in the planning of sludge disposal facilities

The three WTP sludges investigated herein were obtained from the same sources that provided the sludges used in the chemical characterization leaching research. The sludges, listed below, were selected based on raw water characteristics and coagulant employed.

Alum sludge 1	Alum sludge from medium-color, medium-turbidity raw water, dewatered using sand drying beds and obtained from Williams Water Treatment Plant in Durham, N.C.
Alum sludge 2	Alum sludge from high-color, low-turbidity raw water, dewatered with centrifuges and obtained from Chesapeake Water Treatment Plant in Chesapeake, Va.
Ferric sludge 3	Ferric sludge from medium-color, medium-turbidity raw water, dewatered using a lagooning method and obtained from Aldrich Treatment Plant, a Pennsylvania–American Water Company Plant.

The three sludges were investigated in a dewatered state over a wide range of solids concentrations. The impact of bulking agents was also researched to quantify their effect on overall sludge stability. Bulking agents included lime, fly ash, and natural soil. The City of Chesapeake, Va., which generates alum sludge 2, also operates a dedicated sludge monofill. A field sample was collected from the monofill to correlate its physical characteristics with samples collected directly from the city's water treatment plant.

Testing Procedures

Testing procedures utilized in the laboratory were categorized as assessing (1) general physical properties and (2) shear strength properties utilized in sludge stability characterization and bearing capacity analysis. All laboratory methods employed standard geotechnical test procedures, although some results were expressed in terminology more common to the water profession than to the geotechnical field.

General physical properties of the three test sludges were established to characterize each sludge and to allow physical comparison among the test sludges as well as correlation to typical soil properties found in geotechnical engineering. The results of these analyses also provided data useful in correlating variations among the three sludges in subsequent testing. Specific tests performed to establish the general physical properties included grain size analysis, Atterberg limits, density, specific gravity, solids concentration, and compaction.

Following the investigations into the general physical properties of the test sludges, the research focused on the shear strength properties of sludge. This work consisted of conducting cone penetration and triaxial compression tests to quantify the relationship between solids concentration and shear strength. The data generated by these tests were further analyzed with respect to slope stability and the sludges' capacity to support heavy equipment.

The following paragraphs present a general description of the laboratory tests performed. The complete procedures are not presented herein but can be easily obtained from geotechnical literature.

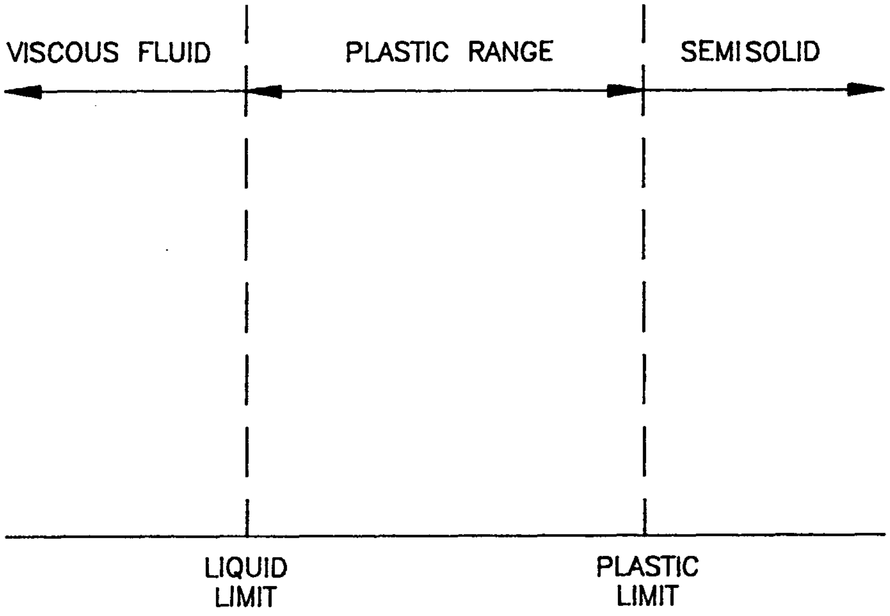
Grain Size Analysis

The hydrometer method (ASTM [American Society of Testing and Materials] D421-58 and D422-63) was used to approximate the grain size distribution of the three sludges. The hydrometer method is based on the relationships between the falling velocities of spheres in a fluid and considers the specific weights of the spheres and fluid viscosity as described under Stokes' law. This analysis is a widely used method for obtaining an estimate of the distribution of soil particle sizes from the no. 200 sieve (0.075 mm) to around 0.001 mm. The data are plotted on a semilog plot of percent finer versus grain diameters and could be combined with the data from a mechanical sieve analysis of the sludge retained on the no. 200 or larger sieve sizes. The importance of the hydrometer analysis is the ability to estimate the clay content of the particular material being analyzed. Sludges frequently contain significant amounts of fine clays and silts and could be characterized as cohesive soils. Cohesive soil behavior depends primarily on the clay content rather than on the distribution of all the particle sizes present.

Atterberg Limit Tests

The Atterberg limit tests consist of five "limits" proposed by Atterberg in 1911 to describe quantitatively the effect of varying the water content on the consistency of fine-grained soils. The five limit tests include tests for cohesion, sticky, shrinkage, plastic, and liquid. The liquid and plastic limits have been most widely used, primarily for soil identification and classification. Clay soils or sludges in this case can be classified as exhibiting either solid, plastic, or liquid behavior, depending on their solids content. The plastic limit identifies the solids concentration at which a sludge transitions from a semisolid to a plastic stage. The consistency of a material in the plastic stage could be described as ranging from that of soft butter to stiff putty. The liquid limit is the solids concentration below which the sludge exhibits viscous behavior; the consistency could be described as ranging from soft butter to a pea soup–type slurry. The relationship between the liquid and plastic limits is shown in Figure 4.2.

The liquid limit test (ASTM D423-66) deals with the workability of a sludge and more specifically measures the shear strength of a sludge at various water



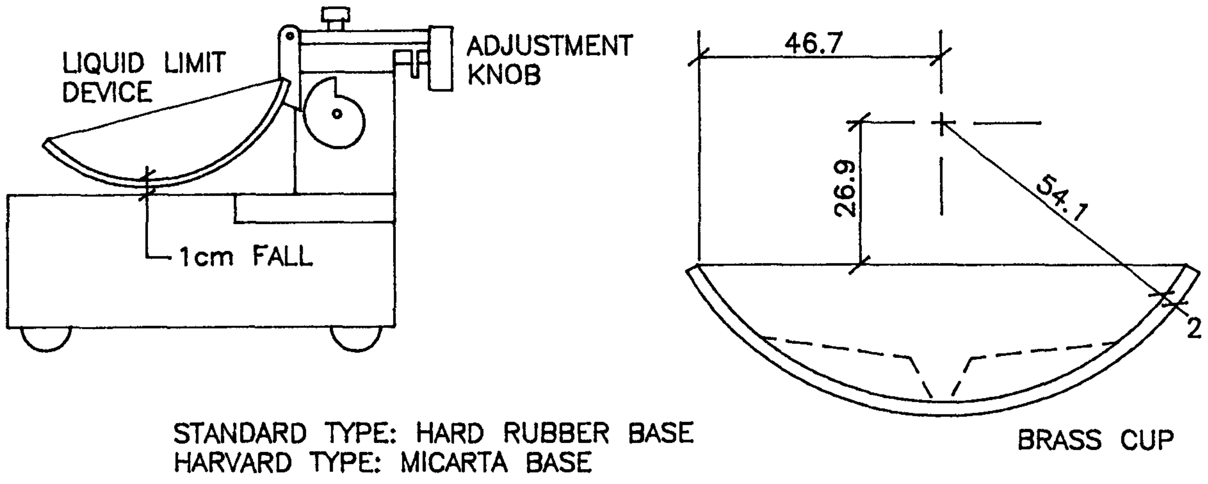
SOLIDS CONCENTRATION (%)

Source: Bowles 1978, reprinted with permission.

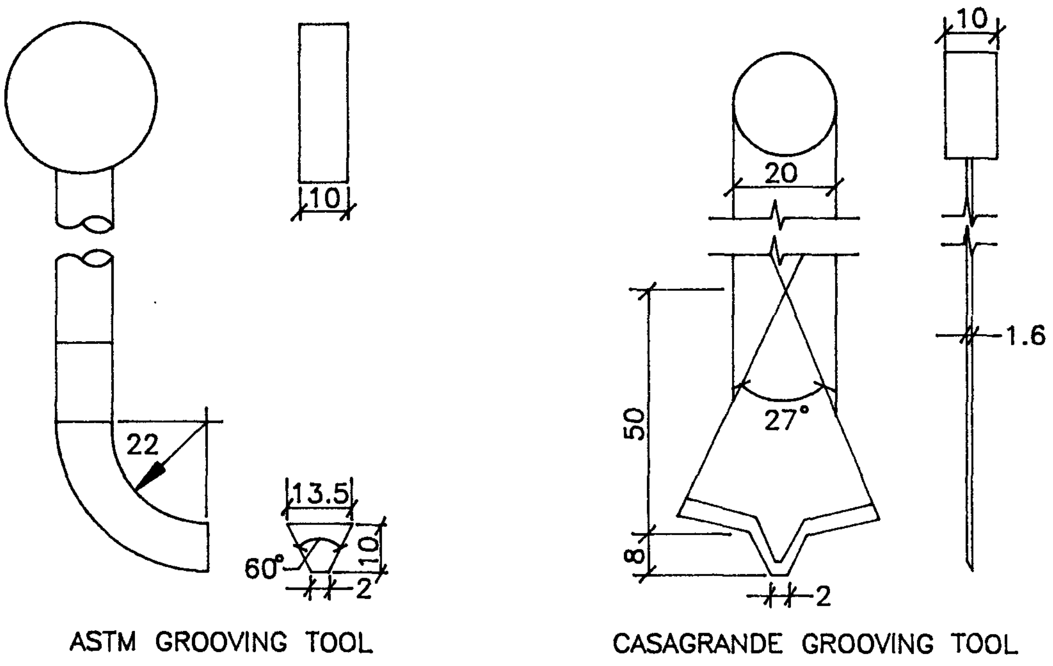
Figure 4.2 Relative location of liquid and plastic limits

contents. The liquid limit is determined in the laboratory by a standardized procedure devised by Casagrande (1932). A small quantity of air-dried sludge (passing the no. 40 sieve) is mixed with water and placed in a round-bottomed brass cup, as shown in Figure 4.3, at a maximum thickness of 0.39 in. (10 mm). The sludge is divided into two segments with a standardized grooving tool producing a 0.50-in. (12.7-mm) groove. The brass cup is mounted so that by turning a crank it can be raised and dropped 1 cm (0.39 in.) onto a hard rubber or micarta base. The impact produced by this fall causes the adjacent sides of the divided sludge pat to move together. The wetter the sludge mixture, the fewer shocks or blows will be required to close the groove, and the drier the mixture, the greater the number of blows. The liquid limit is defined as the solids content at which 25 blows cause the groove to close and is graphically determined by plotting the results of several tests at varying solids concentrations on semilogarithmic paper, as shown in Figure 4.4. At solids concentrations below the liquid limit, the sludge acts as a liquid, with decreasing resistance to shear. At solids contents above the liquid limit, the sludge becomes more plastic. Casagrande (1932) theorized that the liquid limit is a measure of the soil shear strength by determining that each blow of the brass cup equates to 0.014 psi (1 g/cm^2) of shear strength. Thus at the liquid limit of a sludge, the corresponding shear strength is approximately 51 lb/ft^2 (2.44 kN/m^2) or 0.35 psi.

The plastic limit test (ASTM D424-59) also deals with sludge workability and establishes the lower boundary range of the plastic behavior. The plastic limit is determined in the laboratory by rolling out a sludge sample with the palm of the hand on a frosted glass plate until a thread or worm is formed. When the thread has been rolled to a diameter of approximately 1/8 in. (3 mm) it is balled up and rolled out again. As this procedure is repeated, the sample gradually loses its moisture



(a) CONSTRUCTION DETAIL AND DIMENSIONS OF THE LIQUID LIMIT DEVICE



(b) GROOVING TOOLS

NOTE: ALL DIMENSIONS ARE IN MILLIMETERS

Source: Bowles 1978, reprinted with permission.

Figure 4.3 Liquid limit test equipment

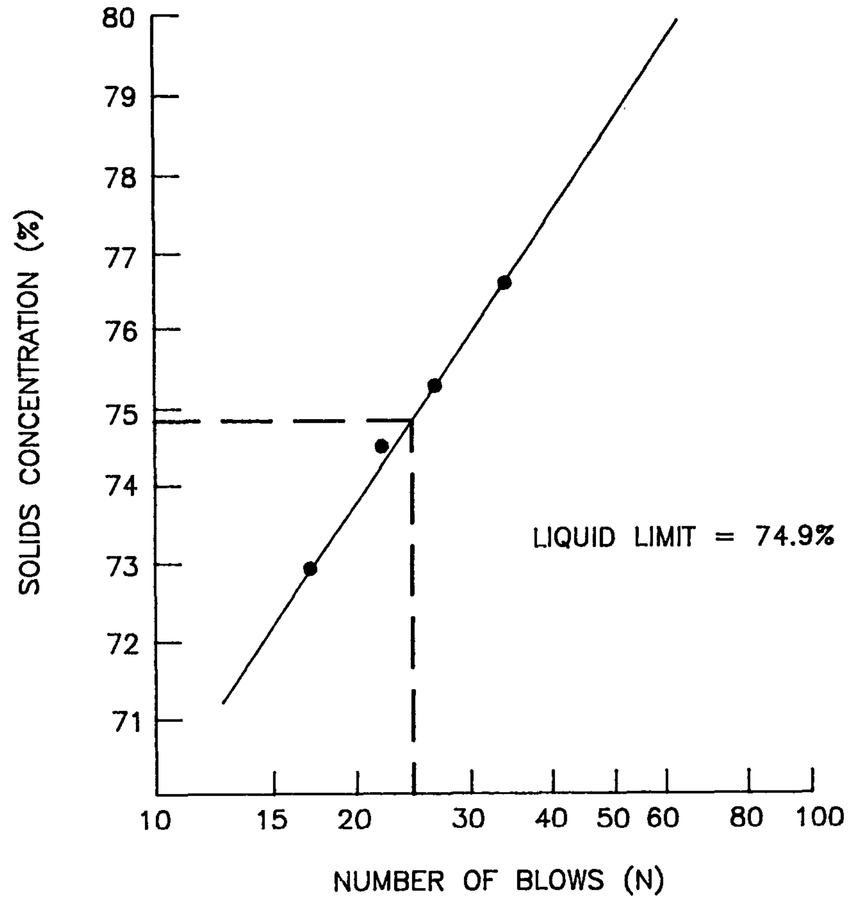


Figure 4.4 Determination of liquid limit

content. Finally, the sample dries out to the extent that it becomes brittle and will no longer hold together in a continuous thread. The solids content at which the thread breaks up into short pieces during the rolling process is considered to be the plastic limit.

The plasticity index is defined as the numerical difference between the liquid limit and the plastic limit of the sludge and is standardized based on moisture content. This represents the moisture concentration range within which the sludge exhibits the properties of a plastic solid. A large plasticity index (i.e., greater than 20 percent) indicates that a considerable amount of water can be added to a sludge before it will change from a semisolid to a liquid.

Density, Specific Gravity, and Solids Concentration

General testing for wet and dry density, specific gravity, and solids concentration was performed on all three sludge types to provide background information and data useful for subsequent physical testing. It is important to note that many relationships in soils engineering utilize the moisture content of the material in question rather than the solids content. Moisture or water content referred to herein is expressed in soil engineering as a percentage of the mass of the dry material. In other words, at a 100 percent moisture content, the mass of water and the mass of solids are equal and the corresponding solids concentration is 50 percent. It should also be noted that moisture concentrations can thus exceed 100 percent, in which case there is more water present than solids. The exact relationship between moisture content and solids concentration is expressed below:

$$\text{Solids content, \%} = \left(\frac{1}{1 + \dfrac{\text{water content, \%}}{100}} \right) \times 100$$

$$\text{Water content, \%} = \left(\frac{100}{\text{solids content, \%}} - 1 \right) \times 100$$

These relationships are useful to remember, particularly if a utility elects to conduct physical characterization tests on its sludge, because geotechnical laboratories typically express all test results in terms of moisture content. The term most familiar in the water profession is solids content.

Various sludge density measurements were taken during the laboratory work, including loose wet and dry densities and compacted dry density. The wet unit weight of a cohesive material such as sludge is determined according to a standardized procedure per ASTM D2937-71. In this test, a tubular specimen is weighed and placed in a container of a known volume. The container is filled with water and the volume of the sample is subsequently determined. The sample is then weighed again and oven dried to determine the solids or water content. Wet unit weight can be calculated as the weight of the sample divided by the volume of the sample in water. The dry unit weight is determined with the relationships shown below:

$$\text{Dry density} = \frac{\text{wet density}}{1 + \dfrac{\text{water content, \%}}{100}}$$

$$\text{Dry density} = \text{wet density} \times \frac{\text{solids content, \%}}{100}$$

Both relationships are useful in data interpretation and in converting laboratory data to more workable terms for the planning of sludge disposal facilities.

Measurements of the test sludges' specific gravities (ASTM D854-58) were computed because their values were necessary in the hydrometer analyses. Specific gravity values are also useful to determine the void ratio of the sludges as well as to predict unit weights. The specific gravity of a sludge is defined as the unit weight of the sludge divided by the unit weight of distilled water at 39.2°F (4°C).

Compaction Tests

Compaction tests or moisture-density relationship tests (ASTM D698-70) were performed on each sludge type to determine the optimum moisture content and corresponding dry unit weight. This information provides data important to establish the degree of compaction of the sludge necessary to increase stability, decrease permeability, and enhance resistance to erosion. In the compaction test (standard Proctor type), the sludge is compacted in a 4-in.-diameter (10.2 cm) cylindrical mold. The sludge is placed in the mold in three equal layers, each layer compacted by 25 blows of a standardized metal tamper. The tamper (a 24.5-N compaction hammer) drops 1 ft (0.305 m) onto the sludge sample, delivering a compaction energy of 12,400 ft-lb/ft^3 (593.7 kN/m^3). The amount of energy applied by the tamper was established by Proctor as the amount that would yield the maximum density in the laboratory and would approximately equal a density feasible to achieve with light rollers or very thorough tamping in thin layers. A typical compaction test generates a number of dry density concentrations versus water content from which the optimum moisture content can be selected to yield the greatest dry unit weight. An example for a soil material is shown in Figure 4.5. For the purpose of this study, the data generated on the test sludges were further reduced to show dry density concentration versus solids concentration rather than water content.

It is important to note that density obtained from the compaction curve is the maximum density achievable at the particular solids concentration. No amount of overcompaction will be sufficient to reach a higher density unless the sludge is dried further. Overcompaction could also rework the sludge and actually cause a reduction in shear strength.

Cone Penetration Tests

The cone penetration test (ASTM D3441) consists of a laboratory method to directly measure the shear strength of the sludge at various solids concentrations. In this test, a weighted conical pointed object, as shown in Figure 4.6, is allowed to drop into a prepared sample while the testing apparatus measures the degree of penetration (or cone resistance). Through standardized tables, the amount of shear strength exhibited by the sample under a confined condition can be determined.

Sludge typically exhibits strong rheotropic (decreasing shear strength due to disturbance) and thixotropic (increasing shear strength with time after disturbance) characteristics. These phenomena were also studied with the cone penetration test by conducting a series of tests at different sample curing times.

Triaxial Compression Tests

A soil's shear strength or its resistance to sliding along internal surfaces is one of its most important engineering properties. Shear strength enables a soil to maintain equilibrium on a sloping surface such as an embankment or a natural hillside. The shear strength of the soil also influences the bearing capacity. All these properties are directly applicable to sludges and their ability to support heavy equipment in a monofilling operation under different surface slope conditions.

Triaxial compression tests and subsequent calculations were conducted to determine the shear strength properties of the sludges. This type of test, shown in Figure 4.7, is considered the most reliable of a host of different types of shear tests. In the triaxial compression test, a cylinder of sludge is placed in a rubber membrane and mounted in a pressure vessel. In the vessel, a pressurized liquid provides a confining pressure uniformly distributed around the sample. This pressure is kept constant during the test. An axial load is then applied to both ends of the sample until the sample fails due to shear on its internal surfaces. The test is repeated for several duplicate samples at different confining pressures such that Mohr stress circles can be drawn for each sludge sample. The Mohr envelope is then developed by drawing a line tangent to the Mohr circles of failure. The vertical intercept of the tangent line represents the cohesion of the sludge, and the angle the tangent makes with the horizontal axis is the internal friction angle of the sludge. Both cohesion and the internal friction angle are important parameters in the analysis of slope stability.

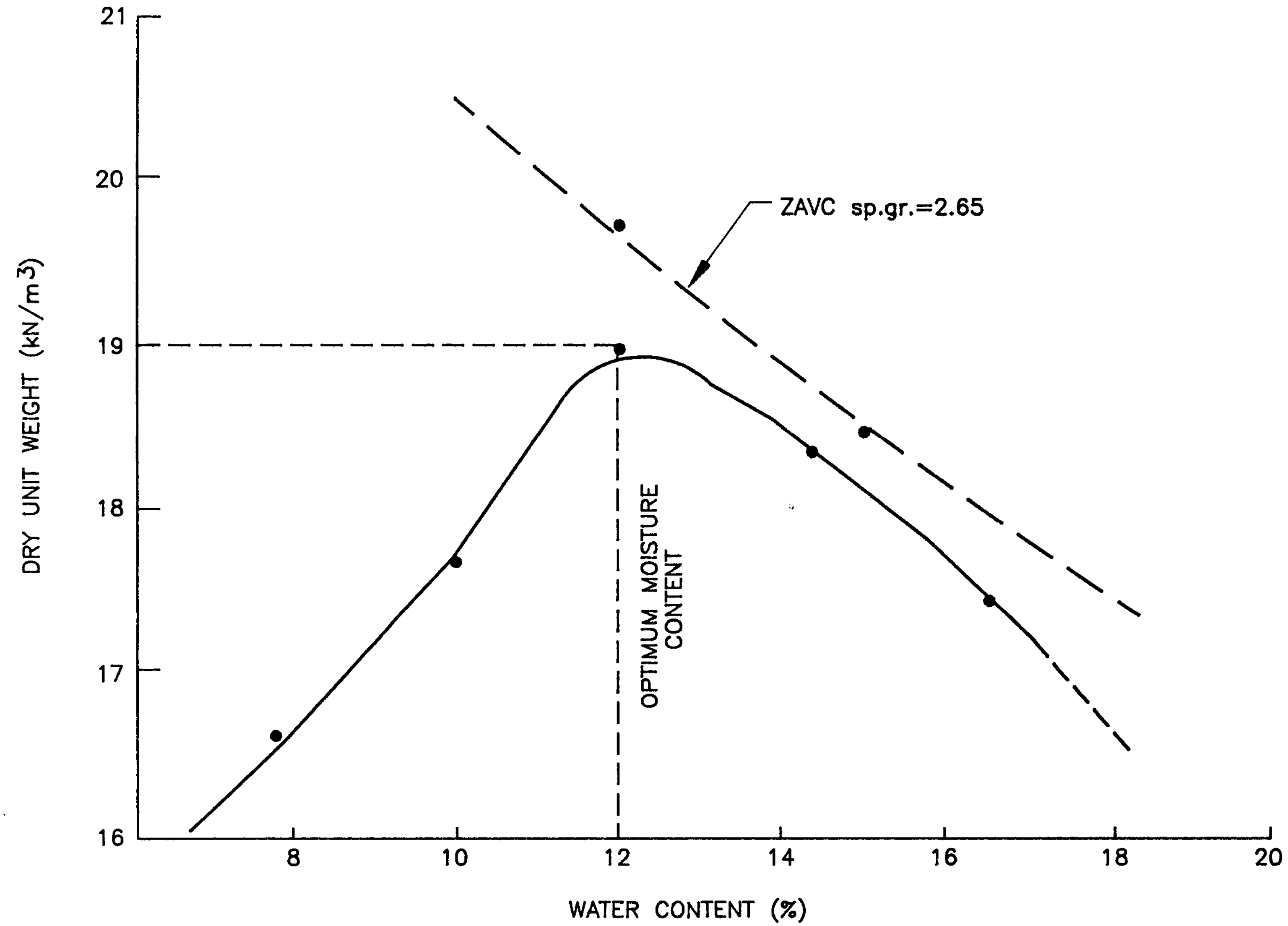
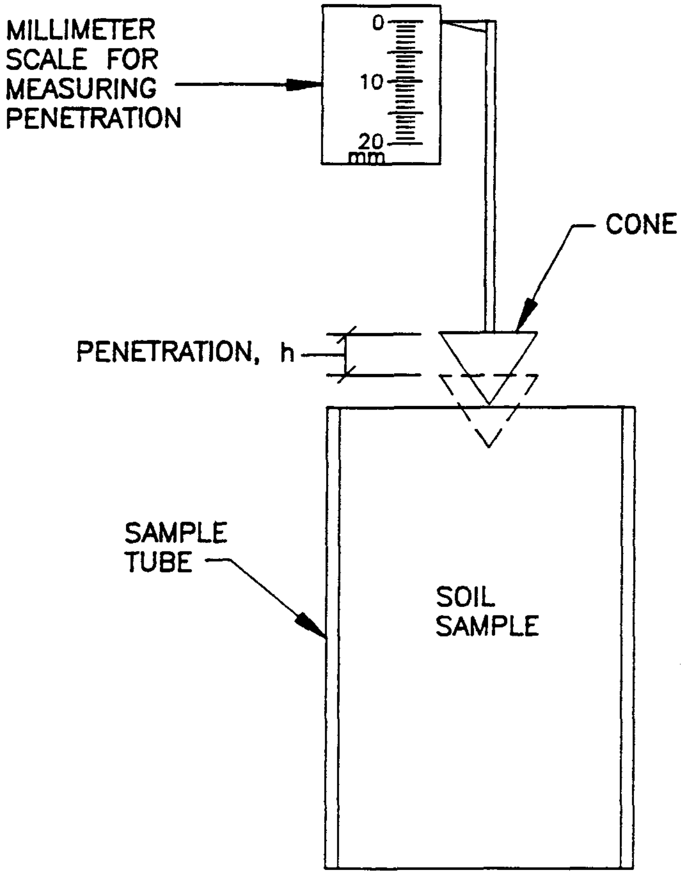


Figure 4.5 Typical soil compaction curve



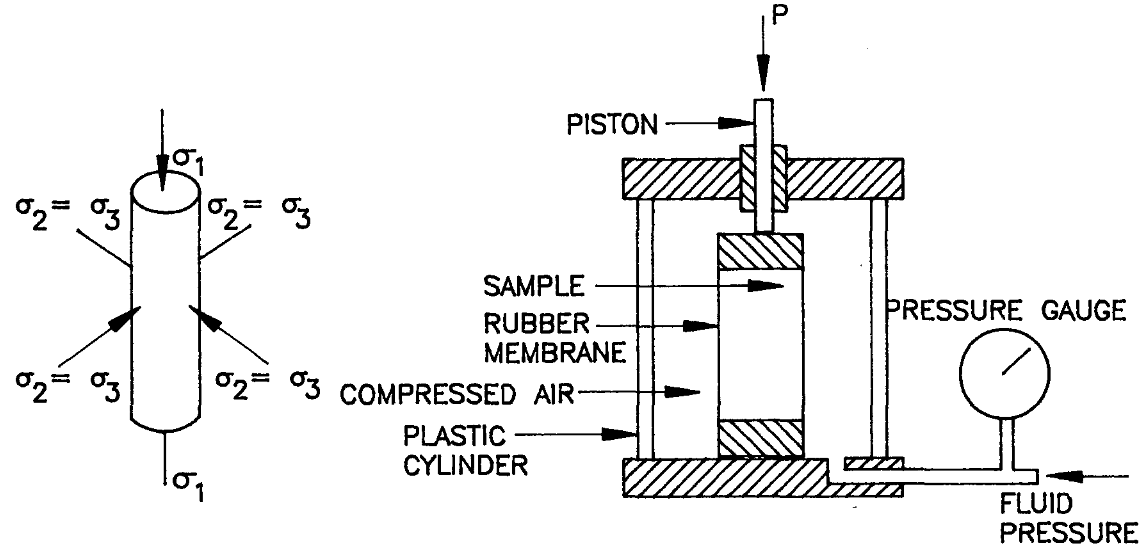
MASS (g)	CONE ANGLE d (DEGREES)	RANGE OF h (kPa)
400	30	10–250
100	30	25–63
60	60	0.5–11
10	60	0.08–2

Figure 4.6 Cone penetration test apparatus

Previous Physical Characterization Research

Tests for physical characteristics of sludge have been performed previously but were usually limited to assessing the sludge's handleability with respect to solids concentration or shear strength. The data obtained, however, were not further analyzed to assess the overall sludge stability and bearing capacity related to the ultimate disposal factors.

Novak and Calkins (1975) reported various physical characteristics of sludge including viscosity and shear strength. Shear strength was measured on air-

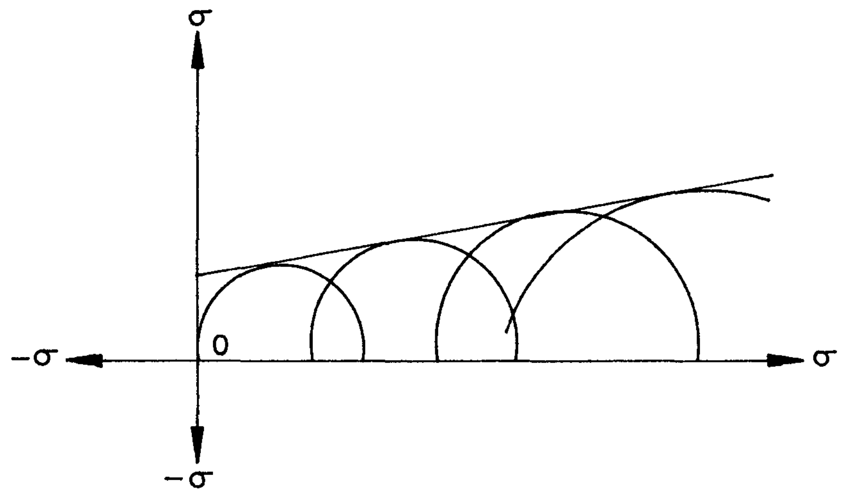


A. STRESSES IN TRIAXIAL SHEAR

σ : STRESS

B. TRIAXIAL SHEAR EQUIPMENT

P : PRESSURE



C. MOHR ENVELOPE DRAWN TANGENT TO MOHR'S CIRCLES OF FAILURE (UPPER HALF)

Source: Sowers 1979.

Figure 4.7 Triaxial shear test

dried sludge samples at different solids concentrations with a Torvane shear tester. In this study, it was noted that the sludges became adequately dewatered for transportation and handling with earth-moving equipment at a shear strength of approximately 60 to 80 lb/ft^2 (2.87 to 3.83 kN/m^2). There was no specific solids concentration noted in this work that correlated to the 60-to-80 lb/ft^2 (2.87-to-3.83-kN/m^2) shear strength. For three alum sludges tested in Novak and Calkins (1975), the solids concentration corresponding to 80 lb/ft^2 (3.83 kN/m^2) ranged from approximately 20 percent to 28 percent, and two lime sludges required a 40 to 45 percent solids concentration.

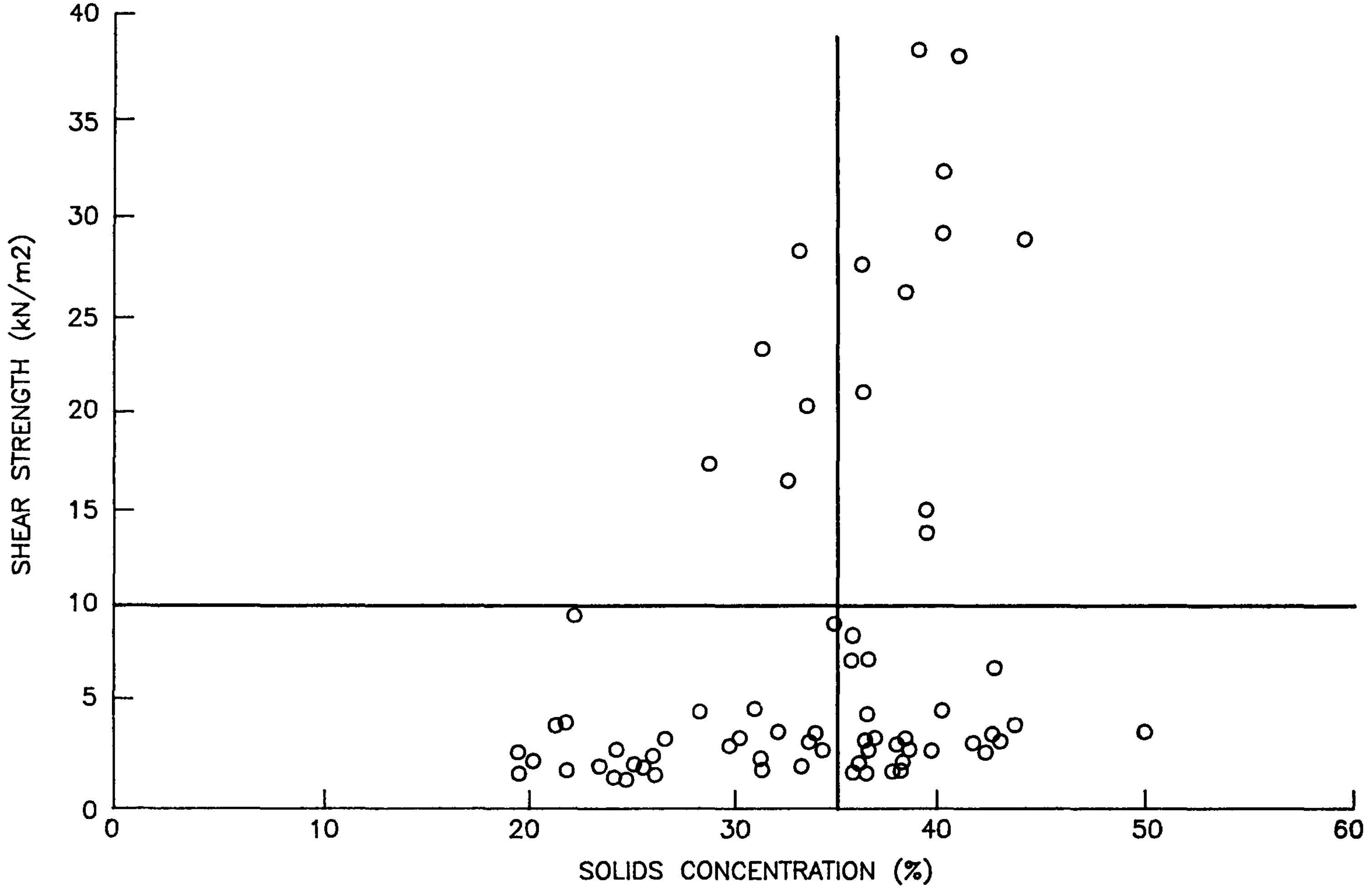
Knocke and Wakeland (1983) conducted further research in the area of sludge handling characteristics by investigating the use of the Atterberg liquid limit test to estimate the sludge handling characteristics. As previously described, the liquid limit test deals with the shear resistance of a material. The test is based on the hypothesis that each blow with the standardized test apparatus equates to a shear resistance of 1 g/m^2. Knocke and Wakeland's research determined that the shear resistance recommended by Novak and Calkins (1975) for handling sludge, 60 to 80 lbs/ft^2 or 0.42 to 0.56 psi (2.87 to 3.83 kN/m^2) corresponded to 30 blows of the standard liquid limit apparatus. By evaluating various sludges, it was concluded that alum sludges achieved the proper level of shear resistance at 17 to 20 percent solids concentration. Lime sludges, on the other hand, needed to be dewatered to beyond 60 percent solids concentration.

Cornwell and Koppers (1990) summarized research conducted in Europe to define the handleability and stability of WTP sludge. This work utilized a motor vane test apparatus to measure the undrained shear strength of various sludges. West Germany and the Netherlands have adopted a preliminary standard of 209 lb/ft^2 or 1.45 psi (10 kN/m^2) as a minimum sludge shear strength to define handleability and stability to support heavy equipment. Test data from 14 different utilities, shown in Figure 4.8, indicate a high degree of variability between solids concentration and shear strength. Even at 35 percent solids concentration, only approximately 25 percent of the sludges tested passed the 209-lb/ft^2 or 1.45-psi (10-kN/m^2) standard. Most of the sludges tested were iron sludges from either groundwater or surface water sources.

It is worth comparing the European work with the research conducted in the United States by Knocke and Wakeland (1983) and Novak and Calkins (1975). The European adopted standard of 209 lb/ft^2 or 1.45 psi (10 kN/m^2) is approximately 3 times greater than the shear strength reported as necessary by the American researchers. It should be pointed out, however, that the European value was preliminarily adopted to provide not only a handleable sludge but also a sludge that would be stable enough to support heavy equipment. The American work considered only handleability.

General Physical Properties

Results from the laboratory test work on the general physical properties of the three test sludges are summarized in Table 4.1. Again, these tests were performed to make a physical comparison among the three sludges as well as to correlate the results to typical values found in soil engineering. The following sections discuss the results of the various test parameters.



Source: Cornwell and Koppers 1990.

Figure 4.8 Shear strength versus solids concentration

Table 4.1 General physical properties of test sludges

Properties	Alum sludge 1	Alum sludge 2	Ferric sludge 3
Water content (percent)	569	714	300
Solids content (percent)	15	12	25
Wet unit weight [lb/ft^3 (kg/m^3)]	68 (1,156)	67 (1,139)	74 (1,258)
Dry unit weight [lb/ft^3 (kg/m^3)]	10 (170)	8 (136)	18 (306)
Specific gravity	2.33	2.26	2.72
Liquid limit (percent solids)	19.1	15.4	48.1
Plastic limit (percent solids)	42.2	68.0	29.5
Plasticity index (percent)	23.1	14.1	19.9
Fine sand content (percent)	10	34	8
Silt content (percent)	13	46	37
Clay content (percent)	77	20	55
Median size (mm)	<0.001	0.013	0.0016
Soil classification	CH*	CH	CH

* The CH soil classification refers to the Unified Soil Classification System. Soil groups with a CH designation are considered highly plastic clays and sandy clays.

Grain Size Analysis

The hydrometer analysis was used to quantify the distribution of sludge particles from the no. 200 sieve (0.075 mm) to around 0.001 mm. The gradation curves for the three sludges are shown in Figure 4.9. The four parameters established by this test include the fine sand, silt, and clay contents and the medium particle size. Because laboratory procedures express the results in terms of percent finer at specific grain sizes, a certain level of mathematical interpretation must be performed to determine the values for the four parameters. Values for the four parameters could be calculated by utilizing the gradation curve as follows:

Fine sand content = 100 – percent finer at 0.075 mm
Clay content = percent finer at 0.002 mm
Silt content = 100 – (fine sand + clay content)
Median size = grain size at 50 percent

Applying these relationships to the gradation curve in Figure 4.9 yielded the values for the three test sludges shown in Table 4.2. These results indicate that sludges 1 and 3 from the medium-turbidity waters consist of predominantly silt- and clay-size particles. Alum sludge 2 from the high-color, low-turbidity raw water contained significantly lower amounts of silt and clay compared to the other sludges. Instead, this sludge had more particles that would be retained in the no. 200 sieve, which would be classified as fine sands. Thus, the grain size was coarsest for alum sludge 2 and finest for alum sludge 1. It is interesting to note that for sludges 1 and 3, from medium-turbidity raw water, between 90 and 92 percent of the particles passed the no. 200 sieve. Tests conducted by others in Oklahoma and Arizona on medium-turbidity raw waters yielded results of 82.6 and 81.4 percent, respectively, passing the no. 200 sieve (Hemphill Corporation 1987; Environmental Engineering & Technology, Inc., 1990). Thus, a value in excess of 80 percent seems to exist for the silt and clay content from medium-turbidity raw water. The high-color, high-organic, and low-turbidity water associated with alum sludge 2 contained only a level of 66 percent passing the no. 200 sieve.

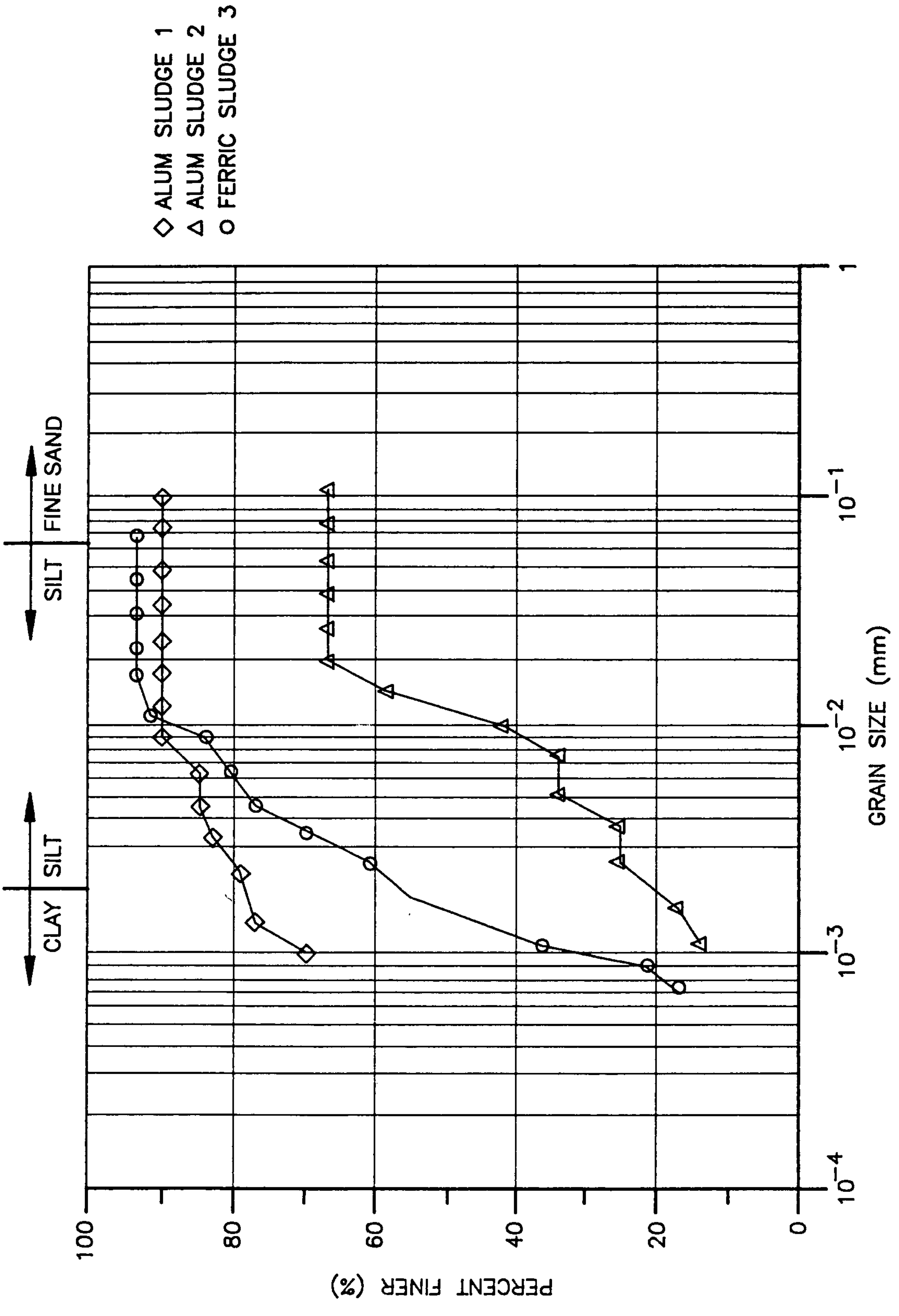


Figure 4.9 Grain size analysis

Atterberg Limit Tests

Atterberg limits tests performed on the three test sludges included (1) liquid limit, (2) plastic limit, and (3) plasticity index. Reviewing the definitions previously discussed for these parameters, the liquid limit establishes the solids concentration, which is viewed as the boundary between viscous and plastic behavior, and deals with resistance to shear (undrained shear strength). The 25 blows at which the test is measured can be theoretically equated to a shear strength of 51 lbs/ft^2 or 0.35 psi (2.44 kg/m^2). The plastic limit establishes the boundary point between plastic and nonplastic behaviors. The plasticity index was previously described as the numerical difference between the liquid and plastic limits. The laboratory test results for the three sludges are presented below in Table 4.3.

Of the three parameters shown in Table 4.3, the liquid limit would be most useful with respect to the physical characterization. For example, in soils engineering, materials with a liquid limit below 50 percent solids concentration (above 100 percent moisture concentration) would contain generally significant amounts of silt and clay and are characterized by low load-carrying capacities. Liquid limit and plasticity index requirements are typically specified for select backfill material. For example, the North Carolina Department of Transportation specifies the following values for a Class III select backfill:

Liquid limit	not greater than 50 percent moisture
Plasticity index	not less than 7 nor greater than 20 percent moisture

Noting that the above values are stated in moisture concentration, and reviewing the test data for the three sludges, it is obvious that none of the three sludges would qualify as a select fill material in North Carolina based on liquid limit and plasticity index. Upon further review, the sludges also exhibit an improper grain size gradation.

Table 4.2 Sludge grain size distribution

	Alum sludge 1	Alum sludge 2	Ferric sludge 3
Fine sand (percent)	10	34	8
Silt content (percent)	13	46	37
Clay content (percent)	77	20	55
Median size (mm)	<0.001	0.013	0.0016

Table 4.3 Atterberg limits test results

	Solids concentration, percent (moisture concentration, percent)		
Limit test	Sludge number 1	Sludge number 2	Sludge number 3
Liquid limit	19.1 (423)	15.4 (550)	48.1 (108)
Plastic limit	42.2 (137)	29.5 (239)	68.0 (47)
Plasticity index	23.1 (286)	14.1 (311)	19.9 (61)

Density, Specific Gravity, and Solids Concentration

Laboratory tests for density, specific gravity, and "as received" solids concentrations were performed on the three test sludges. These data provided background information for each sludge and information that was incorporated into subsequent tests. Results for these parameters are shown below and represent the sludge characteristics upon arrival at the laboratory. Wet unit weights were determined for the three test sludges over a 0 to 100 percent solids concentration range, as shown in Figure 4.10. Between 0 and 40 percent solids concentration, the three sludges exhibited comparable wet unit weights in the range of 62.4 to 82.5 lb/ft^3 (1,060.8 to 1,402.5 kg/m^3). Beyond 40 percent solids concentration, it can be seen that alum sludges 1 and 2 remained comparable within 5 lb/ft^3 (85 kg/m^3), and ferric sludge 3 achieved increasingly higher wet unit weights with a maximum differential of 25 lb/ft^3 (425 kg/m^3). This phenomenon may have been purely coincidental and may simply present the range between various coagulant sludges.

As previously discussed, the dry unit weight could be calculated from the wet unit weight by utilizing the solids concentration:

$$\text{Dry unit weight} = \text{wet unit weight} \times \frac{\text{solids concentration, \%}}{100}$$

It should be noted that both unit weights represent loose or uncompacted values. Compacted materials could possibly achieve higher values as the volume of voids and volume of solids are altered. Further insight into compacted unit weights is provided in subsequent sections of this chapter.

An empirical equation presented by J. M. Montgomery Consulting Engineers (1985) can be used to estimate the wet density of a coagulant sludge as follows:

$$\text{Wet density} = \frac{100}{\dfrac{\text{percent solids}}{\text{density solids}} + \dfrac{100 - \text{percent solids}}{\text{density water}}}$$

It was noted in the literature that this equation is valid for a solids concentration up to 50 percent, above which increased voids in the sludge may influence the results. The dry density of the solids was referenced as 145 lb/ft^3 (2,465 kg/m^3) for coagulant sludges. Applying this empirical equation to the data presented in Figure 4.10 yielded a good correlation between the equation and the results found for alum sludges 1 and 2.

The specific gravity of each sludge was determined in order to perform the grain size analysis with the hydrometer methodology. The specific gravities of the three sludges varied to the extent that ferric sludge 3 had a specific gravity of 2.72, which compares with a typical specific gravity of 2.65 for natural soils, and alum sludges 1 and 2 had specific gravities of 2.33 and 2.26, respectively. Although there is no significance associated with the variation in specific gravities, these values may be indicators of dewaterability of the sludges, particularly with centrifuges. When a centrifugal force is applied, the materials naturally arrange themselves inside the centrifuge bowl according to density and specific gravity, with higher values radiating outward. Alum sludge 2, with a specific gravity of 2.26 and a density of 8.2 lb/ft^3 (139.4 kg/m^3), is currently dewatered with a centrifuge to achieve a dry cake and clear centrate, but with great difficulty, achieving only a 15 to 18 percent cake.

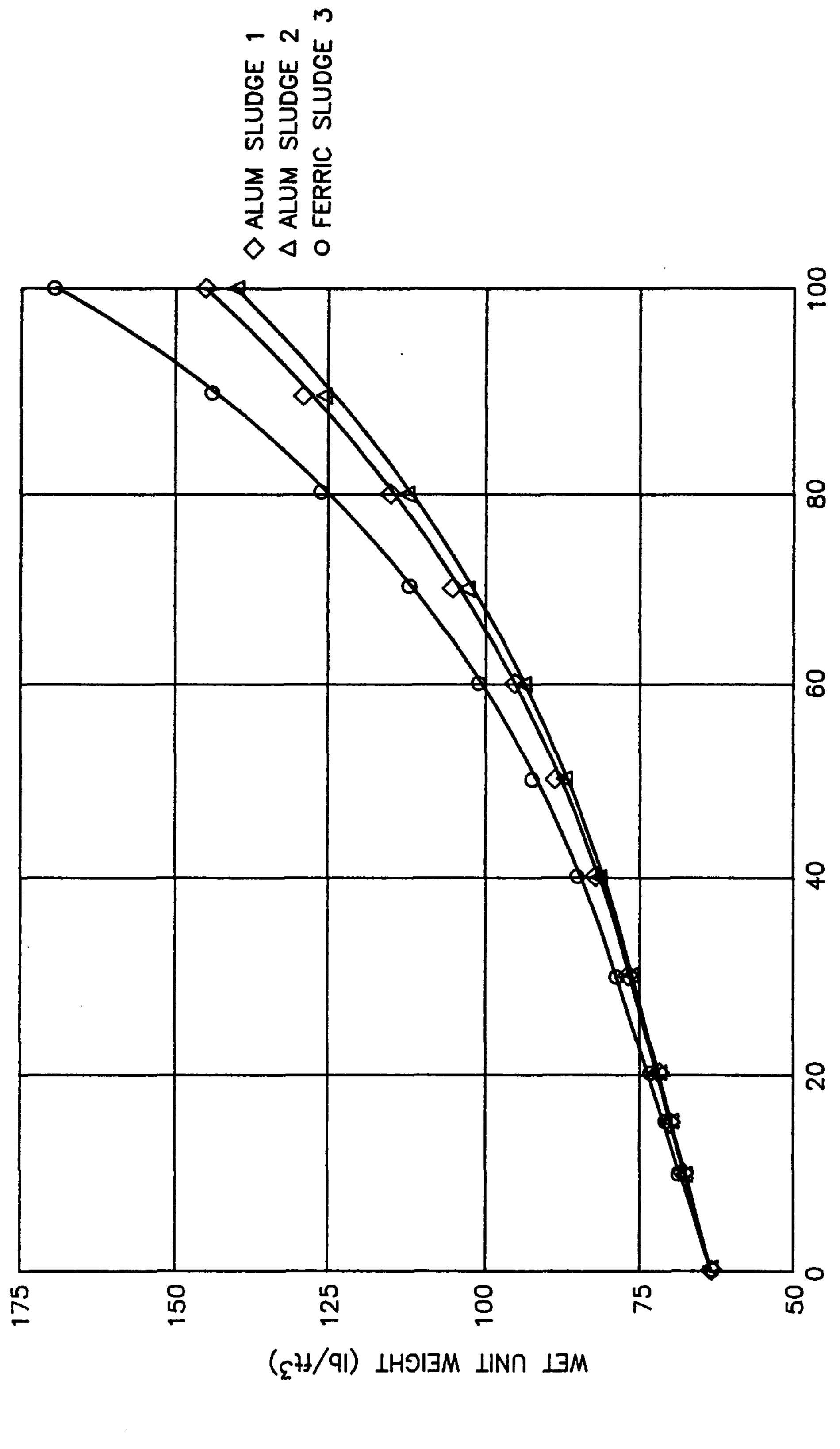


Figure 4.10 Wet unit weight versus solids concentration

Full-scale centrifuge tests have been performed on alum sludge 1 (specific gravity 2.33; density 10.2 lb/ft^3 [173.4 kg/m^3]), with reasonable results of cake concentrations slightly above 20 percent and approximately 98 percent capture. No centrifuge dewatering tests have been conducted on ferric sludge 3. Tests, however, have been performed on a sludge in Phoenix, Ariz. (Environmental Engineering & Technology, Inc., 1990), which had an estimated specific gravity of 2.8. The centrifuge tests yielded exceptional results of 40 percent cake and 99 percent capture, which were attributed to the silty and sandy characteristics of raw water turbidity and are evidenced by the specific gravity comparable to natural sand. It should be emphasized that the relationship between dewaterability and specific gravity and density was not part of this study, but the data presented do suggest a pattern worth further research.

Soil Classification

The results from the hydrometer and Atterberg tests were utilized to classify the sludges according to the Unified Soil Classification System. This system was developed by Casagrande (1932) to rapidly identify and group soils for military construction. The organization of different types of soils within the classification system is shown in Table 4.4. A two-step process identifies the soil group into which the material is classified. First, the material is either coarse grained (50 percent coarser than the no. 200 sieve) or fine grained (50 percent finer than the no. 200 sieve) based on the data obtained from the gradation test. Sludges are typically classified as fine-grained soils, as previously discussed. The second step in the overall classification system involves the liquid limit and separates low compressible (liquid limit less than 50 percent moisture) and high compressible (liquid limit above 50 percent moisture) materials.

Applying the above two steps to the three test sludges results in a grouping of high compressible materials into three types: silts and silty clays (MH), clays (CH), and organic silts and clays (OH). The Casagrande plasticity chart shown in Figure 4.11 is then used for dividing the fine-grained soils. Based on the liquid limit and plasticity index for each of the three test sludges, all three sludges are finally classified as CH-type materials. CH materials can be described as highly plastic clays and sandy clays.

Compaction Tests

Sludge behavior under compaction was evaluated to determine the maximum achievable dry density each sludge could obtain. A standard Proctor test was used to produce the moisture-density relationship for each sludge, with the data further reduced to present the results in terms of percent solids concentration versus dry density. The results for the three sludges are presented in Figures 4.12 through 4.14.

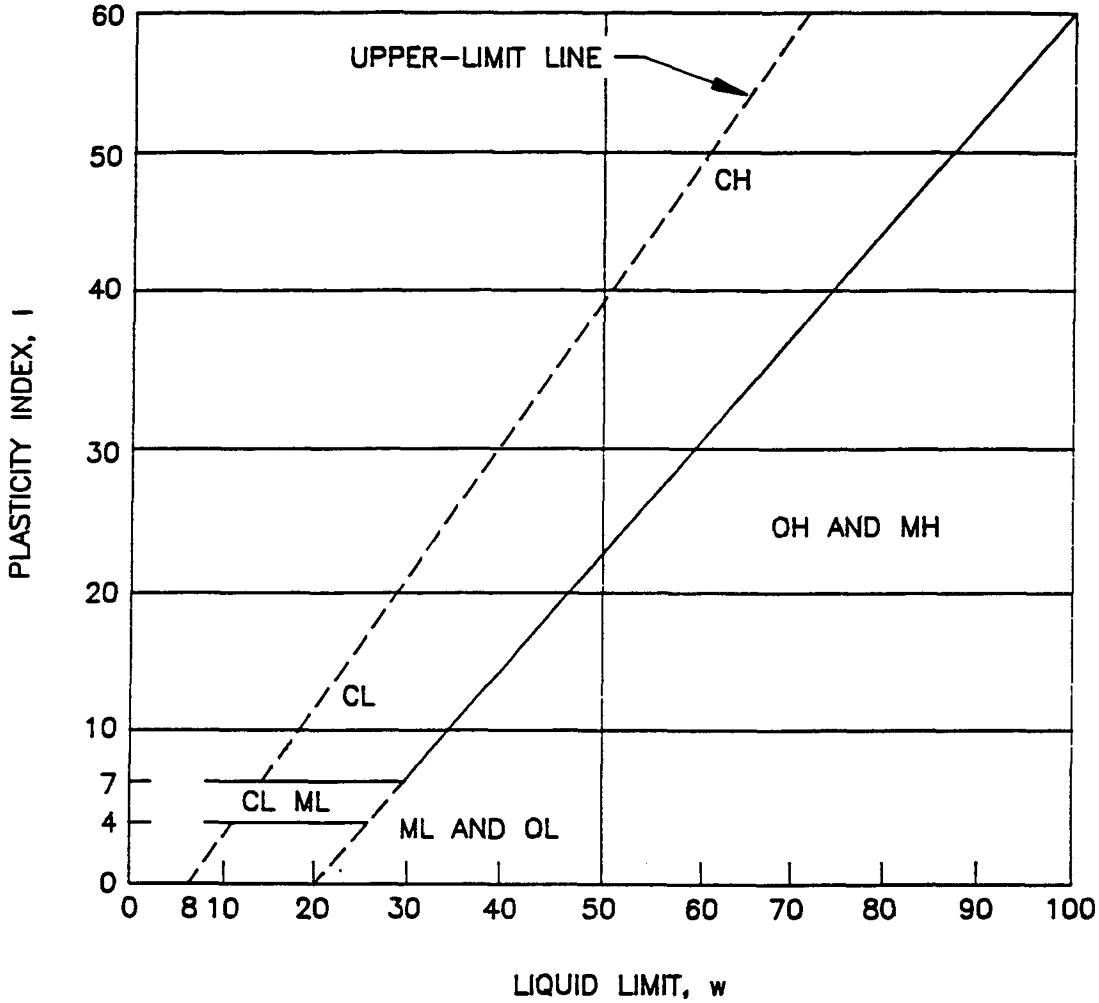
For each sludge, the zero air voids curve (ZAVC) represents what the dry density of the sludge would be if its entire volume consisted of water and solids only. This curve is determined theoretically with the equation shown below, because no matter how much the sludge is compacted, it is impossible to fill all the air voids with water. As a result, the compaction curve for a particular sludge cannot cross its ZAVC curve.

$$\text{Dry unit weight} = \frac{\text{specific gravity} \times \text{unit weight water}}{1 + \text{specific gravity} \times \left(\dfrac{\text{water content, \%}}{100} \right)}$$

Table 4.4 Unified Soil Classification System

Major divisions			Group symbol	Typical names	Classification criteria for coarse-grained soils	
Coarse-grained soils (more than half of material is larger than no. 200)	Gravels (more than half of coarse fraction is larger than no. 4 sieve size)	Clean gravels (little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	$C_U = D_{60}/D_{10} > 4$ $C_C = 1 < D^2_{30}/D_{10} \times D_{60} < 3$	
			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	Not meeting all gradation requirements for GW	
		Gravels with fines (appreciable amount of fines)	GM $\frac{d}{u}$	Silty gravels, gravel-sand-silt mixtures	Atterberg limits below A line or $I_p < 4$	Above A line with $4 < I_p < 7$ are borderline cases requiring use of dual symbols
			GC	Clayey gravels, gravel-sand-clay mixtures	Atterberg limits above A line with $I_p > 7$	
	Sands (more than half of coarse fraction is smaller than no. 4 sieve size)	Clean sands (little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines	$C_U = D_{60}/D_{10} > 6$ $C_C = 1 < D^2_{30}/D_{10} \times D_{60} < 3$	
			SP	Poorly graded sands, gravelly sands, little or no fines	Not meeting all gradation requirements for SW	
		Sands with fines (appreciable amount of fines)	SM $\frac{d}{u}$	Silty sands, sand-silt mixtures	Atterberg limits below A line or $I_p < 4$	Limits plotting in hatched zone with $4 \leq I_p \leq 7$ are borderline cases requiring use of dual symbols
			SC	Clayey sands, sand-clay mixtures	Atterberg limits above A line with $I_p > 7$	
Fine-grained soils (more than half of material is smaller than no. 200)	Silts and clays (liquid limit < 50)		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	1. Determine percentages of sand and gravel from grain-size curve. 2. Depending on percentages of fines (fraction smaller than 200 sieve size), coarse-grained soils are classified as follows: Less than 5%—GW, GP, SW, SP, More than 12%—GM, GC, SM, SC 5 to 12%—Borderline cases requiring dual symbols	
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays		
			OL	Organic silts and organic silty clays of low plasticity		
	Silts and clays (liquid limit > 50)		MH	Inorganic silts, micaeous or diatomaceous fine sandy or silty soils, elastic silts		
			CH	Inorganic clays of high plasticity, fat clays		
			OH	Organic clays of medium to high plasticity, organic silts		
	Highly organic soils		Pt	Peat and other highly organic soils		

Source: Bowles 1978, reprinted with permission.



Source: Bowles 1978, reprinted with permission.

Figure 4.11 Plasticity chart to use with table for Unified Soil Classification System

The compaction curve for ferric sludge 3 exhibits the general bell shape typically seen in a compaction curve for natural soils. For ferric sludge 3, the maximum dry density occurred at 72 lb/ft^3 (1,224 kg/m^3) at a solids concentration of 69 percent. The compaction curves for alum sludges 1 and 2 are notably different from ferric sludge 3 in that there is no peak formation. For these two sludges, the maximum dry density occurs at the highest possible solids concentration. Allowing the sludges to air dry at room temperature for 30 days yielded solids concentrations of 80 and 81 percent for alum sludge 1 and 2, respectively. The corresponding dry densities were 61 and 57 lb/ft^3 (1,037 and 969 kg/m^3), respectively.

Thus ferric sludge 3 was able to be compacted to a significantly higher degree than alum sludges 1 and 2. It is worth noting that ferric sludge 3 has a specific gravity comparable to natural soils, which may have contributed in part to the shape of the compaction curve. Also, the hydrometer analysis of the sludges yielded the coarsest particle sizes for alum sludge 2, which achieved the lowest degree of compaction. With respect to the compaction curve shape for alum sludges 1 and 2,

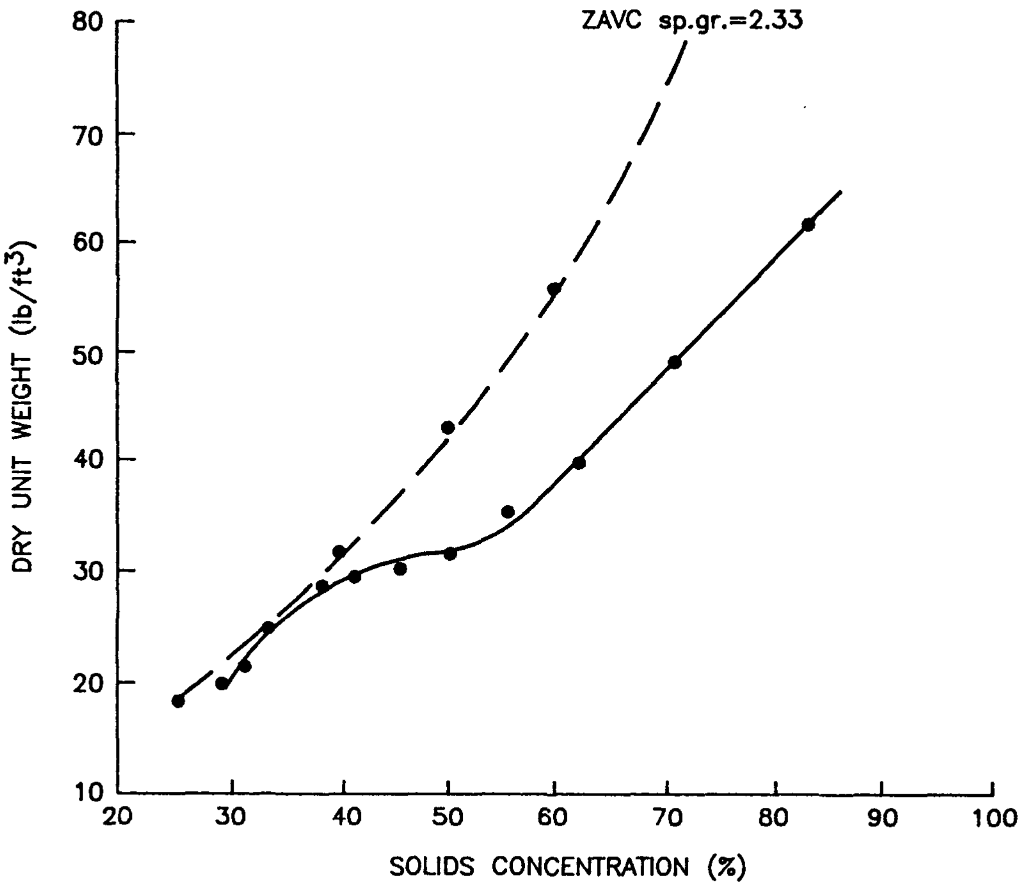


Figure 4.12 Compaction curve, alum sludge 1

there are, generally speaking, four basic types of curves; bell shape with only one peak, double peak curves, one and one-half peaks, and odd-shape curves. The odd-shape curve, characterized by the absence of a definite peak in the data, is occasionally seen for natural soils with a liquid limit greater than 70 percent moisture content. Some desert sands have a one-and-one-half-peak curve, with the maximum dry density at a 100 percent solids concentration.

Shear Strength Properties

The shear strength properties of the three test sludges were thoroughly investigated with cone penetration and triaxial compression tests. Shear strength properties are important physical characteristics because they relate directly to the overall ability of the sludge to support itself and external loadings. The cone penetration and triaxial compression test results were utilized to perform slope stability analyses and to evaluate ability of the sludge to support heavy equipment.

Cone Penetration Tests

Cone penetration tests were performed on the three sludges over a range of solids concentrations. These tests were also employed to research and quantify the impacts of thixotropic behavior typically associated with sludges. Thixotropic

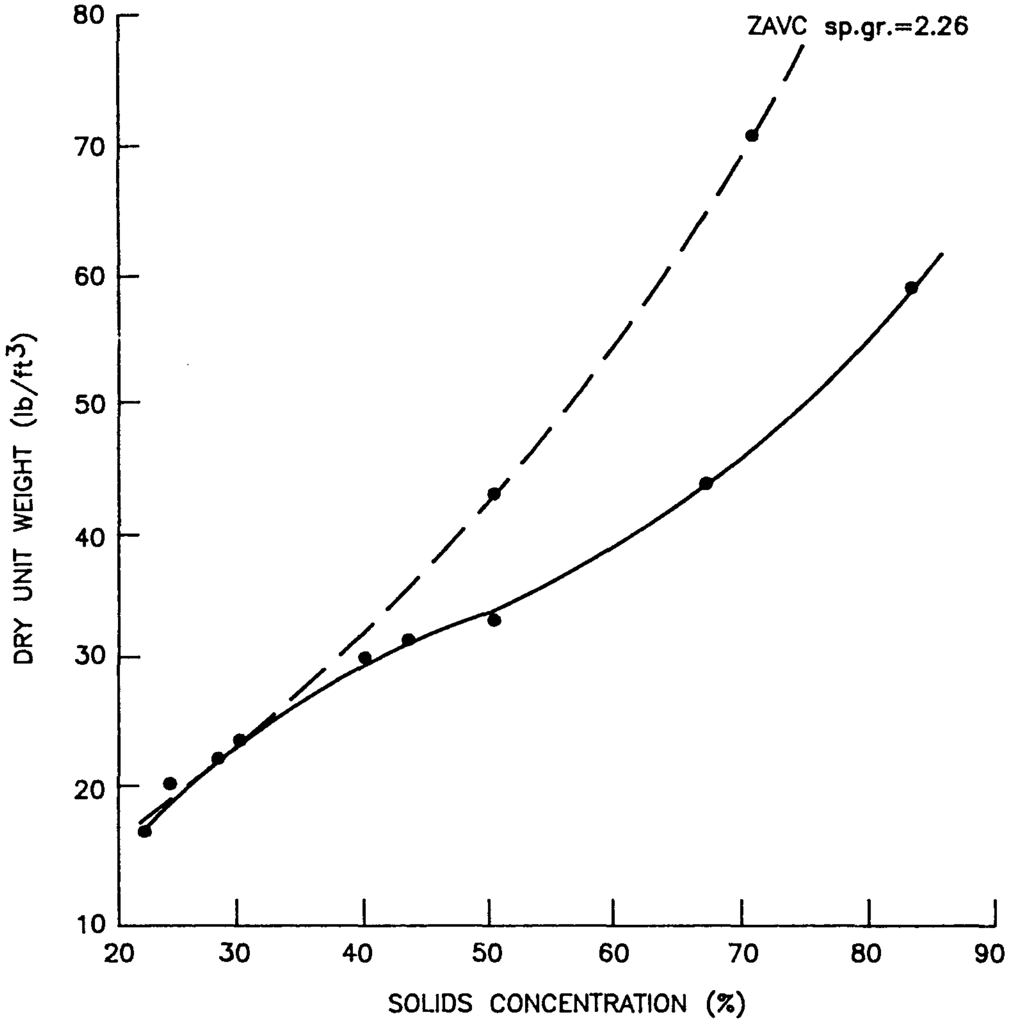


Figure 4.13 Compaction curve, alum sludge 2

behavior refers to a material's increase in strength over time when it is maintained in an undisturbed condition. Due to the relative simplicity of the cone penetration test, it was feasible to perform a number of tests at different sludge ages. In addition, the addition of lime, fly ash, and natural soil bulking agents to sludge was investigated as a possible means to increase sludge shear strength in an economical manner. Finally, the cone penetration test was also used to investigate the shear strength characteristics of a sludge monofill operated by the City of Chesapeake, Va. (alum sludge 2).

The undrained shear strengths obtained from the cone penetration tests are shown in Figure 4.15 for the three test sludges. "Undrained shear strength" refers to the sludge's response to being loaded to failure without a change in solids content. The results in Figure 4.15 are representative of nonaged sludges' shear strength. The tests were conducted immediately after the sludge sample was gently compacted in the sample container, which would have caused significant disturbance of the structure of the sample. The test results, however, do represent a confined condition. As shown in Figure 4.15, the shear strength for the three sludges increased with

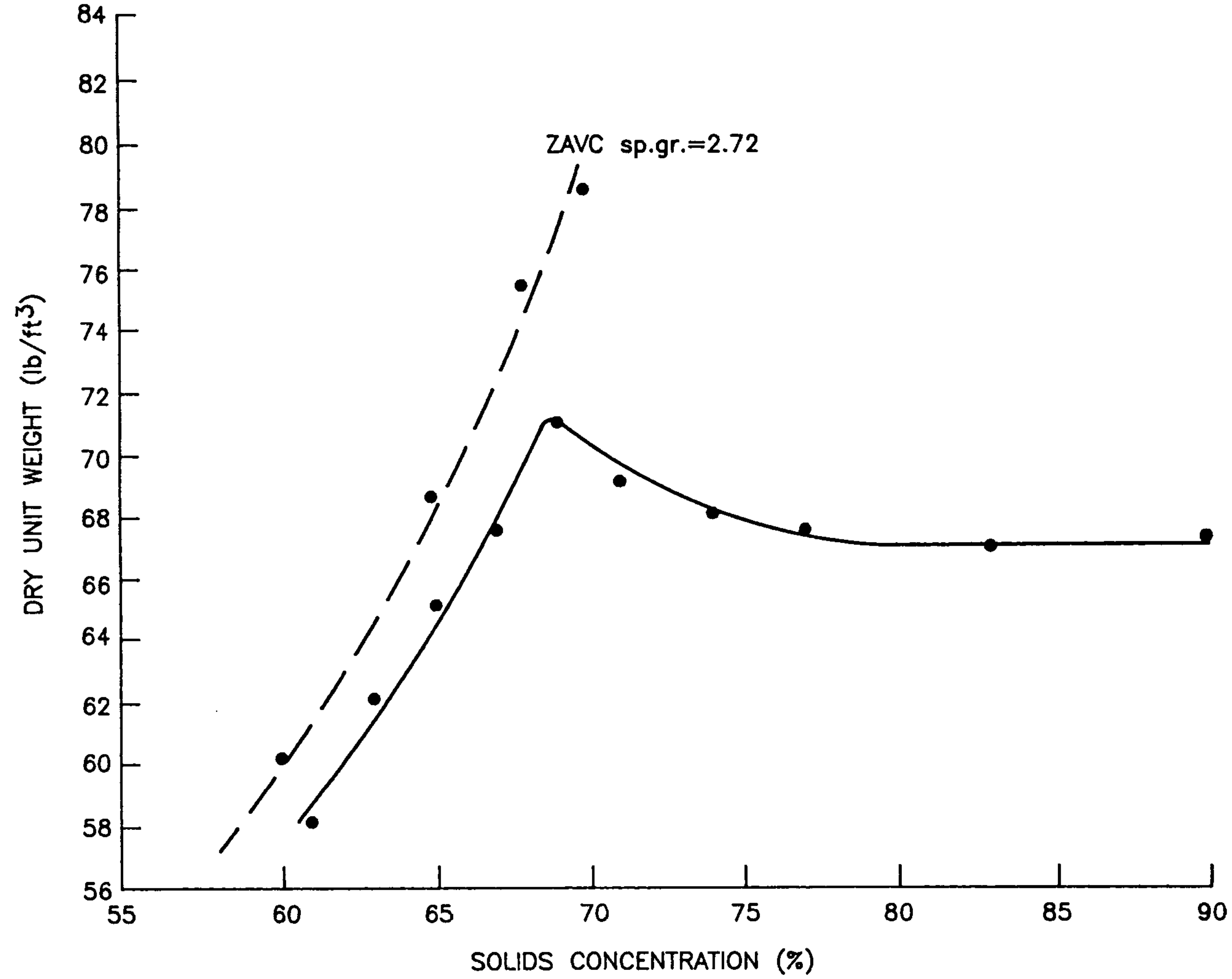


Figure 4.14 Compaction curve, ferric sludge 3

increasing solids concentration, but in a nonlinear manner. Thus, the rate of shear strength increase is small initially but becomes greater as the solids concentration increases. Shear strengths for sludge No. 1 and No. 2 were comparable over the solids concentration range. Ferric sludge 3 required a significantly higher solids concentration to achieve shear strength comparable to those of alum sludges 1 and 2.

The thixotropic behavior of alum sludge 1 was investigated by allowing prepared samples to cure for a specified period of time while maintaining the sample solids concentration. The undrained shear strength was then measured with respect to curing time. As shown in Figure 4.16, a considerable increase in shear strength occurred with time, indicating that the test sludge was highly thixotropic in nature. The data suggested that the shear strength could increase by as much as 3 times the initial value over a 90-day period. This behavior would play an important role in the overall long-term stability of a sludge disposal operation. Design and operation of a sludge monofill, however, should be based on the nonaged sludge condition as a worst-case scenario to provide adequate bearing capacity for heavy equipment. It may also be that disturbance of an aged sludge would lower its shear strength.

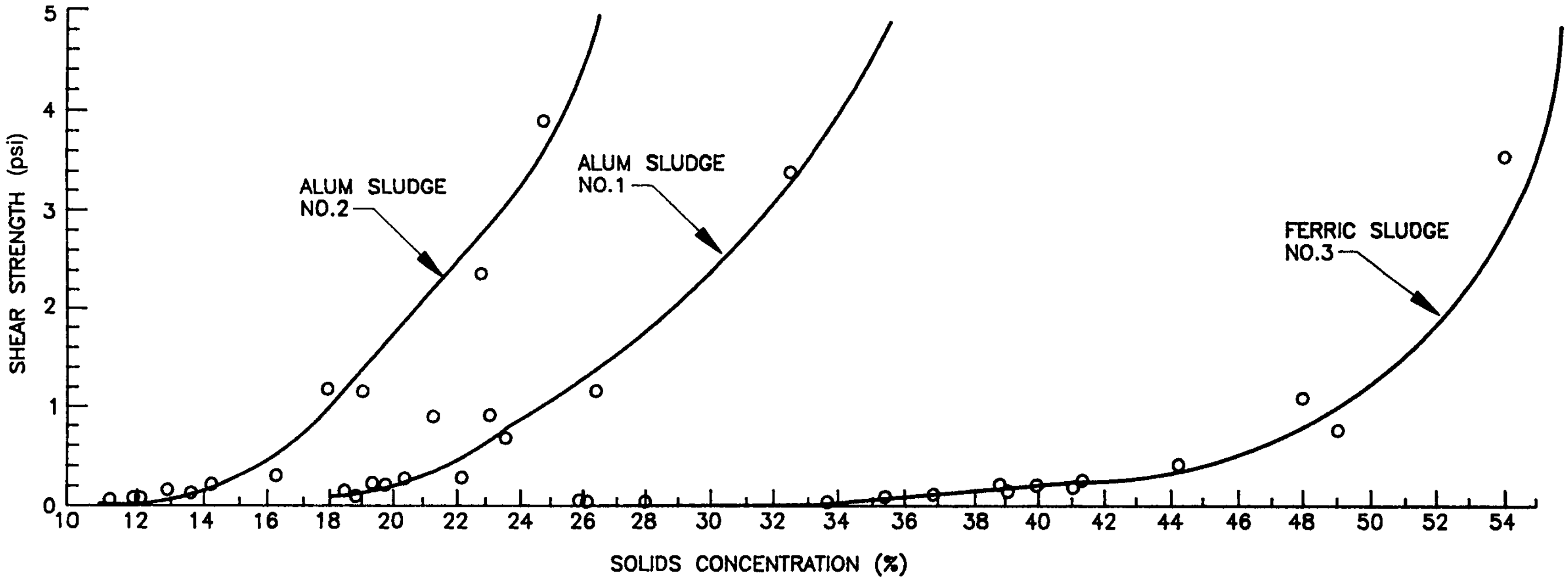


Figure 4.15 Shear strength versus solids concentration, cone penetration method

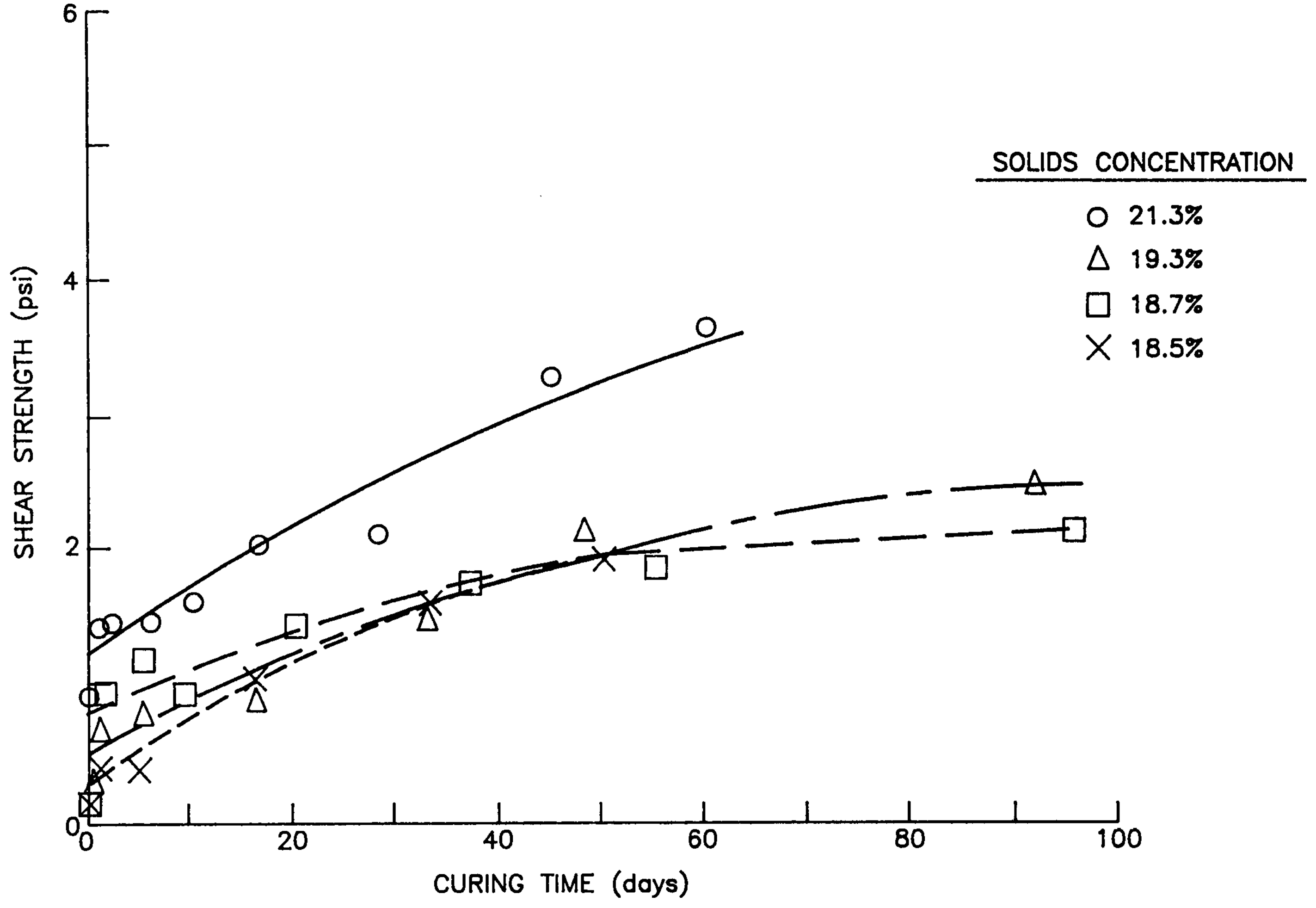


Figure 4.16 Shear strength versus curing time, alum sludge 1

The impacts of various bulking agents on the sludge shear strength are shown in Figures 4.17 and 4.18. These tests were performed on alum sludge 2 for curing times as long as 35 days. The bulking agents included (1) slaked lime with a specific gravity of 2.24, (2) a Class C fly ash from Indiana & Michigan Electric Company with a specific gravity of 2.67, and (3) a natural soil with a specific gravity of 2.65 and a maximum dry unit weight of 130 lb/ft^3 (2,210 kg/m^3). These bulking agents were separately mixed with the test sludge up to a 60 percent weight ratio. The data show a considerable increase in shear strength due to the introduction of additives. The amount of strength increase was more significant with higher treatment levels at both the uncured and cured conditions. For alum sludge 2, lime treatment yielded the greatest increase in strength, followed by the fly ash and then the natural soil. A similar conclusion was obtained by European researchers. They also tested cement and sawdust addition, which yielded results more favorable than fly ash but less pronounced than lime treatment (Cornwell and Koppers 1990).

The final cone penetration test performed was on a field sample obtained from a sludge monofill operated by the City of Chesapeake, Va. The results from this sample were used for comparison to alum sludge 2, which was obtained from the same utility. The city operates a trench-type disposal operation for its alum sludge, which is dewatered by centrifuges to around 15 percent solids concentration. Undisturbed field samples were collected by coring out a sample and were sent to the laboratory for shear strength analysis. The cone penetration test results for the field sample are shown in Figure 4.19. The data reflect a higher shear strength for the field sample than for the laboratory sample but can be explained by the age of the field sample and the thixotropic behavior of the sludge previously discussed. The variation in shear strength seemed more pronounced below the 20 percent solids concentration.

Triaxial Compression Tests

Additional shear strength tests were performed with the triaxial compression method. This method is significantly more sophisticated, time consuming, and costly than the cone penetration test. A larger sample specimen was considered, which, in conjunction with the equipment sophistication, should yield more accurate data than the cone penetration tests. For a thorough investigation of sludge shear strength properties, however, the use of the triaxial compression test only would be cost prohibitive.

The triaxial compression test requires cylindrical specimens with diameters of 36 mm, 72 mm, or more and lengths of at least twice the diameters. Such specimens were difficult to acquire with the sludges at low solids concentrations (below 20 percent solids). The methodology to prepare the samples consisted of consolidating the sludge (i.e., dewatering under a sustained pressure) under different pressures for a period of more than 1 month. The dewatered sludge was then carefully trimmed to the required size for testing. The results of the triaxial compression test should thus be interpreted as showing shear strength of slightly aged sludge. It was anticipated that this method of specimen preparation would yield shear strength values greater than those of the cone penetration test results.

The shear strength properties obtained with the triaxial test could be described in terms of parameters of cohesion and angle of internal friction. These parameters could be obtained from the Mohr circle diagram. Depending on the type of loading used in the testing, the parameters could be expressed for drained,

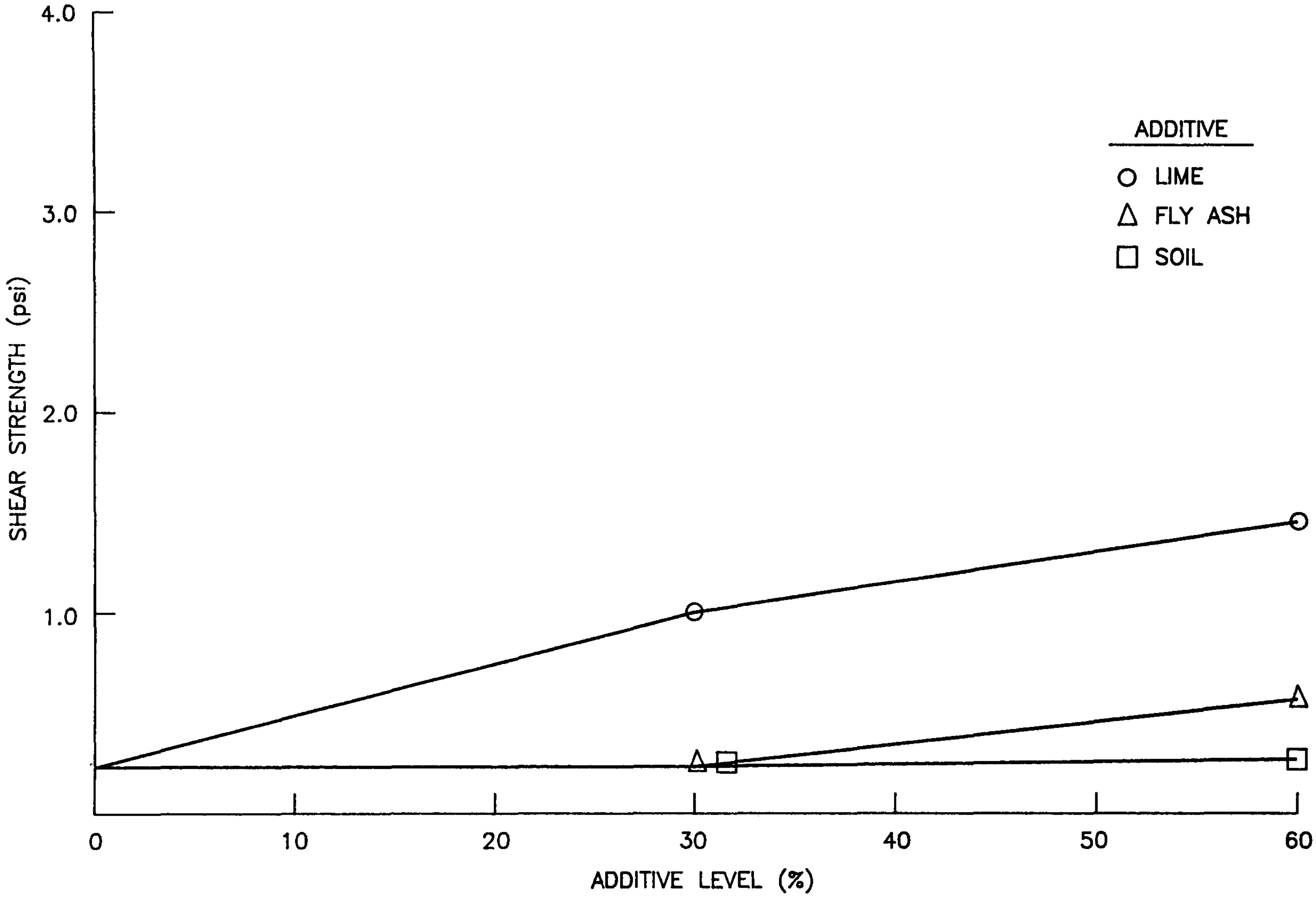


Figure 4.17 Shear strength versus additive level, alum sludge 2 (nonaged)

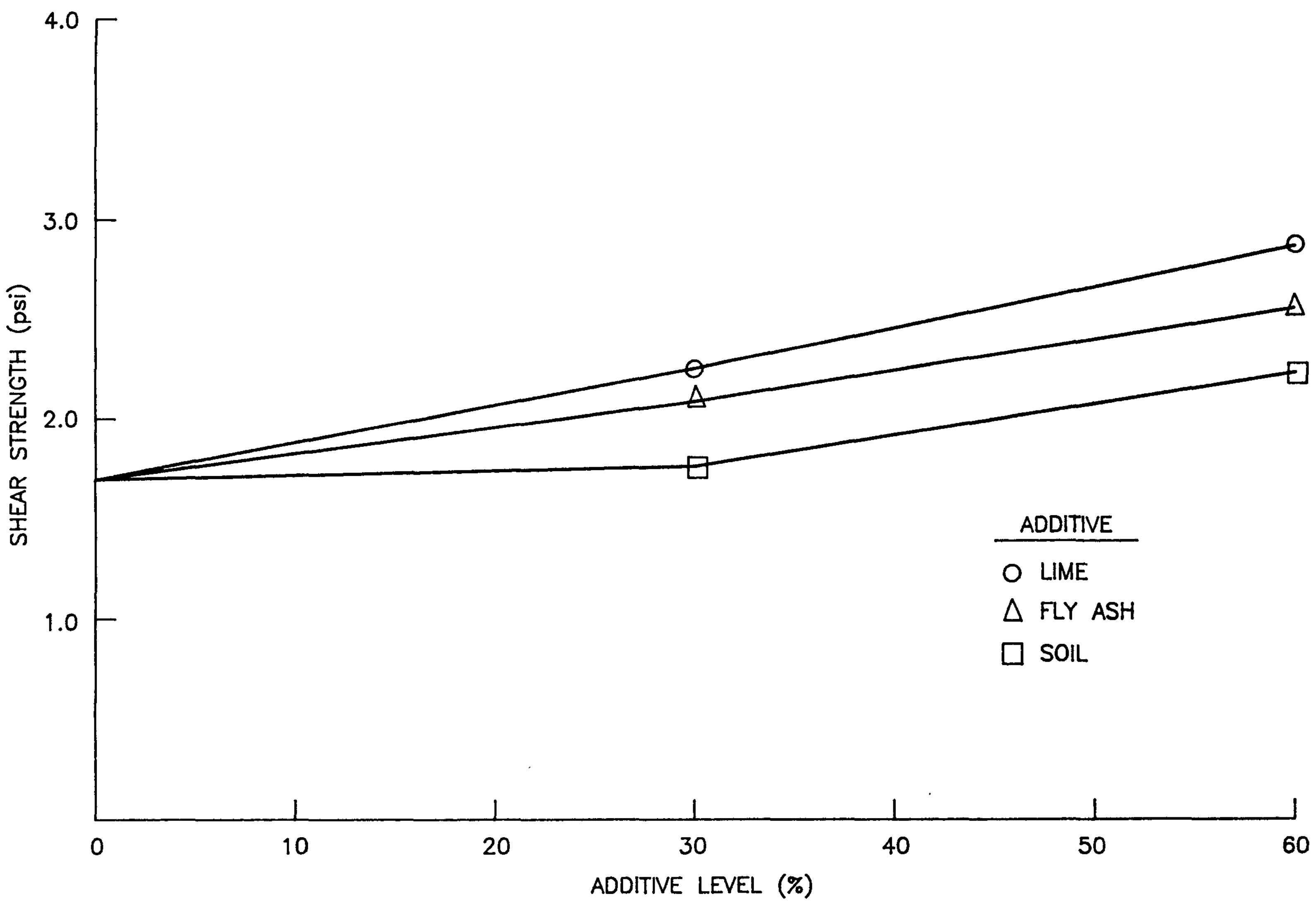


Figure 4.18 Shear strength versus additive level, alum sludge 2 (aged 35 days)

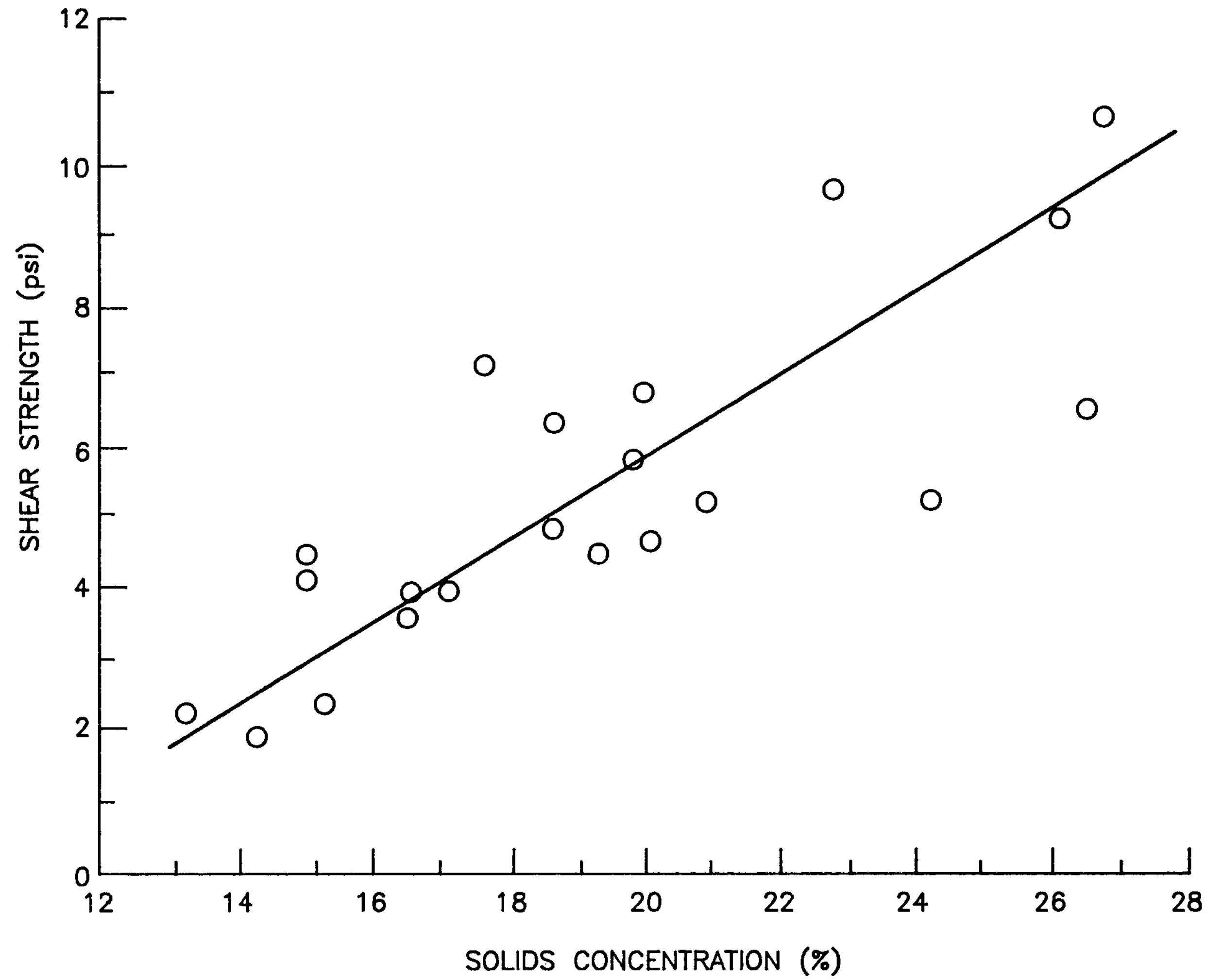


Figure 4.19 Shear strength versus solids concentration, alum sludge 2 field sample

undrained, and consolidated undrained conditions. The cohesion and angle of internal friction for the drained and consolidated undrained parameters are shown in Table 4.5 for the three test sludges and the one field sample (alum sludge 2). Based on these data, it can be seen that the shear strength parameters vary only slightly among the three test sludges. Also, alum sludge 2, the field sample, behaved in a manner similar to that of the sample collected from the water treatment plant prior to disposal.

For the detailed shear strength analysis of the three sludges, the undrained shear strength methodology was utilized. Undrained shear strength compares to a condition where the load changes occur more rapidly than the water content can adjust to. Consolidation does not occur under this scenario, as opposed to a slow increase in load changes, which allows consolidation of the sludge to occur.

The undrained shear strength parameters have a 0° angle of internal friction, and the cohesion, often termed undrained shear strength, increases with increasing solids content of the sludge. The shear strength data for the three sludges are shown in Figure 4.20. Similar to the cone penetration test results, the shear strength level

Table 4.5 Shear strength parameters of test sludges

	Consolidated drained			Consolidated undrained		
	Cohesion		Internal friction angle (degrees)	Cohesion		Internal friction angle (degrees)
Sludge number	(psi)	(kN/m^2)		(psi)	(kN/m^2)	
1	0.5	3.5	40.2	0.6	4.2	18.3
2	1.0	7.0	42.3	0.6	4.2	19.3
3	1.2	8.4	42.8	1.2	8.4	17.5
Field (sludge 2)	1.2	8.4	44.0	0.7	4.9	19.0

increases more dramatically when the solids concentration is high. According to Figure 4.20, the shear strengths of alum sludges 1 and 2 are within comparable ranges, but ferric sludge 3 required a significantly higher solids concentration to achieve the same level of shear strength as alum sludges 1 and 2.

A combined plot of the cone penetration and triaxial compression data is shown in Figure 4.21. The range for each sludge is a result of the variability in the data due to differences in age between cone penetration and triaxial compression tests. The applicability of these data is to determine the solids concentration necessary to support particular earth-moving equipment. Detailed calculations and examples for this evaluation are presented in Chapter 6.

Conclusions

The results from the physical characterization work indicate that conventional laboratory tests used in soil engineering can be adapted to test WTP sludges. The hydrometer method for grain size analysis and the Atterberg limit test are useful to characterize WTP sludges and to compare their properties to properties typically found for natural soils. Results for both laboratory tests seemed to be highly site specific and were influenced by the raw water source characteristics and coagulant employed in the treatment process. Some of the data developed herein suggest that a relationship exists between relative sludge dewaterability and the sludge's specific gravity and density. This could be researched further as a tool to predict sludge dewaterability prior to full-scale testing.

The sludge compaction curves for the three test sludges showed significant variations, which suggested a uniqueness for each sludge. The general trend indicated that achievable dry unit weight was directly related to solids concentration, particularly for alum sludges 1 and 2. Higher solids concentrations resulted in an increased dry unit weight. The dry unit weight for a particular sludge under a compacted condition is critical information for planning and sizing sludge monofills.

The shear strength properties were investigated with cone penetration and triaxial compression tests and yielded a specific relationship between solids concentration and shear strength for each test sludge. The shear strengths for alum sludges 1 and 2 were relatively comparable with respect to solids concentration. Ferric sludge 3 required significantly higher solids concentrations to yield shear strength values equivalent to those of sludges 1 and 2. This phenomenon was documented with both the cone penetration and triaxial compression tests. Tests for other parameters previously discussed also indicated a close relationship between alum sludges 1 and 2, whereas ferric sludge 3 always behaved significantly

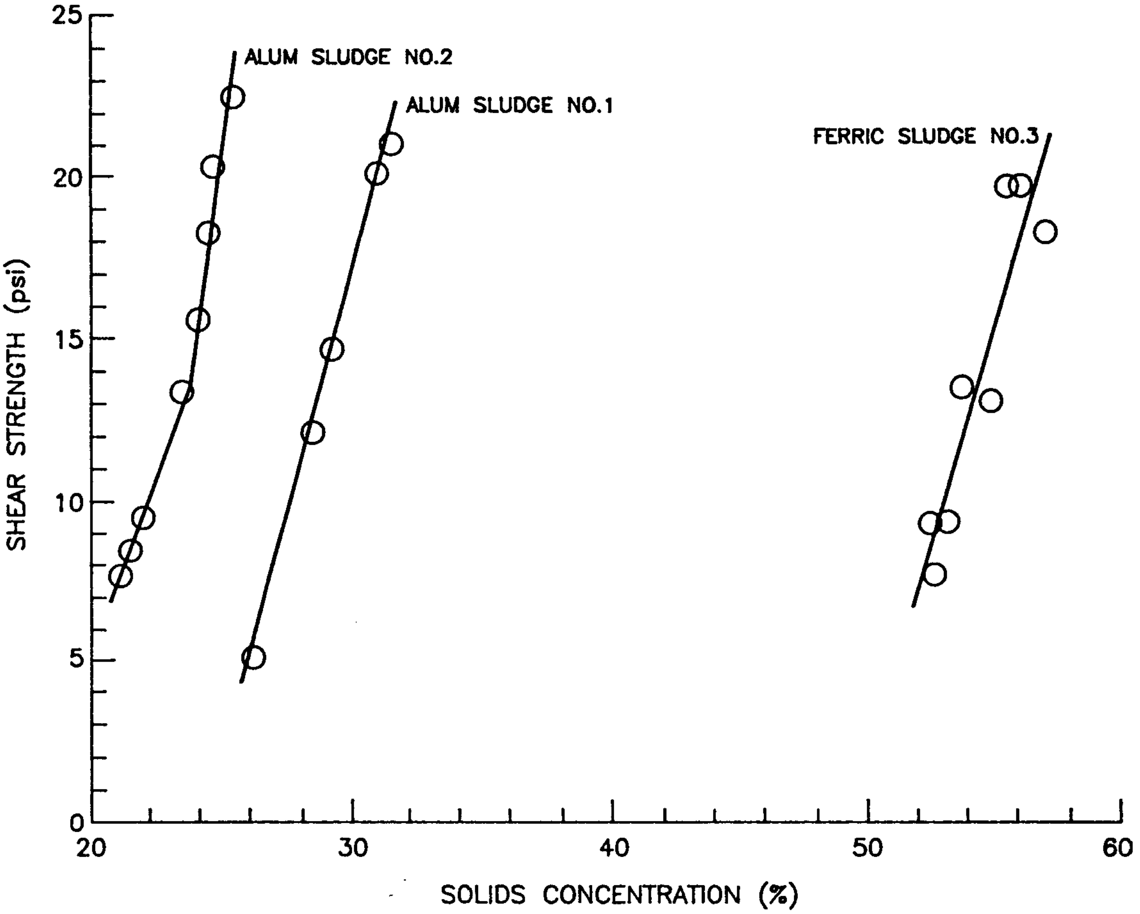


Figure 4.20 Shear strength versus solids concentration, triaxial compression method

differently. The exact reason for this could not be firmly established. It is believed that the sludge particle characterization, as well as possibly the iron coagulant used to generate ferric sludge 3, may have played an important role in the test results.

The impact of lime, fly ash, and natural bulking agents on the sludge shear strength was investigated for alum sludge 2. All three bulking agents generated a higher shear strength as the level of addition increased. The increase in strength was most pronounced for the lime and least for the natural soil. A 60 percent lime addition resulted in a 325 percent increase in sludge shear strength. Economically, however, lime may not be the best choice as a bulking agent, and other agents may prove to be more feasible. The actual need for and level of bulking agents would depend on slope stability and bearing capacity data for a specific sludge. This type of analysis is addressed in Chapter 6.

The data shown herein suggest that no general relationship exists between physical properties and solids concentrations. The three coagulant sludges tested showed a significant level of data variation among themselves such that site-specific sampling and analysis becomes a necessity. For a utility to adequately characterize its sludge, it is suggested that the following tests should be performed as a minimum:

- Grain size analyses
- Atterberg limit tests

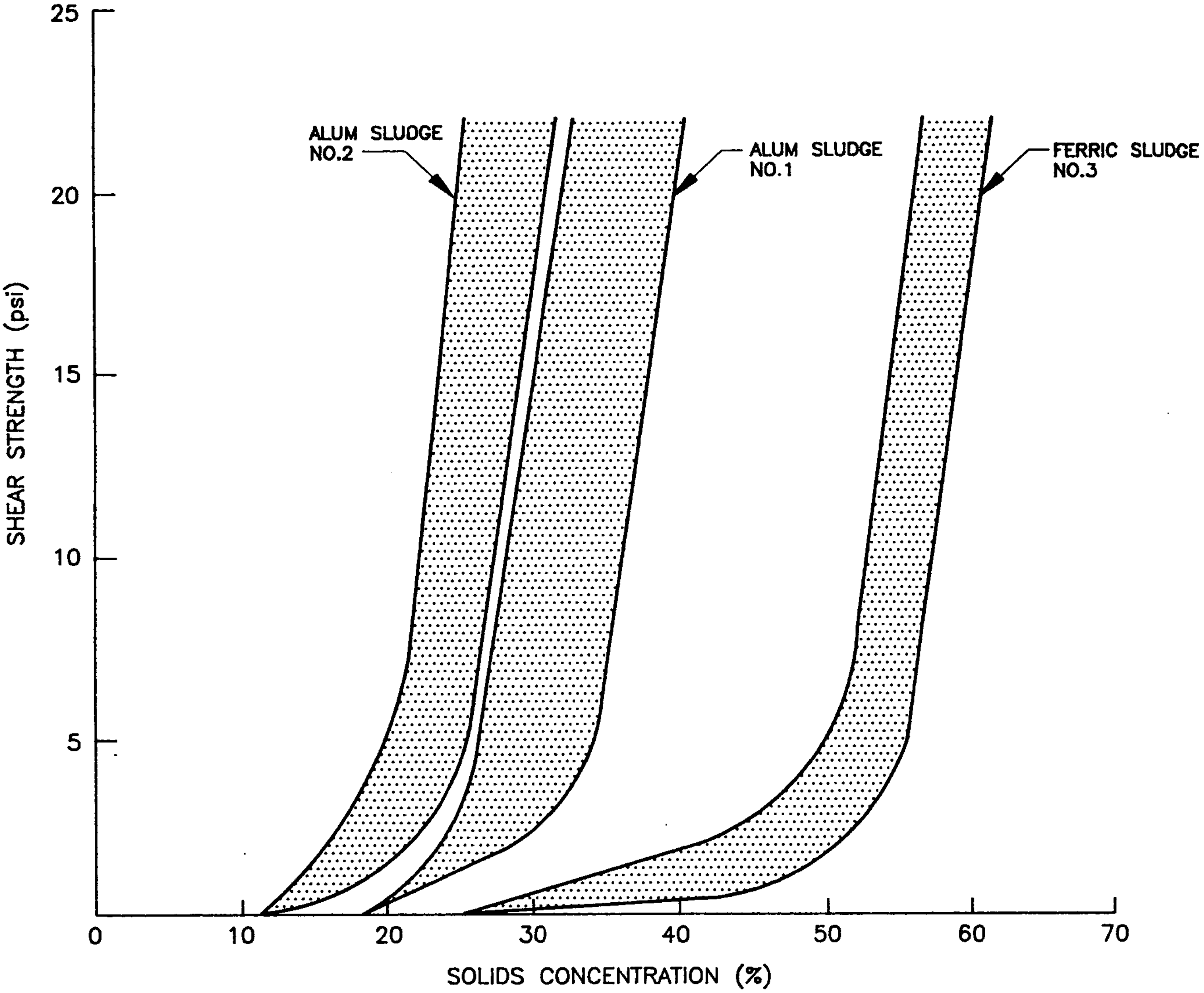


Figure 4.21 Shear strength versus solids concentration, cone penetration and triaxial compression tests

- Compaction tests
- Cone penetration tests
- Triaxial compression tests

Seasonal raw water variations should be taken into consideration in the scheduling of these tests. In cases where a high degree of variability exists between turbidity and organic content, it would be useful to collect sludge samples representative of the various events.

The compaction tests should be performed over a wide enough solids concentration range, representative of dewatered sludge and air-dried sludge. The cone penetration test should be conducted over a solids concentration range up to at least 10 percent higher than the level anticipated for the dewatered sludge. Triaxial compression tests should be performed up to the air-dried sludge solids concentration.

Chapter 5

Landfill Siting Considerations

Siting of landfill facilities has evolved into a time-consuming and complex process. Public opposition to the siting of new landfills has stemmed from previous experiences with "garbage dumps," environmental and health concerns, anxiety over property values, and the well-documented "not in my backyard" (NIMBY) syndrome. Siting problems arise when local politicians are unable to overcome the objections of their constituents.

An inability to successfully site new facilities has resulted in a nationwide shortage of landfill space. In 1988, USEPA indicated that about one-third of all existing landfills were expected to close by 1994. Moreover, USEPA estimated that only 10 percent of landfills were under 5 years old, indicating that few had opened recently (USEPA 1988).

To successfully locate and site new facilities, it is generally recognized that a methodology that provides an objective and broad framework for identifying and evaluating potential sites should be employed. An unbiased, systematic approach that is applied consistently will help foster public trust and support.

This chapter will describe a popular methodology for siting new landfills; however, it should not be viewed as a comprehensive guideline. Before the siting process begins, general estimates on volume requirements, as well as sludge quantities and characteristics, should be known. These determinations are described in detail in Chapters 4 and 6.

Site Selection Methodology

The objective of a formal site selection study is to locate a site that minimizes environmental and safety concerns and at the same time is economically feasible. To accomplish these objectives, the site selection process contains the following nine steps:

1. Develop primary site selection criteria
2. Develop secondary site selection criteria
3. Identify candidate sites
4. Develop ranking system for candidate sites
5. Select sites for detailed evaluation
6. Invite public involvement
7. Make final site selection
8. Hold public hearings
9. Secure local approval

It needs to be stressed that an adequate amount of lead time should be planned to work through all of the steps. Depending on the size of the proposed site and the size of the study area, the process could take from 6 to 12 months or longer. Often site selection gets held up during the local approval phase. During this phase, several public hearings may be required and additional information or studies or both be requested.

Primary and Secondary Site Selection Criteria

The first step in the site selection process involves determining what criteria will be used to eliminate areas from consideration. Most of the eliminating criteria or constraints are regulatory (federal, state, and local) in nature. Therefore, it is important to assemble all pertinent regulations that specifically address siting limitations. Chapter 2 discusses the federal and state regulatory framework that governs site suitability. Local zoning ordinances and codes should also be obtained and reviewed. The following documents should be assembled and reviewed:

1. *Solid Waste Disposal Facility Criteria: Final Rule,* USEPA, 40 CFR, Parts 257 and 258, October 9, 1991
2. State solid waste management regulations (see Chapter 2 and appendix for state agencies)
3. Local zoning ordinance, local comprehensive plan

There are numerous other federal laws that are also considered in siting of landfills. Applicable statutes and regulations include the following:

- National Historical Preservation Act of 1966, as amended
- Endangered Species Act
- Coastal Zone Management Act
- Wild and Scenic Rivers Act
- Fish and Wildlife Coordination Act
- Clean Water Act
- Clean Air Act
- Toxic Substances Control Act

Federal Landfill Siting Criteria

The USEPA has identified six types of locations that must have restrictions for landfill siting:

1. 100-year floodplains
2. Airport zones
3. Wetlands
4. Fault areas
5. Seismic impact zones
6. Unstable areas

The USEPA has specified that new and existing landfills and lateral expansions located in *100-year floodplains* "shall not restrict the flow of the 100-year flood, reduce the temporary water storage capacity of the floodplain, or result in the washout of solid waste so as to pose a hazard to human health and the environment" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51043]). Unless no other sites exist, landfills are generally not sited on 100-year floodplains.

New and existing landfills and lateral expansions located "within 10,000 ft (3,048 m) of any airport runway used by turbojet aircraft or within 5,000 ft (1,524 m) of any airport runway used by only piston-type aircraft shall not pose a bird hazard to aircraft. These distance limits were derived from the Federal Aviation Administration Order 5200.5" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51043]). The reason for this restriction is that landfills that receive putrescible wastes attract birds that can present a significant risk of collisions with aircraft. It is not anticipated that sludge monofills would attract birds; however, it would be the responsibility of the operator to show that no bird hazard exists. Airport zone restrictions should be considered in site selection criteria.

The USEPA has determined that no new landfills or lateral expansions can be placed in *wetlands* unless the owner or operator makes "specific demonstrations to the state that the new unit (1) would not result in 'significant degradation' of the wetland as defined in the CWA section 404 (b)(1) guidelines, published at 40 CFR, Part 230, and (2) would meet other requirements derived from the Section 404 (b)(1) guidelines" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51044]). The important consideration here is knowing what the official definition of wetlands is. In 1989, the USEPA and U.S. Army Corps of Engineers broadened the definition when they published the *Federal Manual for Identifying and Delineating Jurisdictional Wetlands*. On August 14, 1991, USEPA proposed narrowing the definition of what constitutes a wetland (*Federal Register*, vol. 58, no. 157; Wednesday, August 14, 1991; pages 40446–40480). Wetlands as *currently* defined by the USEPA should be avoided in the siting process.

The USEPA has banned "the location of new MSWLF units and lateral expansions within 200 ft (60 m) of *faults* that experienced displacement during the Holocene Epoch" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51004]). This proposed standard is designed to protect landfills from deformation and displacement of the surface of the earth that occur when the fault moves. Such movement could cause catastrophic failure of the landfill. During the siting of new landfills, all fault areas should be eliminated from further consideration.

New landfills and lateral expansions located in *seismic impact zones* are required by USEPA to demonstrate to the state that "the unit is designed to resist the maximum horizontal acceleration in lithified material for the site" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51004]). Seismic impact zones are defined as "areas having a 10 percent or greater probability that the maximum expected horizontal acceleration in hard rock, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10 g in 250 years" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51004]). Siting of landfills in these areas will require designing the landfill to withstand peak ground accelerations. These design features will increase the overall costs of the facility. Unless no other potential sites exist, seismic impact zones should be avoided.

The USEPA has determined that owners or operators of new and existing landfills and lateral expansions located in *unstable areas* must "demonstrate that engineering measures have been incorporated into the MSWLF unit's design to ensure that the integrity of the structural components of the MSWLF unit will not be disrupted" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51019]). The

USEPA has defined an unstable area as "a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity of some or all of the landfill structural components responsible for preventing releases from a landfill" (40 CFR, Parts 257 and 258 [*Federal Register* 1991, p. 51019]). Areas that are considered unstable include (1) subsidence-prone areas, such as areas subject to the lowering or collapse of the land surface either locally or over broad areas; (2) areas susceptible to mass movement or landslides; (3) weak and unstable soils; and (4) karst terrains, which are areas where solution cavities and caverns develop in limestone or dolomitic materials. In evaluating new landfill sites, unstable areas should be considered and avoided if possible.

State Landfill Siting Criteria

Most states impose some location standards and siting restrictions on landfills. These restrictions vary widely and include outright bans at some locations. Many states have already incorporated the proposed federal siting criteria, as previously outlined, into their own regulations. Some states are stringent in prohibiting landfills in certain areas, whereas others issue only avoidance directives. Minimum distances from surface waters and groundwaters and from habitable residences and utility lines are usually specified. Some of the additional siting limitations states may impose include the following:

- Critical habitats of endangered species
- Historic sites
- Areas with excessive slope
- Environmentally sensitive areas

Local Considerations in Site Selection

Localities experience pressures from two perspectives when approving or siting landfills. Although there is a recognized, legitimate public need for landfills, the use itself is often considered offensive. It is generally felt that landfills do not make particularly good neighbors for typical residential development and are usually too land intensive for commercial areas.

Zoning designations vary among localities, but it is most common to find landfills as permitted uses either in heavy industrial districts or in rural or agricultural districts. The logic here is that heavy industries will not mind the more "offensive" characteristics of the landfill, perhaps because the industries are "offensive" themselves, and the rural areas are sparsely populated, so relatively few citizens are directly affected by the site.

Within the zoning requirements of the industrial or rural or agricultural districts, many localities require a special or conditional use permit prior to any operation. The use permit is a mechanism for the locality to attach specific operating conditions to the landfill. Such conditions as screening, hours of operation, and access and traffic restrictions are common types. The use permit process gives the locality the ability to evaluate a particular landfill operation on a specific parcel, rather than granting a by-right zoning privilege.

In researching local zoning codes and ordinances, particular attention must be paid to the locality's comprehensive plan. If there is no mention of landfills, either existing or future sites, and the zoning ordinance does not allow them either by right or with a use permit, it will be extremely difficult to locate a landfill there. Any approval would fly in the face of adopted local policy and zoning laws.

Determining Site Selection Criteria

After the appropriate regulatory review, specific criteria should be selected to begin the site selection process. Once the criteria have been selected, they can be graphically depicted using a series of overlay maps. United States Geological Survey (USGS) 7.5-minute topographic maps can serve as base maps. Each eliminating criterion is depicted on a transparent sheet that is then placed over the base map, as shown in Figure 5.1. When the composite map is complete, areas that have remained unshaded are the most suitable for landfill construction. This series of maps provides an excellent visual aid for reports and presentations.

Identifying Candidate Sites

Once the composite map has been completed, potential sites can be identified. At this stage, access to the site, as well as hauling distances from the water treatment plant, should be considered. Some roads may have load restrictions that must be considered in selecting sites. A good estimate of acreage requirements should be available, including adequate buffer areas.

Ranking of Candidate Sites

The next step in the siting process is to develop a ranking system that compares each individual site with a set of established parameters. Parameters that can be used include:

1. Land use compatibility
2. Traffic impacts
3. Natural screening
4. Zoning consistency
5. Site configuration
6. Site ownership
7. Transportation costs
8. Site development costs

Not all of the ranking parameters are of equal importance. Therefore, it is necessary to assign a relative weight to each of the parameters selected. Often a scale of 1 to 5 is used, with 5 being most important and 1 being least important. It is often helpful to get several opinions on the eight factors, as they are very subjective. Some people may place higher weights on cost-related parameters, and others may favor impact-related parameters.

Further evaluation of each parameter is necessary to determine the quality of the individual parameters. Wording such as "highly acceptable," "acceptable," and "unacceptable" is often used to rate each parameter. These ratings are given a

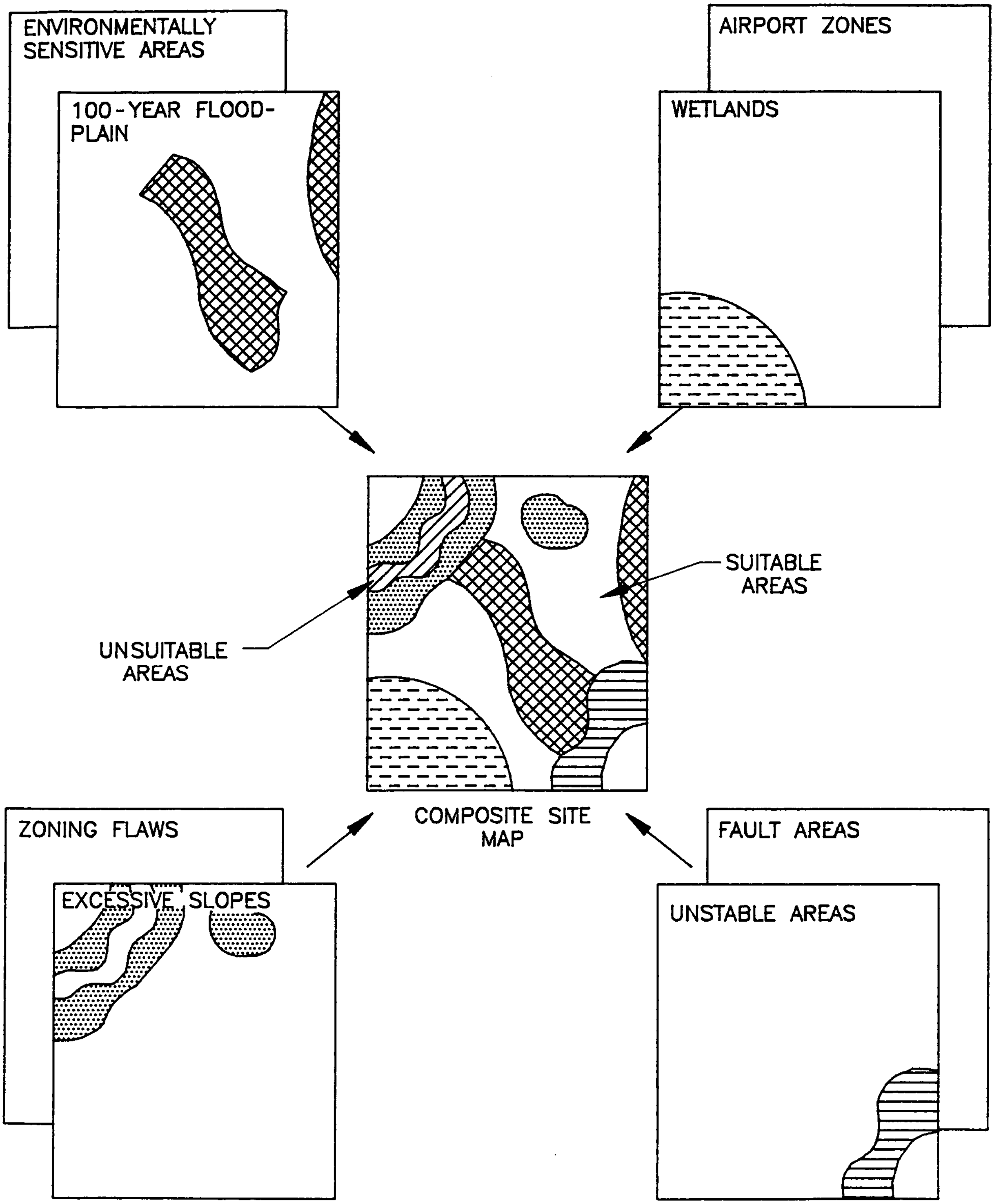


Figure 5.1 Individual overlay maps showing site elimination criteria and composite map

numeric value, such as +1 for highly acceptable, 0 for acceptable, and –1 for unacceptable. This number is then multiplied by the weighting factor assigned to each parameter. All of the scores are added up to arrive at a total score for each candidate site. These scores are not absolute and should be used only for general comparisons. However, the highest ranking sites usually are the more suitable sites.

Selection of Sites for Detailed Evaluations

After the ranking process, several sites should be chosen for more detailed analysis. The detailed evaluations usually consist of the following:

- Hydrogeologic evaluation
- Soils evaluation
- Detailed cost estimates

In the *hydrogeologic evaluation*, four key factors are determined: (1) depth to the water table, (2) water table gradient, (3) estimates of permeability, and (4) distance to nearest supply well or drinking water source.

The *soils evaluation* can be accomplished by using detailed soil surveys and maps for the subject area. Modern soil surveys have tables that describe soil types and soil limitations for construction of landfills. Properties such as flooding, shrink-swell potential, permeability, suitability as cover material, depth to water table, depth to bedrock or cemented pan, and slope are all summarized and rated as posing slight, moderate, or severe restrictions.

Preliminary *cost estimates* should be prepared for each site to allow for general comparisons between the sites.

Public Involvement

Depending on the size of the proposed landfill and the amount of opposition anticipated, public involvement in the siting process may be recommended. This involvement could be as simple as public informational meetings to appointment of a citizens' panel or task force to help select a final landfill site.

Local Approval

Once a final site has been selected, the owner of the proposed facility will have to acquire the necessary local zoning changes and approval *before* submitting a landfill permit application to the state.

The rezoning and conditional or special use permit process varies among localities, but sufficient lead time for review of the zoning request should be allowed. Rezoning requests have two review processes—that by the local planning commission and that by the local "governing body," i.e., city council, village council, board of supervisors, etc. Requests are usually submitted to the planning or zoning department or both, which forward a recommendation to the planning commission. Review time increases with the complexity of issues surrounding specific sites.

Planning commissions are usually required to hold a public hearing and then forward a recommendation to the governing body, generally within 90 days of receiving the request. The governing body then holds public hearings of its own and either approves or denies the rezoning request.

If a use permit is also required, the public hearing process may or may not involve the planning commission, depending upon local ordinance. The final decision on the use permit, however, is always the responsibility of the governing body. Some localities allow the rezoning request and the use permit request to be heard concurrently; others require the processes to run serially.

A significant amount of public input, usually opposition, can be expected during the public hearing process. However, presentation of the siting methodology and decision criteria will help to foster some support for the project.

It can be expected that development and operational conditions will be attached to any approvals. Few localities have sufficient protections built into the existing zoning regulations.

Chapter 6

Monofill Design Considerations

Design Options

Landfill disposal options for WTP coagulant sludges include placement in a sludge monofill and codisposal with refuse in a municipal or industrial solid waste landfill. Codisposal regulatory requirements, which vary from state to state, are presented in Table A.1 and highlighted in Chapter 2. Even though codisposal remains a viable and widely used alternative for the ultimate disposal of WTP sludges, the fact that available sanitary landfills are rapidly decreasing and disposal costs and regulatory constraints are increasing warrants a greater emphasis on sludge monofills and more beneficial disposal options. The focus of this chapter is on sludge monofill planning and design and includes the practical applicability of data presented in previous chapters. The guidelines presented in this chapter summarize the design criteria detailed in USEPA (1978). It should be noted that although this publication was prepared for wastewater sludge, similar basic monofill design principles would apply to WTP sludges.

The two major types of sludge monofilling methods are trench filling and area filling. Trench filling can be further subdivided into narrow trench and wide trench monofilling techniques. The three basic types of area filling include the area fill mound, area fill layer, and diked containment methods. Method selection is determined principally by sludge solids content, sludge stability, site hydrogeology (location of groundwater and bedrock), ground slope, and land availability. The following sections describe specific aspects of the various sludge monofilling methods.

Trench Filling

In trench landfills, sludge is placed entirely below the original ground surface. Trench depth is dependent typically on the depth to groundwater and bedrock; sufficient soil buffers between the sludge and substrata must be maintained. Trench depth is a function of sidewall stability and equipment limitations as well. The trenching method encompasses both narrow and wide trench type disposal areas, which range in width from several feet to 50 ft (15.2 m).

Narrow trenches are generally employed for sludges with low solids concentrations that could not support any type of heavy equipment. Wide trenches are used for sludges when solids concentrations are sufficient to achieve the necessary shear strength to support heavy equipment. Trenching is a convenient way to operate a landfill because trucks can unload sludge from firm ground above the trench while a hydraulic excavator located outside the trench or a tracked dozer operating inside the trench places and compacts the sludge. Trenches are also relatively quick and easy to construct, thus minimizing construction costs.

The planning and design of sludge disposal trenches involve determination of the following parameters in order to predict the acreages needed for a long-term disposal plan:

- Cover thickness
- Excavation depth
- Length
- Orientation
- Sludge fill depth
- Spacing
- Width

Final cover thickness depends on the trench width and type of equipment (land based or sludge based) to be employed in final cover operations. It should be noted that a daily cover for odor control is typically not required for WTP sludges. Factors influencing excavation depth include location of groundwater and bedrock, soil permeability, soil cation exchange capacity, equipment limitations, and sidewall stability. Trench length is limited by sludge solids content and ground slopes; trenches must be discontinued or dikes constructed to contain sludge with a low solids content in a sloping area. For optimal land utilization, trenches should be oriented parallel to one another. Sidewall stability, in addition to ultimately controlling excavation depth, determines trench spacing. In general, for every foot of trench depth 1 to 1.5 ft (0.3 to 0.5 m) of space should be provided between trenches (USEPA 1978). Spacing should not hinder vehicular access or preclude stockpiling of trench spoil. Sludge solids content and equipment limitations are both important considerations in appropriate trench width determinations.

Narrow Trench

The selection of narrow trenches less than 10 ft (3.05 m) in width versus wide trenches is primarily based on the anticipated sludge solids concentration and available property size. Narrow trenches are generally operated with equipment such as hydraulic excavators located on firm ground above the trench. The primary advantage of the narrow trench system is its ability to provide a feasible means of ultimate disposal for relatively wet sludges. On the other hand, substantial land requirements and poor space utilization dictated by the number of trenches and required amount of ground between trenches are significant disadvantages of this system. In addition, if a synthetic liner is required for each individual trench, the construction cost of the trench would increase sharply due to the relatively small scope of the work and high mobilization costs for a lining contractor.

Wide Trench

Wide trenches, classified generally as up to 50 ft (15.2 m) in width, are applicable for adequately dewatered sludges capable of supporting heavy equipment such as tracked dozers or similar types of tracked vehicles. The main advantage of wide trenches over narrow trenches is the better land utilization, because fewer numbers of wide trenches are required to handle the same volume of sludge. Wide trenches also provide better access for installing liners. A disadvantage of wide trenches relates to the fact that sludges, which are typically dewatered sufficiently to prevent free flowing, must be unloaded directly on the trench floor, thus requiring access for trucks.

Area Filling

Unlike the trench landfilling technique, where sludge is placed below ground, in area filling techniques sludge is placed above the original ground surface. Area filling may be accomplished in one of three ways:

- Area mound, where sludge is mixed with soil such that it becomes stable enough to be stacked in mounds
- Area layer, in which sludge is spread evenly in layers over a large tract of land
- Diked containment, where earthen dikes are constructed above ground to form a containment structure into which the sludge can be disposed

Although solids content is not limited in area fill landfills, the requirement that sludge must be capable of supporting heavy equipment due to the lack of sidewall containment necessitates reasonably good sludge stability and bearing capacity. These characteristics are typically achieved through good dewatering, dewatering followed by air drying, or mixing sludge with bulking agents. A combination of these methods can also be employed. Areas with high water tables and those with bedrock close to the surface are particularly amenable to area fill methods of sludge monofilling. Liners are therefore more likely to be required, but their installation is easier than the installation of liners in trenches. A general overview of the three types of area filling techniques is presented below.

Area Fill Mound Method

The area fill mound technique is a disposal method used for wastewater sludges. For wastewater sludge, soil bulking agent is generally mixed with sludge to enhance stability and increase bearing capacity to the degree required based on the sludge depth and the weight of the equipment. After being piled in mounds approximately 6 ft high (1.83 m), the sludge and soil mixture is covered with at least 3 ft (0.91 m) of soil cover material (more if additional lifts are to be piled on top of the first mound). This disposal method allows for good land utilization and reasonably high application rates. On the negative side, the tendency of mounds to slump, particularly under high rainfall conditions, and the resulting need for mound readjustment introduce higher manpower and equipment requirements. This monofilling method should be adaptable to WTP sludges. The need for bulking agents with WTP sludges, however, should be evaluated based on the sludge shear strength, size of the monofill, etc.

Area Fill Layer Method

In the area fill layer disposal method, sludge is spread in 6- to 12-in. (15.2- to 30.5-cm) layers. This provides additional air drying of the sludge and allows higher solids concentration and shear strengths to be achieved. This method seems favorable for coagulant sludges, which are typically difficult to dewater. The layering method eliminates the need for a separate air drying area outside the monofill, provided the monofill cell is large enough. The area fill layering technique usually results in relatively stable fill areas when completed and therefore requires less extensive equipment and manpower efforts for maintenance than the area fill mound technique.

Diked Containment Method

In the diked containment disposal method, earthen dikes are constructed above ground to form a containment structure into which the sludge can be disposed. Containment areas may sometimes be placed at the top of a slope, which can provide part of the containment structure itself. Access roads are constructed on top of the dikes so that sludge haul trucks can unload sludge directly into the disposal cell.

The sludge can be disposed inside the diked containment area in either a layering or a mounding technique, although the layering technique seems to be preferred. Access should be provided into the disposal cell itself for tracked equipment and trucks delivering the sludge.

When the diked containment disposal method is used, available land is developed to its greatest potential. Large cells can be constructed and long-term construction cost savings achieved. The diked containment method allows the highest sludge loading rate per acre (due to greatest available storage volume) of the three types of area filling by providing the stability necessary to increase sludge depth. Because of high sludge loading rates per acre, a liner and leachate collection system may be necessary to prevent moisture from being squeezed into the surrounding dikes or subsurface soil.

One final but essential aspect of monofill planning and design involves effective storm water management. Surface grades of 2 to 5 percent should be maintained to promote runoff, preclude ponding, and limit flow velocities, thereby minimizing soil erosion. Storm water collection should be utilized to route upstream storm water flow around the monofill. Sediment ponds and other erosion control measures should be employed as necessary.

All monofill sites should be provided with an all-weather road providing access from a public road. Gravel roads should be considered the minimum standard. Road slopes should generally be no steeper than 7 and 10 percent for uphill and downhill grades, respectively, to be accessible to fully loaded vehicles. Sludge could be delivered to the working area by way of temporary roads. The need for buildings and utilities is dictated by landfill size, but some consideration should be given to a truck wash station and equipment storage and operations facilities. Necessary limited access can be achieved through installation of gates and peripheral fencing, depending on the relative isolation of the site.

Utilization of Sludge Physical Characteristics

The sludge physical data developed in Chapter 4 yielded shear strength values for the three test sludges at various solids concentrations. These data allow the determination of the required minimum solids concentration with shear strength adequate to (1) create stable side slopes to prevent slope failure and (2) support the heavy earth-moving equipment utilized in monofill operations. Once the required minimum solids concentration is determined, the monofill size can be established based on sludge generation rates, density, and disposal depth. It should be noted that both the slope stability and the bearing capacity analysis must be performed in order to determine which requirement will govern the monofill design. Both analyses were performed on the three test sludges to illustrate the procedures involved and are discussed in the following paragraphs.

Slope Stability Analysis

Sludge monofills operated with an area fill technique require a slope stability analysis to prevent slumping or sliding of the side slopes. The sludge mass on a sloping surface is subject to numerous shearing stresses because gravitational force tends to pull the upper parts of the sludge mass downward. Provided that the shear strength of the sludge is greater than the highest internal stress, the side slope would remain stable. However, if the sludge shear strength becomes less than the internal stress, even for brief periods of time, slope failure occurs to a point where the internal stress again becomes less than the sludge shear strength.

In planning a sludge monofill, it would be useful to determine the required sludge solids concentration and corresponding shear strength in order to maintain a stable side slope condition. A procedure was developed herein to utilize the results from the physical characterization tests to obtain the required minimum solids concentration and shear strength for each of the three test sludges. The slope analysis methodology assumed a uniform side slope with a constant angle from the toe of the monofill to the top of the slope, and a monofill supported on a firm level ground. Using the method of limiting equilibrium, the maximum monofill height with a stable slope was computed for different levels of shear strength. Figure 6.1 shows the relationship between the monofill height and the ratio of shear strength to wet unit weight for five slope levels. The five slope levels ranged from 6H:1V (where H is horizontal, V is vertical) (16.7 percent slope, 9.5 degree slope angle) to 2.5H:1V (40 percent slope, 21.8 degree slope angle). The results shown in Figure 6.1 incorporate a factor of safety of 1.2 for planning purposes.

By utilizing Figure 6.1, the minimum solids concentration required for maintaining a stable slope can be determined. The procedure of determination involves an iterative process and can be accomplished as follows:

1. Select the desired slope angle and landfill height.
2. Find the required ratio of shear strength to wet unit weight from Figure 6.1.
3. Assume a wet unit weight of sludge and compute the shear strength.
4. Find solids concentration for the computed shear strength from Figure 4.21.
5. Check the wet unit weight for the solids concentration using Figure 4.10 and for the empirical density equation.
6. Repeat steps 3 through 6 until the assumed and actual unit weights balance.

This procedure was applied to the three test sludges. The side slope was set at 3H:1V, and a 20- and 40-ft (6.1- and 12.2-m) monofill height was considered. The results of this analysis are shown in Table 6.2, and example calculations for alum sludge 1 are shown in Table 6.1.

Two key conclusions can be drawn for the slope stability results. First, it is evident that the required solids concentration increases as the side slope becomes steeper. Second, the results show unique solids requirements for each test sludge, suggesting that site-specific tests should always be considered. The slope stability

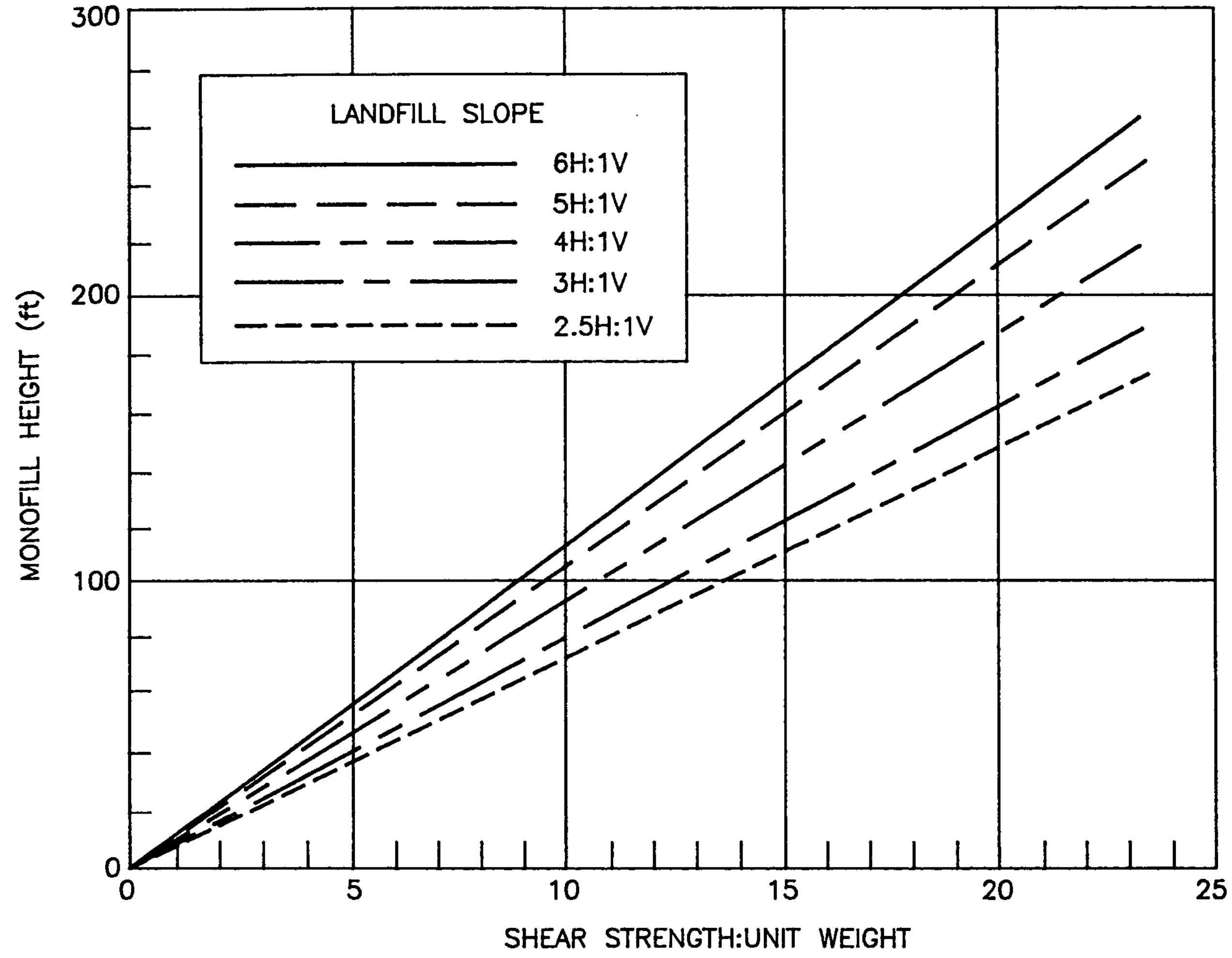


Figure 6.1 Monofill height versus shear strength: unit weight

Table 6.1 Slope stability analysis, alum sludge 1

Trial No. 1		
Required slope	3H:1V	
Monofill height [ft (m)]	20 (6.1)	40 (12.2)
Shear strength/wet unit weight	2.7	5.0
Assumed wet unit weight [lb/ft^3 (kg/m^3)]	72 (1,224)	72 (1,224)
Shear strength [lb/ft^2 (kN/m^2)]	194.4 (9.3)	360.0 (17.2)
Shear strength (psi)	1.35	2.50
Solids concentration (%)	26	30
Actual wet unit weight [lb/ft^3 (kg/m^3)]	73 (1,241)	75 (1,275)
Calculated wet unit weight [lb/ft^3 (kg/m^3)]	73.2 (1,244.4)	75.3 (1,280.1)
Trial No. 2		
Assumed wet unit weight [lb/ft^3 (kg/m^3)]	74 (1,258)	75 (1,275)
Shear strength [lb/ft^2 (kN/m^2)]	199.8 (9.6)	375.0 (17.9)
Solids concentration (%)	26	31
Actual wet unit weight [lb/ft^3 (kg/m^3)]	74 (1,258)	75 (1,275)
Calculated wet unit weight [lb/ft^3 (kg/m^3)]	73 (1,241)	75.5 (1,283.5)

Table 6.2 Minimum solids contents required for maintaining a 3:1 slope

Landfill height (ft)	Shear strength wet unit weight	Wet unit weight		Shear strength			Solids content (percent) by type of sludge
		(lb/ft³)	(kg/m³)	(lb/ft²)	(psi)	(kN/m²)	
20	2.7	74	1,258	199.8	1.39	9.56	sludge 1: 26
20	2.7	71	1,207	191.7	1.33	9.17	sludge 2: 19
20	2.7	93	1,581	251.1	1.74	12.01	sludge 3: 52
40	5.0	75	1,275	375.0	2.6	17.94	sludge 1: 31
40	5.0	72	1,224	360.0	2.5	17.22	sludge 2: 22
40	5.0	96	1,632	480.0	3.33	22.96	sludge 3: 56

analysis would also be quite useful in the overall planning of a monofill. For example, if the side slope is fixed by regulatory requirements (say, 3H:1V), a graph can be developed to determine the optimum monofill height in order to minimize the land requirements. An example for alum sludge 1 is shown in Figure 6.2. This illustrates the minimum sludge solids concentration required to maintain a stable side slope.

From the data shown in Table 6.2, it is evident that the shear strength exhibited by the sludge is an important parameter. However, the shear strength required to ensure a stable side slope may not be sufficient to prevent heavy equipment from settling into the sludge. Thus, an equipment-bearing capacity analysis must be conducted to determine whether the shear strength required to maintain a stable slope or the shear strength required to support heavy equipment should govern in the design of a monofill.

Equipment-Bearing Capacity Analysis

The objective of the equipment-bearing capacity analysis was to determine the minimum sludge shear strength necessary to support various types of heavy equipment commonly used in the operation of a sludge monofill. The resulting sludge shear strength was then compared with the slope stability data to establish the governing shear strength.

The bearing capacity analysis considered the bearing capacity failure of the sludge under the drive wheel (or track) of the equipment, or in other words, equipment settlement into the sludge. The failure condition considered the equipment static weight on a level surface and utilized the general bearing capacity equation. The bearing capacity equation, developed by Terzaghi and Meyerhof (Spangler and Handy 1982), is shown below and incorporates dimensionless bearing capacity factors designated N_c, N_q, and N_γ:

$$q_\mu = cN_c + qN_q + 0.5\ B\gamma N_\gamma$$

where q_μ = bearing capacity in force per unit area
c = undrained shear strength
q = surcharge loading
B = width
γ = soil unit weight

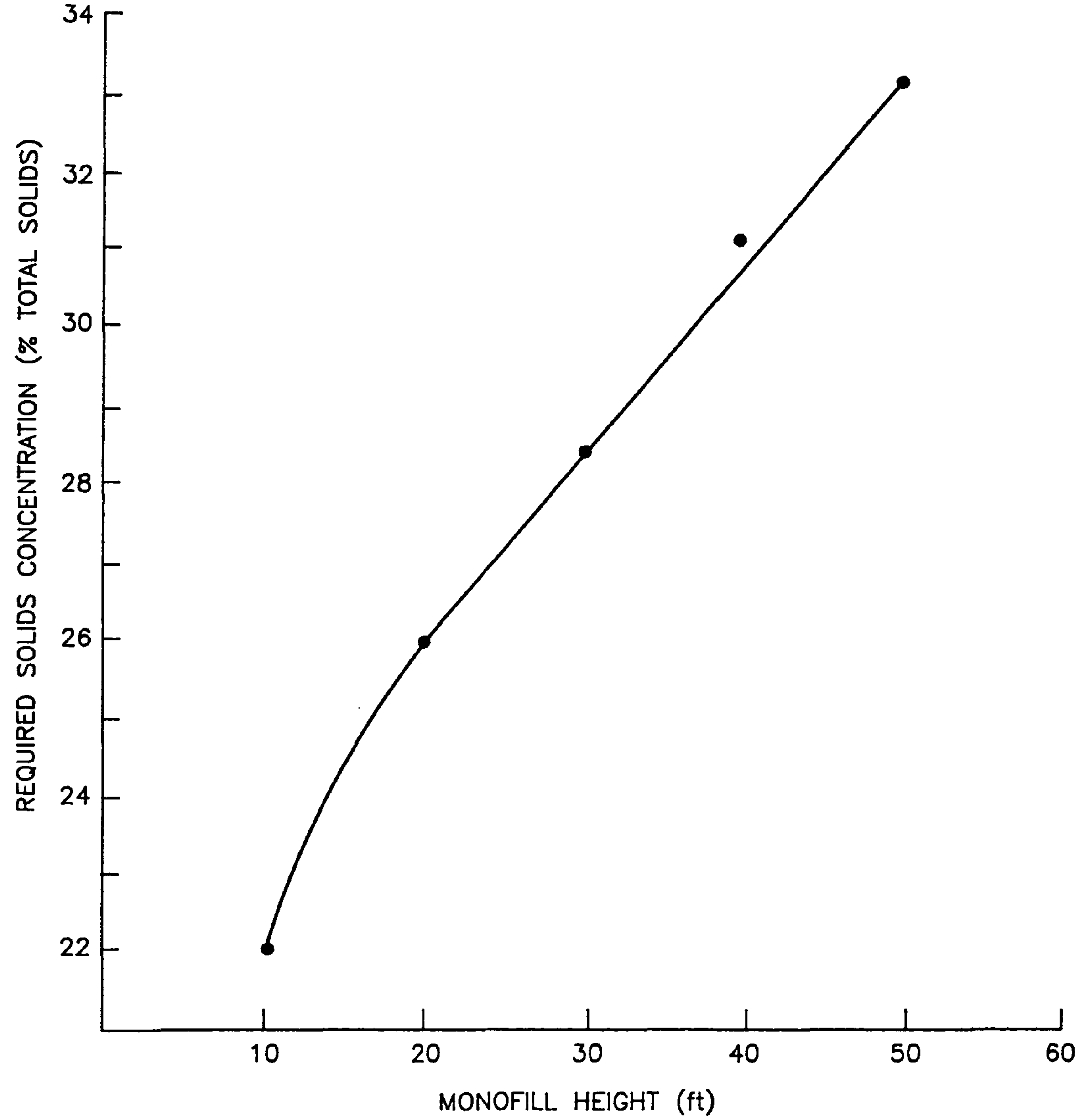


Figure 6.2 Solids concentration required for slope stability (slope = 33%)

The three N bearing capacity factors are functions of the internal friction angle ϕ and the assumed shape of the failure zone. For a failure analysis of clay in an undrained shear condition, $\phi = 0$. This yields values of $N_c = 6.16$, $N_q = 1.0$, and $N_\gamma = 0$, based on Terzaghi and Meyerhof standardized tables. Also, $q = 0$ assuming no surcharge pressure exists around the equipment wheel. Thus, by substituting these values, the bearing capacity equation yields

$$q_\mu = 6.16\ c$$

Factors of safety are commonly applied in this type of analysis, and by incorporating a safety factor of 3.0, the allowable bearing pressure is

$$q_a = \frac{q_\mu}{F} = \frac{6.16\ c}{3.0} = 2.05\ c$$

where q_a = allowable bearing pressure
F = safety factor

The pressure (q) exerted by the equipment on the sludge therefore cannot exceed the allowable bearing pressure. Calculating the induced pressure and solving for the undrained shear strength as shown below yields the shear strength required for the sludge to support the equipment with a factor of safety of 3.0.

$$c = \frac{q_a}{2.05}$$

Various types of equipment applicable to monofill operation were considered. Typically, crawler dozers would be utilized for spreading and stacking sludge in an area mound operation. The crawler dozers can be equipped with extra wide and long tracks to minimize the ground pressure exerted by the equipment's static weight. Hydraulic excavators would also be applicable to sludge monofilling in either an area mound technique or a trench disposal method. Empty and fully loaded tandem dump trucks were included in the analysis to compare their shear strength requirements with those of the tracked equipment. Table 6.3 summarizes the equipment specifications considered in the bearing capacity analysis and the related ground pressure for the individual types of equipment.

As shown in Table 6.3, the crawler dozers exert relatively low ground pressure in comparison to the dump trucks. Crawler dozers with extended tracks for low ground pressure would be quite suitable for monofilling operations. Proceeding with dump trucks onto a sludge monofill would require careful consideration and possibly special unloading areas.

The required sludge solids concentrations for the three test sludges can be determined for the individual types of heavy equipment simply by substituting the calculated ground pressure in the equation $c = q_a/2.05$. The resultant c equates to the minimum sludge shear strength required to support the equipment. Based on the triaxial compression or cone penetration data, the corresponding sludge solids concentration can be determined. Table 6.4 summarizes these results for the three test sludges. As shown in the table, the tracks on the crawler dozers and hydraulic excavator provide low minimum shear strength requirements, and consequently the

Table 6.3 Equipment specifications and ground pressure

		Track width		Track length		Static weight		Ground pressure	
Type	**Horsepower**	**(in.)**	**(cm)**	**(ft, in.)**	**(m)**	**(lb)**	**(kg)**	**(psi)**	**(kN/m²)**
Crawler dozer	67	25	63.5	6 ft, 9 in.	2.1	17,170	7,788	4.25	29.07
Crawler dozer	90	30	76.2	8 ft, 7 in.	2.6	25,822	11,713	4.20	28.73
Crawler dozer	120	34	86.4	10 ft, 3 in.	3.1	34,782	15,777	4.20	28.73
Crawler dozer	165	36	91.4	10 ft, 8.3 in.	3.3	43,355	19,666	4.70	32.14
Dump truck (empty)	250	—	—	—	—	20,000	9,072	25	170.98
Dump truck (full)	250	—	—	—	—	38,900	17,645	50	341.96
Excavator	10	18	45.7	11 ft, 0 in.	3.4	28,000	12,701	5.89	40.28

Table 6.4 Required shear strength and solids concentration for various types of heavy equipment

Type	Ground pressure (psi)	Ground pressure (kN/m²)	Minimum shear strength (psi)	Minimum shear strength (kN/m²)	Approximate sludge concentration (percent) 1	2	3
Crawler dozer	4.2	28.7	2.0	13.7	29	22	52
Crawler dozer	6.7	45.8	3.3	22.6	33	25	54
Excavator	5.9	40.4	2.9	19.8	32	23	53
Dump truck (empty)	25	171.0	12.2	83.5	37	28	58
Dump truck (full)	50	342.0	24.4	166.9	41	33	62

laboratory data yield manageable sludge solids concentrations for these types of equipment. For alum sludges 1 and 2, the sludge solids concentration should be at least around 30 and 25 percent, respectively, to support the tracked equipment. Empty and fully loaded tandem dump trucks typically required at least 7 percent higher solids concentrations compared with the tracked equipment even though the minimum required shear strength was significantly higher. The shear strength data, however, exhibit a nonlinear relationship with respect to the solids concentration, and hence a significant increase in required shear strength does not necessitate a similar increase in solids concentration.

Once the required minimum sludge solids concentration is determined a decision can be made as to how the solids concentration can be achieved. Options to be considered include the level of sludge dewatering, subsequent air drying requirements, and use of bulking agents. As the data in Table 6.4 indicate, the solids requirements are site specific. This fact coupled with site-specific evaporation rates for natural drying and additive levels for bulking agents precludes generalized methods of predicting the minimum solids concentration for a particular utility. Rather, a certain degree of preliminary laboratory work would be required in the feasibility phase of a disposal plan.

Field Investigations

The minimum sludge solids concentration necessary to support earth-moving equipment was investigated in the field for alum sludge 2. Alum sludge 2 is generated by the City of Chesapeake, Va., and dewatered with centrifuges to around 15 percent solids. Although the centrifuges are capable of achieving higher solids concentrations, the city prefers to maintain a 15 percent concentration to facilitate its disposal method. Currently, the city disposes of the dewatered sludge in a trench-type monofill. Normal operations consist of unloading the sludge from trucks directly into the trench. A hydraulic excavator is occasionally brought out to the site to stack the sludge inside the trench and separate naturally dried sludge from wetter material.

Normally, the hydraulic excavator remains outside the trench. For the purpose of this study, 18 sludge samples were collected along a 40-ft-wide (12.2 m) cross-sectional area of the disposal trench to develop a solids concentration profile through the trench. Samples were collected from various depths and analyzed as composite samples. The solids concentrations of recently deposited sludge (approximately 0 to 3 months old) ranged from 11 percent to 23 percent, with an average of 16 percent. The older sludge solids concentrations ranged from 25 percent to 36 percent, with an average of 29 percent. The city uses a hydraulic excavator that proceeds on top of the sludge to spread the sludge out. The excavator has a static weight of 28,000 lb (12,197 kg) and a 4,752-in.^{2} (3.07-m^2) track-bearing area.

During the field testing, it was observed that the excavator could operate with relative stability on top of the older sludge with an average solids concentration of 29 percent. It was not possible to support the equipment on the newer sludge at the 16 percent average solids concentration. At the interface between stable and unstable operating conditions, the sludge solids concentration reduced from 29 to 20 percent over a 4-ft (1.22-m) distance. The limiting solids concentrations for the field conditions were thus in this 20 to 29 percent range.

Based on the excavator's physical operating characteristics, the calculated exerted ground pressure was 5.9 psi, which correlates with a minimum allowable shear strength of 2.9 psi (19.8 kN/m^2) according to the empirical equation previously developed. Figure 4.15 indicates that for alum sludge 2, the corresponding solids concentration at 2.9 psi (19.8 kN/m^2) shear strength is approximately 24 percent. The 24 percent solids concentration appears to correlate reasonably well with the field conditions, which were in the 20 to 29 percent solids range around the excavator. Two factors influence a true correlation between laboratory and field data: sludge age and sludge disturbance. As previously discussed, sludge age increases the sludge shear strength for similar sludge solids concentrations. On the other hand, the movement of the excavator disturbs the shear strength gained by age. The Chesapeake crews experience this latter phenomenon as they work the sludge inside the trench. Sludge that was initially stable to operate on becomes weak and unstable over time. The 24 percent solids concentration developed on the basis of the laboratory data represents a disturbed sample but in comparison to the field data appears to be a reasonable solids concentration for planning purposes. Further research in this area is certainly warranted.

Environmental Considerations

Contamination of underlying groundwater is in many ways the most prominent concern in the siting, construction, and operation of a sludge monofill. In addition to constituting the most costly environmental safeguard required at many sludge monofills, groundwater protection measures are an integral part of the recently finalized federal regulations that govern the disposal of solid waste in municipal solid waste landfills. The need for liners under sludge monofills is handled on a state-by-state basis and within individual states typically on a case-by-case basis. Design controls can prevent or minimize the adverse environmental impacts that can result from leachate and methane gas. Additional concerns regarding odor and dust generation and disease vector control can best be addressed through operational, rather than design, strategies.

Minimization of leachate generation can be achieved through adequate drainage design. Monofill slopes should be substantial enough to effect natural drainage of storm water, and upland drainage should be collected and diverted around the monofill through drainage pipes or earthen ditches. The permeability of loose and compacted coagulant sludges will also greatly influence the volume of leachate generated. As was shown in Chapter 4, the three test sludges contained significant amounts of clay, which caused a fairly low permeability coefficient. The sludge permeability was not actually determined, but based on the Unified Soil Classification System, the sludges exhibited the characteristics of a CH soil group, which typically has a permeability of less than 2×10^{-8} in./s (5×10^{-8} cm/s). Typically, clay liners under sanitary landfills are required to have a permeability coefficient of at least 4×10^{-8} in./s (10^{-7} cm/s). Soils with permeabilities less than 4×10^{-7} in./s (10^{-6} cm/s) are essentially impervious, and a soil is considered pervious when the coefficient is greater than 4×10^{-5} in./s (10^{-4} cm/s).

Groundwater and surface water contamination by leachate can be controlled through implementation of the following design strategies:

- Assessment of natural hydrogeologic and topographic conditions and analysis of contaminant attenuation probabilities
- Use of imported soils
- Use of membrane liners
- Utilization of leachate collection and treatment systems

Depth to the groundwater table and hydraulic conductivity of underlying soil strata are the most influential hydrogeological characteristics of a site with regard to leachate containment. Leaching of contaminants from WTP coagulant sludges was the focus of Chapter 3 of this report. Attenuation of leachate contaminants through soils can be achieved through any of the following mechanisms:

- Filtration
- Ion exchange
- Adsorption
- Chemical precipitation
- Biodegradation
- Complexation

Among other factors, soil pH, cation exchange capacity, and organic content influence operation of these mechanisms. In general, a high clay content, high cation exchange capacity, low permeability, and relatively high pH are favorable soil characteristics.

If soils having substantial clay content are available on site, they can be used to line the sludge monofill if lining is required by the permit. Otherwise, imported clays can be utilized if necessary to effect enhanced attenuation of pollutants and containment of leachate. The use of membrane liners is another available option (a requirement in some states) in situations where soil depths or permeabilities are not adequate to protect groundwater. The most common types of synthetic liners used in monofill applications are those made from polymeric membranes. In addition to cost and effectiveness, durability and installation time should be considered when selecting a liner. Upon installation, the liner should be covered with a porous soil blanket at least 1 ft (0.30 m) thick.

Once the decision to install a liner has been made, a leachate collection system above the liner is recommended. Leachate collection systems vary in operation and design. In one type, leachate collects in a sump, from which it is pumped to a holding pond or tank. Perforated drain pipes or tiles can be utilized to channel leachate to the surface or to a sump. Leachate disposal options must be evaluated on a case-by-case basis in view of anticipated leachate quality. Leachate quality is influenced by a variety of factors including sludge chemical characteristics, sludge volume and density, rainfall amounts and chemical composition, and sludge permeability. Based on the sludge leachability characteristics developed in Chapter 3, reasonable estimates of the leachate characteristics can be developed in order to properly plan for leachate handling.

The following assumptions were made in order to illustrate the quantification of potential leachable constituents from a typical alum sludge:

Monofill size: 10 acres (40,470 m^2), 20 ft (6.1 m) deep
Alum sludge: in-place dry density of 60 lb/ft^3 (1,020 kg/m^3)
solids content of 80 percent
fully permeable
Leachate volume: 46.2 million L (12.2 mil/gal), based on annual rainfall in Virginia amounting to approximately 450 in. (1,143 cm)

To fill the monofill to capacity, sludge having the characteristics described above would have a total dry weight of approximately 262 tons (237,686 kg). In a worst-case scenario, the sludge would be fully permeable, thereby allowing all rainfall to contribute directly to leachate generation.

Estimation of the concentration of specific leachate constituents is outlined in the following series of calculations and is based on the cumulative percentage of contaminants leached from the sludge as developed in Chapter 3.

$$\left(\begin{array}{c}\text{cumulative amount}\\ \text{leached, percentage}\end{array}\right)\left(\begin{array}{c}\text{background}\\ \text{concentration, mg/kg}\end{array}\right)=\begin{array}{c}\text{cumulative amount leached,}\\ \text{mg/kg}\end{array}$$

$$\left(\begin{array}{c}\text{cumulative amount}\\ \text{leached, mg/kg}\end{array}\right)\left(\begin{array}{c}\text{total sludge dry}\\ \text{weight, kg}\end{array}\right)=\begin{array}{c}\text{cumulative amount leached,}\\ \text{mg}\end{array}$$

$$\left(\begin{array}{c}\text{cumulative amount}\\ \text{leached, mg}\end{array}\right)\left(\begin{array}{c}\text{cumulative rainfall,}\\ \text{L}\end{array}\right)=\begin{array}{c}\text{concentration in}\\ \text{leachate, mg/L}\end{array}$$

Expected leachate constituents are quantified in Table 6.5 and are based on the above assumptions regarding monofill size and sludge volumes and density along with actual background concentrations and experimentally determined leaching percentages. Drinking water regulatory limits and fresh water in-stream guidelines are shown for comparison. Although the pH of the rainwater used in the monofill leaching research was only 4.5, pH fluctuations over the course of the study were minor, and pH values remained in the 6 to 7 range. The apparent buffering capacity of the sludge dampened the potential effects of low pH on metals release, which are well documented in the literature.

As shown in Table 6.5, the secondary maximum contaminant level (SMCL) for drinking water was exceeded only for manganese. The predicted concentrations of constituents can be used as a rough gauge of potential leachate quality; however, they should not be used as the sole basis for determining whether a liner and leachate collection system is warranted. Because regulations specifically governing WTP sludge disposal are currently nonexistent at the federal level, state standards regarding groundwater monitoring, groundwater quality goals, and liner and leachate collection systems should be followed. In addition, site-specific pilot testing of sludge leachability should always be considered to ensure accurate results.

Table 6.5 Estimated leachate characteristics for alum sludge monofills

				Regulatory limits	
Constituent	Percentage leached (%)	Background concentration (mg/kg)	Estimated concentration in leachate (mg/L)	Drinking water MCLs (mg/L)	Fresh water in-stream guidelines (mg/L)
Durham, N.C., sludge					
Arsenic	0.05	25.0	6.42×10^{-6}	0.05	0.072
Copper	0.12	168	0.0001	1*	0.002
Iron	0.03	48,500	0.0075	0.3*	1
Manganese	12.48	1,180	0.0757	0.05*	—
Zinc	0.13	91.7	0.0001	5*	0.047
Chesapeake, Va., sludge					
Arsenic	0.05	32.0	8.22×10^{-6}	0.05	0.072
Copper	0.42	16	3.45×10^{-5}	1*	0.002
Iron	0.05	15,200	0.0039	0.3*	1
Manganese	3.38	233	0.004	0.05*	—
Zinc	0.05	393	0.0003	5*	0.047

* These values are secondary maximum contaminant levels (SMCLs).

Permitting Process

Design requirements for sludge monofills vary from state to state; however, in the majority of instances the general design criteria for sludge monofills mirror those that are imposed on municipal solid waste landfill design. It is likely that strong similarities would also be found in the permitting processes, particularly with regard to the required components of an application package. Two examples revealed this to be the case, to a certain extent.

In addition to site acceptability and detailed design, permit application approval for most landfills involves submittal to reviewing authorities of the following standard information:

- Soils and hydrogeological analyses
- Operational plan
- Erosion and sedimentation control plan
- Groundwater monitoring plan

Because most of the concern regarding land disposal of WTP sludge stems from fear of groundwater contamination, more detailed information regarding the characteristics of the waste to be landfilled, such as background metals concentrations (determined by a total metals analysis) and results of leaching tests, may be required as part of the permit application.

The permitting process for two dedicated sludge monofills, one in Connecticut and one in Pennsylvania, was reviewed and is summarized in the following paragraphs. Both are American Water Company facilities. As evidenced in the following commentary, approval can be a lengthy process.

For one WTP sludge disposal site in Pennsylvania, a phased approach to approval was followed. Phase I of the required application process was initiated in October 1987 with submittal of the information detailed below in addition to general information such as site location on a USGS topographic map. Final phase I approval was not granted until February of 1989 and was contingent upon review of the following information:

- Assessment of soils and geology
- Conceptual design—cover material availability, site access, site life, and capacity volumes
- Groundwater—direction of movement, proposed monitoring points

Phase II of the permitting process required submittal to the Pennsylvania Department of Environmental Resources of the following information:

- Waste quantities and characteristics—chemical and leaching analysis results
- Detailed design plans regarding required grades and final cover elevations, liners and leachate collection
- Operational plan indicating proposed landfill method, schedule of filling, surface water management, final slopes, and closure procedures
- Quality assurance and quality control plan
- Erosion and sedimentation control plan
- Revegetation plan
- Groundwater monitoring plan

The American Water Works Service Company designed and constructed a landfill to be used for disposal of water treatment residuals by Connecticut–American Water Company. Pertinent stages in the process along with the dates on which they occurred are listed below.

- Application for construction and operation of a solid waste facility—June 1985
- Application for state discharge permit—July 1985
- Information supplemental to application for special waste disposal facility—July 1986
- Connecticut Department of Environmental Protection construction permit—April 1987

Permission to construct a solid waste disposal area was granted based on submittal and approval of a completed solid waste application form, site map, application package received by the solid waste management unit, and revisions thereto. The application package contained, among other things, an operation and management plan, discharge permit, and sludge analysis. Issuance of the permit was subject to a number of conditions, some of which are listed below:

- Disposal shall occur only in delineated areas and in strict accordance with the facility operation and management plan.
- Prior to commencement of disposal operations, an inspection shall be conducted.
- Only drinking water plant sludge from the Dean's Mill facility is acceptable for disposal.
- In the event that erosion, dust, or odor problems develop, a daily cover requirement may be instituted.

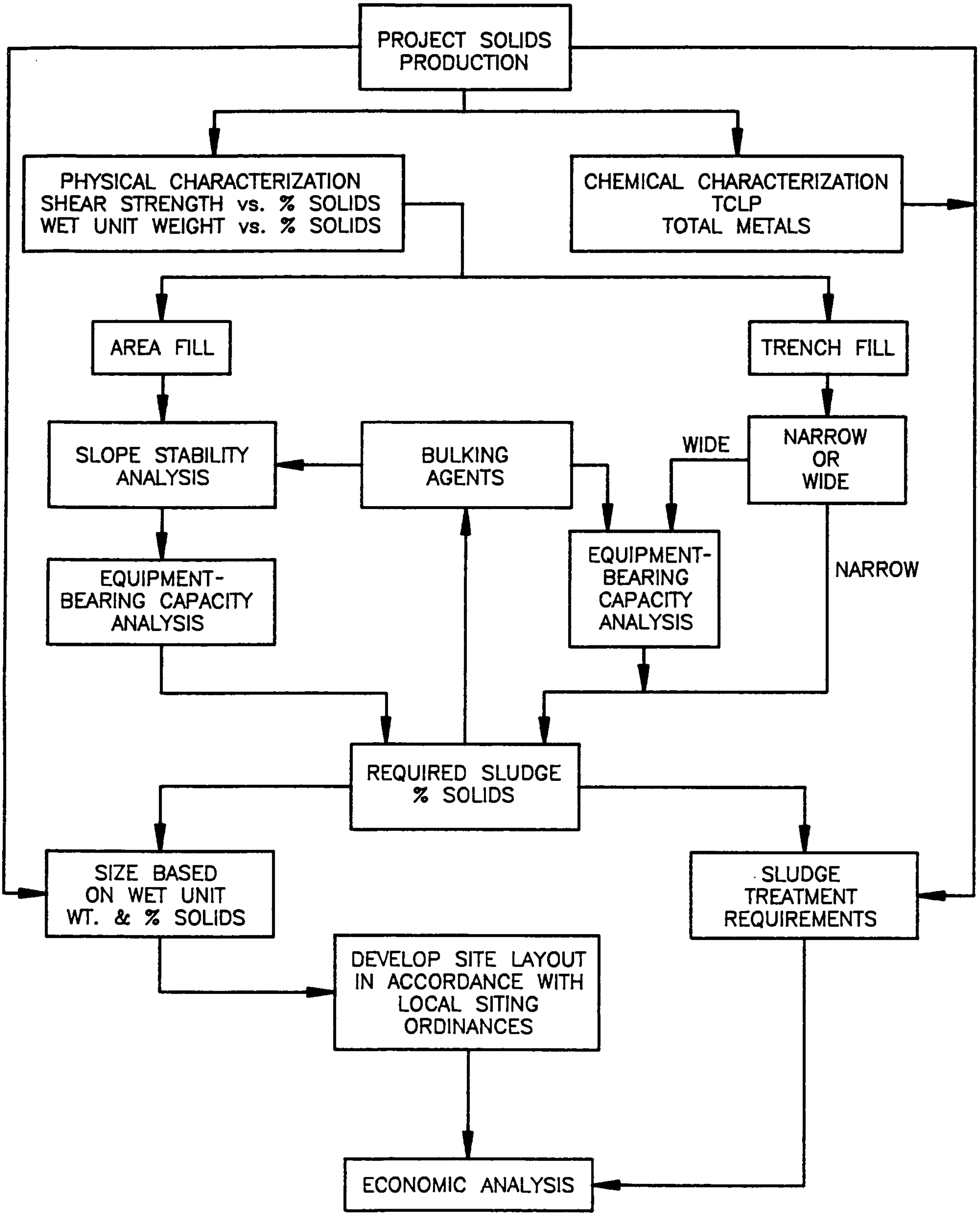


Figure 6.3 Considerations for sludge monofill design

- Surface and groundwater shall be monitored for a number of leachate indicator parameters at specified locations and in accordance with acceptable procedures.

Summary of Planning Process

Figure 6.3 presents a schematic diagram that highlights the essential planning considerations for disposal of WTP sludge in dedicated monofills. The diagram depicts the determining factors and the effects of each decision and stage in the planning process. For example, an integral parameter dictated largely by slope stability and equipment-bearing capacity analyses, required sludge solids content impacts both monofill size and sludge treatment, which in turn influence economics. As indicated on the figure, sludge treatment requirements and project economics are affected not only by the quantity of sludge produced but also by the sludge's physical and chemical characteristics. Physical and chemical characterization techniques utilized in defining monofill design details are explored in earlier chapters of this report. In summary, Figure 6.3 presents a logical path to be followed in planning a sludge monofill and defines the interrelationships of the principal design considerations.

Appendix

State Survey and Leaching Data

Figure A.1

Sludge disposal in landfills questionnaire

Person Contacted______________________________

Position/Title______________________________

Office______________________________

I. Landfilling of sludge from water treatment plants

1. How is sludge classified in your state? ____________________

2. Is landfilling of WTP sludge allowed in your state?

   Yes______ No______

3. Who has regulatory jurisdiction for landfilling sludge? ____________________

4. Do your regulations include these sludges?

alum sludges	Yes______	No______
ferric sludges	Yes______	No______
lime sludges	Yes______	No______

5. Are there different requirements for the various types of sludges?

   Yes______ No______

   Explain______________________________

Figure A.1 (continued)

II. Landfilling WTP sludge with municipal solid waste

1. Is landfilling WTP sludges in a municipal solid waste landfill permissible?

   Yes______ No______

2. Who has regulatory jurisdiction for landfilling sludges with MSW?________

3. What are the requirements for landfilling sludge with MSW?____________

   a. Percentage solids?________________________________

   b. Free water test?________________________________

   c. Ratio of sludge/MSW mixture?________________________

   d. Can sludge be used as a cover material?

      Yes______ No______

   e. Requirements for use as a cover material?______________________

Figure A.1 (continued)

III. Sludge monofills

1. Are sludge monofills allowed?

   Yes______ No______

2. Who has regulatory jurisdiction?________________________________

3. What requirements need to be met?________________________________

   a. Percentage solids?________________________________

   b. Monitoring requirements?________________________________

   c. Leachate collection?________________________________

   d. Other requirements?________________________________

Figure A.1 (continued)

IV. Lagoons and landfills

1. How are lagoons and landfills differentiated?____________________

2. Are lagoons allowed to be used for sludge disposal?

   Yes______ No______

3. Who has regulatory jurisdiction for lagoons?____________________

4. What are the requirements for lagoons?____________________

   a. Liners____________________

   b. Monitoring____________________

   c. Other____________________

Figure A.1 (continued)

V. In-stream aluminum standards

1. Does your state have an in-stream aluminum standard?

   Yes______ No______

2. What impact is the standard having on discharges to streams?___________

3. Is the standard leading to zero discharges for WTPs?

   Yes______ No______

   a. What are the requirements for recycling backwash and settling basin waters?___________

   b. Can WTP waste waters be sent to lagoons (as a disposal method)?

      Yes______ No______

Table A.1

State regulatory requirements for landfilling and direct discharge

State and regulatory authority	Co-disposal at MSWLF	Monofill	Direct discharge requirements
Alabama Department of Environmental Management Municipal Waste Division 1751 Dickinson Drive Montgomery, AL 36130	No free liquids.	Similar to MSWLF requirements, case-by-case basis.	Permit required for discharge of liquid wastes.
Alaska Department of Environmental Conservation Treatment Section P.O. Box O Juneau, AK 99811-1800	Permit required by state statute for discharge of waste to state lands.	Permit required by state statute for discharge of waste to state lands.	Permit required by state statute for discharge of waste to state waters.
Arizona Department of Environmental Quality P.O. Box 600 Phoenix, AZ 85001-0600	Paint filter test required. Sludge must be non-hazardous and dewatered prior to disposal. No permit required for disposal of non-hazardous WTP sludge.	Similar to MSWLF.	In-stream aluminum standard (currently implementing NPDES program and obtaining primacy from EPA).
Arkansas Department of Pollution Control and Ecology P.O. Box 8913 Little Rock, AR 72219-8913	>30% solids commonly practiced.	General permitting waste characterization. Similar to MSWLF.	General NPDES permit required-aluminum, iron, pH, and TSS are regulated in the permit.
California Regional Water Quality Control Board Los Angeles Region 101 Centre Plaza Drive Monterey Park, CA 91754	50% solids.	Similar to MSWLF.	Regulated by Regional Board.
Colorado Department of Health Water Quality Control Division 4210 E. 11th Avenue Denver, CO 80220	Paint filter test.	Site specific - similar to MSWLF.	In-stream aluminum standard.
Connecticut Solid Waste Unit	>25-30% solids suggested, no free-draining liquid.	Case-by-case, demonstrate operating without polluting.	
Delaware Delaware Pollution Control Branch P.O. Box 1401 Dover, DE 19903	>20% solids, no free liquids.	No provision.	Permitted according to NPDES guidelines.

(continued)

Table A.1 (continued)

State and regulatory authority	Co-disposal at MSWLF	Monofill	Direct discharge requirements
Florida Department of Environmental Regulation Drinking Water Section 2600 Blair Stone Road Tallahassee, FL 32399-2400		Same as MSWLF - depends on solids content.	In-stream aluminum standard in shellfish waters.
Georgia Drinking Water Program 205 Butler Street, S.E. Floyd Tower East Suite 1066 Atlanta, GA 30334	Varies from landfill to landfill.		
Hawaii Department of Health Safe Drinking Water Branch 5 Waterfront Plaza Suite 250-C 500 Ala Moana Boulevard Honolulu, HI 96813	At the time of the survey there were only a few water treatment plants in the state producing sludge. No formal regulatory structure was in place.		
Idaho Division of Environmental Quality Water Quality Bureau 1410 North Hilton Boise, ID 83706		Conditional use permit, case-by-case.	
Illinois Environmental Protection Agency 2200 Churchill Road Springfield, IL 62794-9276	>20% solids suggested, paint filter test, 1:4 (sludge: MSW) or suggested ratio.	Same as MSWLF.	Treatment plant wastes regulated by Illinois EPA. NPDES permits required for discharge to streams.
Indiana Department of Environmental Management 105 S. Meridian Street P.O. Box 6015 Indianapolis, IN 46206	Paint filter test.	Similar to MSWLF extensive requirements.	NPDES program administered by the State.
Iowa Department of Natural Resources Environmental Protection Division Wastewater Permit Section 900 East Grand Des Moines, IA 50319	Paint filter test.	Same as MSWLF - monitoring, liners, leachate collection required.	NPDES permit required for discharges to surface waters.
Kansas Department of Health and Environment Bureau of Water Forbes Field Topeka, KS 66620		Case-by-case, monitoring wells required.	In-stream aluminum standard, NPDES program for discharges administered by the State.

(continued)

Table A.1 (continued)

State and regulatory authority	Co-disposal at MSWLF	Monofill	Direct discharge requirements
Kentucky Division of Waste Management Solid Waste Branch 18 Reilly Road Frankfort, KY 40601	Paint filter test, 1:4 (workable mixture).	Type I residual landfill-cannot pollute. Much liability on designer. Insert landfill-minimal requirements. Much done case-by-case.	
Louisiana Department of Environmental Quality Water Pollution Control Division P.O. Box 82215 Baton Rouge, LA 70884-2215	>15-18% solids, paint filter test.	Similar to MSWLF.	NPDES permit administered jointly by State and EPA required for surface water discharges.
Maine Solid Waste Bureau	Minimum 20% solids, leachate collection system.	Landfill requirements for special waste-liners, leachate collection, monitoring.	
Maryland Department of the Environment Drinking Water Supply	No free liquid.	Same as MSWLF.	
Massachusetts Division of Solid Waste Management	>20% solids, 1:3 ratio of sludge/MSW (workable mixture).	Same as MSWLF.	
Michigan Department of Public Health 3423 N. Logan Lansing, MI 48909	Paint filter test.	Same as MSWLF.	NPDES permit required for discharge to a surface water. In-stream aluminum standard.
Minnesota Pollution Control Agency Groundwater & Solid Waste Division	No free liquids.	Case-by-case. Similar to MSWLF.	
Mississippi Office of Pollution Control P.O. Box 10385 Jackson, MS 39289-0385	Dewatered.	Case-by-case. No existing monofills.	Federal effluent guidelines.
Missouri Department of Natural Resources P.O. Box 176 Jefferson City, MO 65102	No free water, solids requirement varies from landfill to landfill.	Similar to MSWLF.	NPDES permits required. Solids may be discharged only to large rivers. Treated filter backwash may be discharged to small rivers.
Montana Department of Health and Environmental Services Water Quality Bureau Cogswell Building Helena, MT 59620	Paint filter test.	Similar to MSWLF.	NPDES permits required - limits on pH, TSS, and aluminum.

(continued)

Table A.1 (continued)

State and regulatory authority	Co-disposal at MSWLF	Monofill	Direct discharge requirements
Nebraska Department of Environmental Control P.O. Box 98922 Lincoln, NE 68509-8922	70% solids required.	Light hydrogeological investigation, light planning, some monitoring.	NPDES permits required.
Nevada Division of Environmental Protection 123 W. Nye Lane Carson City, NV 89710	Free water test. Low ratio of sludge to MSW (not specific).	Case-by-case, demonstrate compliance.	Permits required for discharge of treated wash water to rivers.
New Hampshire Waste Management Division	>2% solids, 1:3 ratio (sludge/MSW).	Same as MSWLF.	In-stream aluminum standard.
New Jersey Division of Solid Waste Management	Dewatered, no free water.	Same as for non-hazardous inert waste landfill.	NPDES permits required.
New Mexico Environmental Department P.O. Box 26110 Santa Fe, NM 87502		Groundwater discharge plan, geohydrologic investigation, must demonstrate 10-5 risk. Site specific, similar to MSWLF, case-by-case.	In-stream aluminum standard NPDES permit required (EPA has primacy).
New York Department of Environmental Control	>20% solids, no free water.	Case-by-case, similar to MSWLF.	In-stream aluminum standard.
North Carolina Division of Environmental Management P.O. Box 29535 Raleigh, NC 27626	Paint filter test. Individual landfill determines sludge/MSW ratio.	Solids >30%, monitor for NO_5, TOC, NH_4^+, TOX, Cl^-, heavy metals, pH.	
North Dakota Department of Health Solid Waste Division P.O. Box 5520 Bismarck, ND 58502-5520	Paint filter test (used sometimes).	Special use permit, no liners or monitoring required at this time.	
Ohio Environmental Protection Agency Division of Public Drinking Water 18 W. Water Mark Drive Columbus, OH 43266	30% solids required, no free liquids - paint filter test, ratio of sludge to MSW controlled by workability.		NPDES permitting program administered by the State.
Oklahoma State Department of Health 1000 Northeast 10th Street Oklahoma City, OK 73152	>18% solids required, paint filter test, 10% of daily volume by weight (sludge).	Site specific, case-by-case.	NPDES permit required for surface water discharge, analysis for pollutants listed in 40 CFR 122, Appendix D. Tables II & III.

(continued)

Table A.1 (continued)

State and regulatory authority	Co-disposal at MSWLF	Monofill	Direct discharge requirements
Oregon Department of Environmental Quality 811 S.W. Sixth Avenue Portland, OR 97204	Minimum solids at discretion of landfill.	Similar to MSWLF.	NPDES permit required for discharge to a surface water.
Pennsylvania Department of Environmental Resources Room 518, Executive House South 2nd Street Harrisburg, PA 17105	Paint filter test.	Same as MSWLF.	NPDES classification system used - organics, inorganics, TSS, and pH monitored. In-stream aluminum standard (toxicity standard <0.1 96 hr. LC50).
Rhode Island Division of Water Resources		Same as MSWLF.	
South Carolina Department of Health and Environmental Control 2600 Bull Street Columbia, SC 29201	>20% solids required, paint filter test, sludge spread over refuse.	Regulations in progress	
South Dakota Department of Environment and Natural Resources Office of Drinking Water Joe Foss Building, Room 412 Pierre, SD 57501		Similar to MSWLF.	
Tennessee Water Quality Control Department Industrial Facilities Section 150 Ninth Avenue, North 4th Floor Nashville, TN 37247-3001		Same as MSWLF.	In-stream aluminum standard.
Texas Department of Environmental Health 1100 W. 49th Street Austin, TX 78756	>10% solids required.	Case-by-case.	
Utah Bureau of Water Pollution Control P.O. Box 16690 Salt Lake City, UT 84116		Similar to MSWLF.	In-stream aluminum standard.
Vermont Solid Waste Division	>20-25% solids required, separate cells required for sludge.	Same as MSWLF.	
Virginia Department of Health State Water Control Board			Monitored by State. Constituents of concern include aluminum, TSS, pH, and chlorine residual.

(continued)

Table A.1 (continued)

State and regulatory authority	Co-disposal at MSWLF	Monofill	Direct discharge requirements
Washington Department of Ecology Mail Stop PV-11 Olympia, WA 98504-8711	Paint filter test.	Similar to MSWLF.	NPDES permit required. State statute allows plants on specific rivers to discharge directly.
West Virginia Department of Natural Resources Water Resources Division 1201 Greenbriar Street Charleston, WV	>25% solids required, 1:10 by weight (sludge/MSW) ratio.	Same as MSWLF.	NPDES permit required for discharge to rivers.
Wisconsin Department of Natural Resources Madison, WI	>40% solids suggested, free water test required, 1:10 ratio sludge: MSW suggested.	Similar to MSWLF.	In-stream aluminum standard, (acute toxicity standard), NPDES permit required for discharge to surface waters.
Wyoming Department of Environmental Quality Water Quality Division Herscher Building 4 West Cheyenne, WY 82002	Sludge must be non-flowable, paint filter test required.	Required to meet industrial landfill requirements, case-by-case basis.	

Table A.2

State survey responses

State	Classification of WTP sludge	Sludge lagoons allowed	Recycle of backwash and sludge supernatant allowed
Alabama	Solid waste	Yes	Yes, case-by-case basis
Alaska	Municipal waste	Yes	At discretion of regional engineer
Arizona	Solid waste	Yes	Yes, no restrictions
Arkansas	Special waste	No	Yes, no regulations
California	Sludge	Yes	Yes, some restrictions
Colorado	Special waste	Yes	Yes, frequently done - no restrictions
Connecticut	Special waste	Yes	Yes, case-by-case basis
Delaware	Sludge	Yes	No regulations - never requested
Florida	Not classified	Yes	Yes, case-by-case basis
Georgia	Not classified	Yes	Yes, case-by-case basis
Hawaii	Nonhazardous waste		
Idaho	Not classified	Yes	Yes, no restrictions
Illinois	Special waste	No (permissible on site)	No regulations
Indiana	Special waste	Yes	Yes, no regulations
Iowa	Solid waste	Yes (permitted landfill)	Yes, recycle at 10% of plant flow provided no domestic waste or wash down water (e.g. from floors) is mixed with plant waters
Kansas	Solid waste	Yes	Yes, no specific regulation

(continued)

Table A.2 (continued)

State	Classification of WTP sludge	Sludge lagoons allowed	Recycle of backwash and sludge supernatant allowed
Kentucky	Special waste	Yes	Yes, encouraged to recycle - no regulations
Louisiana	Commercial waste	Yes	Not practiced - no restrictions on discharges
Maine	Special waste	Yes	Yes, case-by-case basis
Maryland	Industrial waste	No	Yes, case-by-case basis
Massachusetts	Special waste	No	Yes, case-by-case basis
Michigan	Special waste	No	Yes, no regulations
Minnesota	Solid waste	No	No regulations - not practiced widely
Mississippi	Not classified	Yes	Yes, no regulations (not practiced in state)
Missouri	Special waste	No	Yes, not widely practiced - usually not cost effective
Montana	Nonhazardous waste	Yes	Yes, no restrictions
Nebraska	Special waste	Yes	Yes, case-by-case basis
Nevada	Nonhazardous waste	Yes	Yes, little incentive to recycle
New Hampshire	Special waste	No	Yes, case-by-case basis
New Jersey	Industrial solid waste	No	No regulations
New Mexico	Special waste (see note)	Yes	No regulations in place - only one WTP in state
New York	Solid waste	No	Yes, >10% of influent
North Carolina	Waste by-product of WTP	No	Yes, limit recycle to 5% of influent
North Dakota	Special waste	Yes (permitted landfill)	Yes, no regulations

(continued)

Table A.2 (continued)

State	Classification of WTP sludge	Sludge lagoons allowed	Recycle of backwash and sludge supernatant allowed
Ohio	Solid waste		
Oklahoma	Solid waste	No	Yes, minimum 2-cell lagoon and less than 10% of influent
Oregon	Special waste	Yes	Yes, no restrictions
Pennsylvania	Municipal waste	No	Yes, case-by-case basis
Rhode Island	Not classified	No	Yes, case-by-case basis
South Carolina	Special waste	No	Yes, case-by-case basis
South Dakota	Solid waste	No	Yes, no regulations
Tennessee	Special waste	Yes	Yes, must have appropriate facilities
Texas	Special waste	No	Yes, can not affect effluent quality
Utah	Not classified	Yes	Yes, no regulations - case-by-case basis
Vermont	Solid waste	No	Yes, <5% of influent (10 state standard guidelines)
Virginia	Industrial waste	Yes	No, some exceptions
Washington	Industrial waste	No	Yes, no restrictions
West Virginia	Special waste	Yes	No regulations - no WTP recycling
Wisconsin	Special waste	No	Yes, limited to 10% of influent
Wyoming	Industrial waste	Yes	Yes, required - use 2-cell lagoon, must recycle

Note: At the time of this survey, New Mexico did not allow the disposal of any sludge in MSWLFs

Table A.3

Arsenic leached from alum sludge 1, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached arsenic (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Arsenic leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original arsenic
1	44.10	18.68	44.10	18.68	0.0025	0.11	0.11	0.002	0.002	0.007
1	44.10	18.68	88.20	37.36	0.0010	0.04	0.15	0.001	0.003	0.010
1	44.10	18.68	132.30	56.04	0.0035	0.15	0.31	0.003	0.005	0.021
3	132.30	56.04	264.60	112.08	0.0027	0.36	0.67	0.006	0.011	0.045
4	176.40	74.72	441.00	186.80	<0.0005	0.00	0.67	0.000	0.011	0.045
4	176.40	74.72	617.40	261.52	<0.0005	0.00	0.67	0.000	0.011	0.045
4	176.40	74.72	793.80	336.24	<0.0005	0.00	0.67	0.000	0.011	0.045
6	264.60	112.08	1058.40	448.32	<0.0005	0.00	0.67	0.000	0.011	0.045

Note: Initial concentration 25.0 mg/kg

Table A.4

Copper leached from alum sludge 1, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached copper (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Copper leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original copper
1	44.10	18.68	56.70	24.03	0.10	4.41	4.41	0.074	0.074	0.044
1	44.10	18.68	100.80	42.71	0.12	5.29	9.70	0.089	0.163	0.097
1	44.10	18.68	144.90	61.39	0.06	2.65	12.35	0.044	0.207	0.123
3	132.30	56.04	277.20	117.43	<0.03	0.00	12.35	0.000	0.207	0.123
4	176.40	74.72	453.60	192.15	<0.03	0.00	12.35	0.000	0.207	0.123
4	176.40	74.72	630.00	266.87	<0.03	0.00	12.35	0.000	0.207	0.123
4	176.40	74.72	806.40	341.59	<0.03	0.00	12.35	0.000	0.207	0.123
6	264.60	112.08	1071.00	453.67	<0.03	0.00	12.35	0.000	0.207	0.123

Note: Initial concentration 168 mg/kg

Table A.5

Iron leached from alum sludge 1, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached iron (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Iron leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original iron
1	44.10	18.68	44.10	18.68	<0.01	0.0	0.0	0.00	0.00	0.000
1	44.10	18.68	88.20	37.36	<0.01	0.0	0.0	0.00	0.00	0.000
1	44.10	18.68	132.30	56.04	0.21	9.3	9.3	0.16	0.16	0.000
3	132.30	56.04	264.60	112.08	2.00	264.6	273.9	4.43	4.59	0.009
4	176.40	74.72	441.00	186.80	0.50	88.2	362.1	1.48	6.06	0.013
4	176.40	74.72	617.40	261.52	0.30	52.9	415.0	0.89	6.95	0.014
4	176.40	74.72	793.80	336.24	0.30	52.9	467.9	0.89	7.84	0.016
6	264.60	112.08	1058.40	448.32	1.42	375.7	843.6	6.29	14.13	0.029

Note: Initial concentration 48,500 mg/kg

Table A.6

Manganese leached from alum sludge 1, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached manganese (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Manganese leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original manganese
1	44.10	18.68	48.75	18.68	8.30	366	366	6.13	6.13	0.52
1	44.10	18.68	92.85	37.36	8.50	374	740	6.28	12.41	1.05
1	44.10	18.68	136.95	56.04	7.50	330	1071	5.54	17.95	1.52
3	132.30	56.04	269.25	112.08	8.70	1151	2222	19.28	37.23	3.16
4	176.40	74.72	445.65	186.80	6.70	1181	3404	19.80	57.03	4.83
4	176.40	74.72	622.05	261.52	7.60	1340	4745	22.46	79.48	6.74
4	176.40	74.72	798.45	336.24	8.70	1534	6279	25.71	105.19	8.91
6	264.60	112.08	1063.05	448.32	9.50	2513	8793	42.11	147.30	12.48

Note: Initial concentration 1,180 mg/kg

Table A.7

Zinc leached from alum sludge 1, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached zinc (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Zinc leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original zinc
1	44.10	18.68	44.10	18.68	0.036	1.59	1.59	0.027	0.027	0.029
1	44.10	18.68	88.20	37.36	<0.005	0.00	1.59	0.000	0.027	0.029
1	44.10	18.68	132.30	56.04	0.016	0.71	2.30	0.012	0.038	0.042
3	132.30	56.04	264.60	112.08	0.010	1.32	3.62	0.022	0.061	0.066
4	176.40	74.72	441.00	186.80	0.011	1.94	5.56	0.033	0.093	0.101
4	176.40	74.72	617.40	261.52	0.008	1.41	6.97	0.024	0.117	0.127
4	176.40	74.72	793.80	336.24	<0.005	0.00	6.97	0.000	0.117	0.127
6	264.60	112.08	1058.40	448.32	<0.005	0.00	6.97	0.000	0.117	0.127

Note: Initial concentration 91.7 mg/kg

Table A.8

Arsenic leached from alum sludge 2, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached arsenic (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Arsenic leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original arsenic
1	44.10	18.68	44.10	18.68	<0.0005	0.000	0.000	0.000	0.000	0.000
1	44.10	18.68	88.20	37.36	<0.0005	0.000	0.000	0.000	0.000	0.000
1	44.10	18.68	132.30	56.04	0.0019	0.084	0.084	0.004	0.004	0.013
3	132.30	56.04	264.60	112.08	0.0005	0.066	0.150	0.003	0.008	0.024
4	176.40	74.72	441.00	186.80	0.0010	0.176	0.326	0.009	0.017	0.052
4	176.40	74.72	617.40	261.52	<0.0005	0.000	0.326	0.000	0.017	0.052
4	176.40	74.72	793.80	336.24	<0.0005	0.000	0.326	0.000	0.017	0.052
6	264.60	112.08	1058.40	448.32	<0.0005	0.000	0.326	0.000	0.017	0.052

Note: Initial concentration 32 mg/kg

Table A.9

Copper leached from alum sludge 2, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumula-tive rain (L)	Cumula-tive rain (in.)	Leached copper (mg/L)	Total leached (mg)	Cumula-tive leached (mg)	mg Copper leached per kg of solids	Cumula-tive leached (mg/kg)	% Leached of original copper
1	44.10	18.68	44.10	18.68	<0.03	0.00	0.00	0.00	0.00	0.00
1	44.10	18.68	88.20	37.36	0.03	1.32	1.32	0.07	0.07	0.42
1	44.10	18.68	132.30	56.04	<0.03	0.00	1.32	0.00	0.07	0.42
3	132.30	56.04	264.60	112.08	<0.03	0.00	1.32	0.00	0.07	0.42
4	176.40	74.72	441.00	186.80	<0.03	0.00	1.32	0.00	0.07	0.42
4	176.40	74.72	617.40	261.52	<0.03	0.00	1.32	0.00	0.07	0.42
4	176.40	74.72	793.80	336.24	<0.03	0.00	1.32	0.00	0.07	0.42
6	264.60	112.08	1058.40	448.32	<0.03	0.00	1.32	0.00	0.07	0.42

<u>Note</u>: Initial concentration 16 mg/kg

Table A.10

Iron leached from alum sludge 2, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumula-tive rain (L)	Cumula-tive rain (in.)	Leached iron (mg/L)	Total leached (mg)	Cumula-tive leached (mg)	mg Iron leached per kg of solids	Cumula-tive leached (mg/kg)	% Leached of original iron
1	44.10	18.68	44.10	18.68	<0.01	0.0	0.0	0.00	0.00	0.00
1	44.10	18.68	88.20	37.36	<0.01	0.0	0.0	0.00	0.00	0.00
1	44.10	18.68	132.30	56.04	0.03	1.3	1.3	0.07	0.07	0.00
3	132.30	56.04	264.60	112.08	<0.01	0.0	1.3	0.00	0.07	0.00
4	176.40	74.72	441.00	186.80	0.20	35.3	36.6	1.80	1.87	0.01
4	176.40	74.72	617.40	261.52	<0.01	0.0	36.6	0.00	1.87	0.01
4	176.40	74.72	793.80	336.24	0.10	17.6	54.2	0.90	2.77	0.02
6	264.60	112.08	1058.40	448.32	0.30	79.4	133.6	4.05	6.82	0.05

Note: Initial concentration 15,200 mg/kg

Table A.11

Manganese leached from alum sludge 2, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached manganese (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Manganese leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original manganese
1	44.10	18.68	44.10	18.68	0.36	15.9	15.9	0.81	0.81	0.35
1	44.10	18.68	88.20	37.36	0.27	11.9	27.8	0.61	1.42	0.61
1	44.10	18.68	132.30	56.04	0.20	8.8	36.6	0.45	1.87	0.80
3	132.30	56.04	264.60	112.08	0.11	14.6	51.2	0.74	2.61	1.12
4	176.40	74.72	441.00	186.80	0.06	10.6	61.7	0.54	3.15	1.35
4	176.40	74.72	617.40	261.52	0.03	5.3	67.0	0.27	3.42	1.47
4	176.40	74.72	793.80	336.24	0.06	10.6	77.6	0.54	3.96	1.70
6	264.60	112.08	1058.40	448.32	0.29	76.7	154.4	3.92	7.88	3.38

Note: Initial concentration 233 mg/kg

Table A.12

Zinc leached from alum sludge 2, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached zinc (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Zinc leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original zinc
1	44.10	18.68	44.10	18.68	<0.005	0.00	0.00	0.00	0.000	0.000
1	44.10	18.68	88.20	37.36	<0.005	0.00	0.00	0.00	0.000	0.000
1	44.10	18.68	132.30	56.04	0.009	0.40	0.40	0.02	0.020	0.005
3	132.30	56.04	264.60	112.08	0.017	2.25	2.65	0.11	0.135	0.034
4	176.40	74.72	441.00	186.80	<0.005	0.00	2.65	0.00	0.135	0.034
4	176.40	74.72	617.40	261.52	0.006	1.06	3.70	0.05	0.189	0.048
4	176.40	74.72	793.80	336.24	<0.005	0.00	3.70	0.00	0.189	0.048
6	264.60	112.08	1058.40	448.32	<0.005	0.00	3.70	0.00	0.189	0.048

Note: Initial concentration 393 mg/kg

Table A.13

Arsenic leached from ferric sludge 3, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached arsenic (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Arsenic leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original arsenic
1	44.10	18.68	44.10	18.68	0.0110	0.4851	0.4851	0.007	0.007	0.078
1	44.10	18.68	88.20	37.36	0.0110	0.4851	0.9702	0.007	0.014	0.157
1	44.10	18.68	132.30	56.04	0.0146	0.6439	1.6141	0.010	0.024	0.261
3	132.30	56.04	264.60	112.08	0.0366	4.8422	6.4562	0.072	0.096	1.043
4	176.40	74.72	441.00	186.80	0.0153	2.6989	9.1552	0.040	0.136	1.479
4	176.40	74.72	617.40	261.52	0.0195	3.4398	12.5950	0.051	0.187	2.034
4	176.40	74.72	793.80	336.24	0.0048	0.8467	13.4417	0.013	0.200	2.171
6	264.60	112.08	1058.40	448.32	0.0139	3.6779	17.1196	0.055	0.254	2.765

Note: Initial concentration 9.2 mg/kg

Table A.14

Cadmium leached from ferric sludge 3, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached cadmium (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Cadmium leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original cadmium
1	44.10	18.68	44.10	18.68	0.01	0.49	0.49	0.007	0.007	0.360
1	44.10	18.68	88.20	37.36	0.01	0.49	0.97	0.007	0.014	0.721
1	44.10	18.68	132.30	56.04	<0.01	0.00	0.97	0.000	0.014	0.721
3	132.30	56.04	264.60	112.08	<0.01	0.00	0.97	0.000	0.014	0.721
4	176.40	74.72	441.00	186.80	<0.01	0.00	0.97	0.000	0.014	0.721
4	176.40	74.72	617.40	261.52	0.01	1.76	2.73	0.026	0.041	2.031
4	176.40	74.72	793.80	336.24	<0.01	0.00	2.73	0.000	0.041	2.031
6	264.60	112.08	1058.40	448.32	<0.01	0.00	2.73	0.000	0.041	2.031

Note: Initial concentration 2.0 mg/kg

Table A.15

Iron leached from ferric sludge 3, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached iron (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Iron leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original iron
1	44.10	18.68	44.10	18.68	<0.01	0.0	0.0	0.000	0.000	0.0000
1	44.10	18.68	88.20	37.36	<0.01	0.0	0.0	0.000	0.000	0.0000
1	44.10	18.68	132.30	56.04	0.03	1.3	1.3	0.020	0.020	0.0000
3	132.30	56.04	264.60	112.08	1.00	132.3	133.6	1.966	1.986	0.0025
4	176.40	74.72	441.00	186.80	0.20	35.3	168.9	0.524	2.510	0.0032
4	176.40	74.72	617.40	261.52	0.10	17.6	186.5	0.262	2.772	0.0035
4	176.40	74.72	793.80	336.24	0.10	17.6	204.2	0.262	3.034	0.0038
6	264.60	112.08	1058.40	448.32	0.52	137.6	341.8	2.045	5.078	0.0064

Note: Initial concentration 79,500 mg/kg

Table A.16

Nickel leached from ferric sludge 3, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached nickel (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Nickel leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original nickel
1	44.10	18.68	44.10	18.68	0.06	2.65	2.65	0.04	0.04	0.03
1	44.10	18.68	88.20	37.36	<0.05	0.00	2.65	0.00	0.04	0.03
1	44.10	18.68	132.30	56.04	<0.05	0.00	2.65	0.00	0.04	0.03
3	132.30	56.04	264.60	112.08	<0.05	0.00	2.65	0.00	0.04	0.03
4	176.40	74.72	441.00	186.80	<0.05	0.00	2.65	0.00	0.04	0.03
4	176.40	74.72	617.40	261.52	<0.05	0.00	2.65	0.00	0.04	0.03
4	176.40	74.72	793.80	336.24	<0.05	0.00	2.65	0.00	0.04	0.03
6	264.60	112.08	1058.40	448.32	<0.05	0.00	2.65	0.00	0.04	0.03

Note: Initial concentration 131 mg/kg

Table A.17

Manganese leached from ferric sludge 3, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached manganese (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Manganese leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original manganese
1	44.10	18.68	44.10	18.68	22.80	1005	1005	14.94	14.94	0.31
1	44.10	18.68	88.20	37.36	21.30	939	1945	13.96	28.90	0.60
1	44.10	18.68	132.30	56.04	13.00	573	2518	8.52	37.42	0.78
3	132.30	56.04	264.60	112.08	8.90	1177	3696	17.50	54.91	1.14
4	176.40	74.72	441.00	186.80	7.30	1287	4983	19.13	74.05	1.54
4	176.40	74.72	617.40	261.52	5.00	882	5865	13.11	87.15	1.82
4	176.40	74.72	793.80	336.24	5.14	907	6772	13.47	100.62	2.10
6	264.60	112.08	1058.40	448.32	4.32	1143	7916	16.98	117.61	2.45

Note: Initial concentration 4,800 mg/kg

Table A.18

Zinc leached from ferric sludge 3, AWWARF landfill leaching study

Test weeks in period	Rain in period (L)	Rain in period (in.)	Cumulative rain (L)	Cumulative rain (in.)	Leached zinc (mg/L)	Total leached (mg)	Cumulative leached (mg)	mg Zinc leached per kg of solids	Cumulative leached (mg/kg)	% Leached of original zinc
1	44.10	18.68	44.10	18.68	0.373	16.45	16.45	0.244	0.244	0.031
1	44.10	18.68	88.20	37.36	0.123	5.42	21.87	0.081	0.325	0.042
1	44.10	18.68	132.30	56.04	0.055	2.43	24.30	0.036	0.361	0.046
3	132.30	56.04	264.60	112.08	0.037	4.90	29.19	0.073	0.434	0.056
4	176.40	74.72	441.00	186.80	0.024	4.23	33.43	0.063	0.497	0.064
4	176.40	74.72	617.40	261.52	0.027	4.76	38.19	0.071	0.568	0.073
4	176.40	74.72	793.80	336.24	0.021	3.70	41.90	0.055	0.623	0.080
6	264.60	112.08	1058.40	448.32	0.008	2.11	44.01	0.032	0.654	0.084

Note: Initial concentration 781 mg/kg

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Abbreviations

APHA	American Public Health Association
ASTM	American Society of Testing and Materials
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
°C	degrees Celsius
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm	centimeter
cm^2	square centimeters
cu	color unit
CWA	Clean Water Act
d	day
EE&T	Environmental Engineering & Technology, Inc.
EP	extraction procedure
°F	degrees Fahrenheit
ft	foot
ft^2	square feet
ft^3	cubic feet
ft-lb	foot-pound
g	gram
H	horizontal
ha	hectare
i.e.	that is
in.	inch
kg	kilogram
KIWA	Keuringsinstituut voor Waterleidingartikelen
kN	kilo-Newton
kPa	kiloPascal
L	liter
lb	pound
LC50	lethal concentration at which 50 percent mortality occurs
m	meter
m^2	square meters
m^3	cubic meters
MCL	maximum contaminant level
meq	milliequivalent
mg	milligram
mgd	million gallons per day
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mil gal	million gallons
min	minute
mL	milliliter
mm	millimeter
MSW	municipal solid waste
MSWLF	municipal solid waste landfill
N	Newton
NPDES	National Pollutant Discharge Elimination System
ntu	nephelometric turbidity unit
PCBs	polychlorinated biphenyls
pH	negative logarithm of the effective hydrogen ion concentration
ppm	parts per million
psi	pounds per square inch
RCRA	Resource Conservation and Recovery Act
s	second

SARA	Superfund Amendments and Reauthorization Act
SMCL	secondary maximum contaminant level
sp. gr.	specific gravity
TCLP	toxicity characteristic leaching procedure
TOC	total organic carbon
TOX	total organic halide
TSS	total suspended solids
U.S.	United States
USEPA	U.S. Environmental Protection Agency
USGAO	U.S. General Accounting Office
USGS	U.S. Geological Survey
V	vertical
WPCF	Water Pollution Control Federation
WTP	water treatment plant
ZAVC	zero air voids curve
ZHE	zero-headspace extraction

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