

**Development of an Electrokinetic Method of Dewatering and
Upgrading Sludge to Class A / Excellent Quality Biosolids:
Comparison of Aerobic and Anaerobic Municipal Sludge**

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Abstract

Development of an Electrokinetic Method of Dewatering and Upgrading Sludge to Class A / Excellent Quality Biosolids: Comparison of Aerobic and Anaerobic Municipal Sludge

Jin Huang

Biosolids are organic - rich residuals resulting from the wastewater treatment processes. Thousands of tons of biosolids are produced every year currently in Canada and the U.S., which should be treated and disposed of safely according to the strict environmental standards. This study aims to investigate different sludges and generate Class A biosolids due to electrokinetic (EK) simultaneous dewatering and inactivation of pathogenic organisms such as *Salmonella spp.* and Fecal coliforms.

Bench scale experiments had been conducted operating under batch regime in the environmental research laboratory at Concordia University. Ten cells were set up with three different types of sewage sludge: primary, secondary (attached growth culture and suspended culture), and anaerobic digested sludge. They were taken from Auteuil Wastewater Treatment Plant, Laval, Quebec, and R.O. Pickard Environmental Centre, Ottawa, Ontario. The characterization of the sludge was performed followed by electrokinetic system (EK) tests and data analysis. A conditioning liquid was also added to five cells. Low and high potential such as 1 V/cm and 1.5 V/cm were applied to the cells. Blower system was integrated into the EK for four cells. In order to access the dewatering, disinfection efficiency and other applications of EK system, parameters such as total solids contents, Fecal coliforms, pH, *Salmonella spp.*, and anions concentration were analyzed. The highest total solids (TS) content (98.5% TS) was achieved in the cell

with combined primary and secondary sludge where the lower voltage gradient, conditioner and blower system were applied. No Fecal coliforms were detected after treatment in most of the EK cells. The highest log reduction of *Salmonella spp.* was achieved in the EK cell with anaerobic digested sludge, under lower voltage gradient. In general, *Salmonella spp.* log-reduction was found to be between 6 and 11 in EK cells. The cells without the conditioner exhibited *Salmonella spp.* inactivation mostly in the anode area, while the cells with conditioner observed the inactivation of *Salmonella spp.* in cathode area. Different types of biosolids were observed having different responses to the EK system in terms of dewatering efficiency and pathogen inactivation. It was concluded that the anaerobic digested sludge had better inactivation of *Salmonella spp.* and achieved higher dewatering efficiency under lower voltage gradient. The mixed sludge had better inactivation of *Salmonella spp.* under higher voltage gradient, while the lower voltage gradient yielded higher dewatering efficiency.

This study showed that Electrokinetic dewatering can be applied simultaneously to upgrade both aerobic and anaerobic digested sludge to Class A / Exceptional Quality biosolids.

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Abbreviations

ATAD	Autothermal Thermophilic Aerobic Digestion
BGA	Brilliant Green Agar
BPW	Buffered Peptone Water
BNQ	Bureau de Normalisation du Québec
EEC	European Economic Communiât
EK	Electrokinetic System
FC	Fecal Coliforms
MCLB1	Mixed, Conditioner, Laval, with Blower, and under 1 V/cm (sludge type)
MDDEP	Le Ministère du développement durable, de l'environnement et des parcs du Quebec
MO	Moisture Content
NMA	Nutrient Management Act
PRI	Primary Sludge
RPM	Revolutions per Minute
RV	Rappaport Vassiliadis broth
SEC	Secondary Sludge
TS	Total Solids
VS	Volatile Solids
WC	Water Content
WWTP	Waste Water Treatment Plant
XLT4	Xylose-Lysine-Tergitol 4 agar

CHAPTER 1 INTRODUCTION

1.1 Preamble

Wastewater treatment plants are facing greater challenges due to increasing populations and stringent standards for water quality. As a result, the production of sewage sludge, the solid, semisolid or liquid residue generated during the treatment of sewage, increases dramatically with more efficient treatment operations and processes. Biosolids, regarded as treated sewage sludge, are organic nutrient – rich materials which have been broadly applied for soil-amendment and land reclamation purposes.

The term “sludge” usually refers to the materials used before the applicable beneficial recycling criteria have been achieved. There are specific types of sludge according to the different wastewater treatment processes, such as primary sludge and waste activated sludge. Biosolids are used after the applicable beneficial recycling criteria have been achieved, which usually occurs at the end of the stabilization processes. Stabilization processes include aerobic digestion, anaerobic digestion, autothermal thermophilic aerobic digestion (ATAD), composting, alkaline stabilization, thermal drying, and heat treatment. After treatment, biosolids can be recycled and applied as a beneficial agricultural product. Biosolids can be used as fertilizer to improve and maintain soil productivity, and stimulate plant growth. Farmers and gardeners have been using biosolids for fertilizing gardens, farms and parks for a long time. Biosolids can also be used to reclaim mining sites.

“Increasingly efficient process technology and wastewater treatment processes are producing increasing volumes of complex waste sludges.” (Eckenfelder and Santhanam,

1981). In North America, the U.S. Environmental Protection Agency estimated that 7.1 million tonnes sludge were produced in 2000, with more than 50% of them recycled as soil conditioner (EPA, 1999a). In Europe, more than 6.5 million tonnes are produced each year and it is predicted that the amount will increase exponentially later on (Sánchez et al. 2005). Current Canadian production of biosolids is about 667,000 tonnes per year (Renzetti, 2005). On the island of Montreal, Quebec, approximately 270 dry tonnes are generated daily (Meunier et al. 2002). The great demand for better solutions of sludge treatment technologies makes better knowledge of biosolids management essential. How to manage biosolids becomes a monumental problem to wastewater treatment plants throughout the world.

Landfilling, incineration, and land application are three main options for biosolids disposal. Landfilling and incineration each has health and environmental drawbacks, such as leachate contamination and CO₂ emission. Land application takes advantages of biosolids components, but involves potential adverse effects caused by pathogens in biosolids and nuisance odor problems.

1.2 Biosolids and Environmental Safety

The application of biosolids which meet the regulatory requirements can lead to public concerns toward the potential adverse health effects, environmental and nuisance impacts. The biosolids need to meet regulatory requirements prior to land application due to the constituents of the biosolids. Decades of studies have demonstrated that biosolids can be applied on land safely. The current practices, public health concerns, and regulatory standards have provided the facts that the use of biosolids when practiced in accordance with existing federal and provincial guidelines and regulations presents

negligible risk to the consumer, to crop production and to the environment (National Research Council, 2002).

Biosolids is a valued by-product from wastewater treatment plant and recycling biosolids is good for the environment (Smith et al. 1998). Biosolids contains organic matter which has been reused for centuries to improve soil fertility and productivity. When properly applied and managed, biosolids can add organic matter, provide essential plant nutrients, and improve soil structure, enhance moisture retention, and reduce soil erosion.

Biosolids recycling is regulated and encouraged by the United States, Canadian, and European Environmental Protection Agencies, and federal and provincial authorities. Research and years of recycling experience have demonstrated that properly managed land application of biosolids is environmentally safe.

However, untreated biosolids may have some problems associated with heavy metals, toxic organic matter, pathogens and vectors attraction, and odors. Ten heavy metals are of great importance for environmental concerns, which are arsenic, nickel, cadmium, chromium, copper, lead, mercury, selenium, zinc, molybdenum (Benitez et al. 2001). Those heavy metals could pose a potential risk to the environment and the public health. The regulatory limits of heavy metals in biosolids have been made for land application.

Organic chemicals enter water bodies from domestic waste runoff, industrial wastes, street runoff, and consumer products. During the biosolids processing, some of the organic chemicals are persistent and attract into the biosolids through lipophilic compound bound (Chaney et al., 1996). Many known toxic organic chemicals have been found to cause adverse effects. PCBs, DDT, dieldrin and heptachlor are common toxic

organic matter found in the biosolids, but most of them are found present in low concentrations in biosolids (Chaney et al., 1996).

In addition, the disease causing organisms – pathogens and the vector attraction pose a threat to public health and the environment. The pathogens include *Salmonella spp.* bacteria, enteric viruses, and helminth ova (Gerba et al., 2002). There is also a potential for humans to be exposed to pathogens in biosolids from ingestion of contaminated food, water, or soil, skin contact, and inhalation of bioaerosols (aerosolized biological particles). Depending on the type of treatment it has been through, biosolids may have their own distinctive odor such as a slight musty, and stronger odor caused by ammonia, dimethyl disulfide, carbon disulfide, formic acid, acetic acid, and sulfur dioxide (or carbonyl sulfide) (Paul et al., 2004). The offensive odors may lead to public complaint. Therefore, the treatment prior to land application and disposal of biosolids becomes increasingly important.

Biosolids management has posed a great challenge to engineers for the following reasons:

Firstly, sludge contains a high content of water (more than 90%) and the cost of sewage sludge dewatering is typically very expensive. Sewage sludge treatment and disposal account for approximately half of the operational costs that a wastewater treatment facility must bear (Abu-Orf et al., 2004). Approximately, one million Euros per year is spent on the management of treated sludge in Europe (Sánchez, et al., 2005). Secondly, land application of sewage sludge poses the potential health and environmental risks by microbiological agents, heavy metals and other hazardous materials in the sludge.

The problems of dealing with solid waste and biosolids are very complex for four reasons. Firstly, the components of biosolids are largely coming from the complex characteristics of sewage. Secondly, organics contained in biosolids undergoing biological treatment have different forms from those in wastewater, and will decompose and become offensive as well (Tchobanoglous et al., 2002). Thirdly, biosolids usually contain more than 90% liquid by weight and only a small part of solids which requires technical efforts in dewatering processes. Fourthly, the toxic organic matter, the pathogens, the heavy metals in biosolids have posed a great challenge to biosolids management.

1.3 Legislations

Sewage sludge treatment, defined by the European Environmental Agency (EPA, 2004), is the process to render sludge fit to meet the applicable environmental standards, land-use regulations or other quality norms for recycling or reuse.

Biosolids are provincially regulated in Canada. In Quebec, Manitoba, and Nova Scotia, special environmental regulations such as Canadian Fertilizer Act, Nutrient Management Act, have been enacted governing biosolids management and beneficial recycling. An overview of the regulatory and policy framework of the provinces of Quebec, Manitoba, Ontario, Nova and Scotia addressing biosolids management and disposal is presented in the literature review.

EPA has established two categories of biosolids: Class A and Class B. Class A biosolids have undergone treatments to the point where the concentration of pathogens in biosolids is reduced to levels low enough that no additional restrictions or additional limitations are required by Federal Regulations. Whereas, biosolids B have undergone treatments that

have reduced but not eliminated pathogens. By definition, Class B biosolids may contain pathogens. Therefore, the use of Class B biosolids is restricted to public access and to limit livestock grazing for specified time period after land application. This time period allows the natural die-off of pathogens in the soil. Due to very strict regulations on biosolids land application, researches on methods of upgrading biosolids class B to class A is becoming increasingly important.

1.4 Objectives

Previous studies on application of electrokinetics to sludge dewatering did not address the fate of pathogens. The objective of the study is to investigate the efficiency of dewatering electrokinetic systems on the pathogens inactivation in order to upgrade sewage sludge to Class A and “Exceptional Quality” biosolids. This study focuses on the inactivation of *Salmonella spp.* bacteria and Fecal coliforms in biosolids by means of electrokinetic systems applied to combined primary and secondary sludge, and anaerobic digested sludge.

CHAPTER 2

LITERATURE REVIEW

Sewage sludge has been viewed a nuisance by-product of wastewater treatment processes. However, it is being realized that within the treatment processes it can be a valuable resource, and the treated products, biosolids, are perhaps one of the most beneficial agricultural conditioner and fertilizer. The concerns regarding biosolids management are becoming increasingly important to achieve the desired quality of final product.

In this chapter, a literature survey about biosolids management is presented in five parts. First, regulations and standards for biosolids management are briefly reviewed. Second, biosolids treatment methods are summarized. Third, microbiological characteristics of biosolids are examined, followed by review of pathogen reduction and virus removal in biosolids. Finally, the literature review of electrokinetic systems is presented.

2.1 Canadian Regulations and Guidelines for Biosolids

Canadian guidelines and regulations for recycling biosolids have been in effect since the 1970s. Biosolids sales and land applications are regulated both federally under Fertilizers Act, and provincially in Québec, Ontario, Alberta, and other provinces, where special environmental regulations have been enacted for biosolids management and beneficial recycling.

2.1.1 Québec: Provisional Criteria for Land Application of Fertilizing Residues

Three sets of regulations are presently governing the biosolids land application in Québec. They are the Environment Quality Act, the Québec Residual Materials Management Policy (1998-2008), guidelines for the beneficial use of fertilizing residuals (Environment Quebec, 2006), and Canadian Fertilizer Act (Webber, 2003).

Sewage biosolids products are regulated by a voluntary Canadian Standard which was developed by the BNQ (Bureau de Normalisation du Québec) under the Canadian Standards Council. Following this standard, certification of biosolids products will be issued to municipal wastewater treatment plants so that no Certificates of Authorization is required for land application by Le Ministère du Développement Durable, de l'Environnement et des Parcs du Québec (MDDEP) developed criteria for the management of biosolids under the provisional criteria for land application of fertilizing residues. The criteria set out a classification, which is called C-P-O classification, for fertilizing residual according to the chemical contaminant content (C category), to pathogen content (P category) and odor (O category). There are two C categories (C1 and C2), three P categories (P1, P2 and P3) and three O categories (O1, O2 and O3). A residual that does not meet the minimum C2-P3-O3 requirements is considered "out of category," and may not be used for agricultural or silvicultural purposes, except for some mitigation (Environment Quebec, 2004). Biosolids pathogen criteria were revised in February 2006. The P category for pathogens in biosolids is summarized in Table 2-1.

Table 2-1 Residual quality criteria for categories (Environment Quebec, February 2006 version)

Residual	Category P1 options	Category P2 options
Residuals contaminated by: • municipal or domestic wastewater • human fecal matter • manure • abattoir residuals or manure • animal carcasses • egg residuals	a) <i>Salmonella</i> not detected (in 50g wet weight) ⁽¹⁾ and drying at a temperature $\geq 80^{\circ}\text{C}$, and resulting dryness $\geq 92\%$ b) Any other combination that meets the USEPA Class A requirements for the reduction of pathogens (including mandatory analysis of <i>Salmonella</i>) and vector attraction	a) Lime to $\text{pH} \geq 12$ for at least 2 hours and maintain at $\text{pH} \geq 11.5$ for at least 22 hours ⁽²⁾ b) <i>E. coli</i> $< 2\,000\,000$ MPN/g (d.w.) ⁽³⁾ and aerobic biological treatment and O_2 uptake rate $\leq 1\,500$ mg O_2/kg organic matter/hour. c) <i>E. coli</i> $< 2\,000\,000$ MPN/g (d.w.) ⁽³⁾ and incorporation of residual into soil in < 6 hours ⁽⁴⁾ . d) <i>E. coli</i> $< 2\,000\,000$ MPN/g (d.w.) ⁽³⁾ and biological treatment and sludge age ≥ 20 days e) <i>E. coli</i> $< 2\,000\,000$ MPN/g (d.w.) ⁽⁴⁾ and biosolids from a lagoon not emptied since ≥ 4 years f) <i>Salmonella</i> not detected (in 50g wet weight) ⁽¹⁾ and odour category O_1 or O_2 g) Any other USEPA-approved combination that meets Class B requirements for the reduction of pathogens and vector attraction.
Compost	<i>Salmonella</i> not detected (in 50 g wet weight) ⁽¹⁾ and respect of one of the following CAN/BNQ 0413-200 maturity criteria: a) O_2 uptake rate ≤ 400 mg/kg organic matter/hour or b) CO_2 production ≤ 4 mg $\text{C-CO}_2/\text{g}$ organic matter/day or c) Compost heats $< 8^{\circ}\text{C}$ above ambient temperature (self heating test)	<i>E. coli</i> $< 2\,000\,000$ MPN/g (d.w.) ⁽³⁾ , and O_2 uptake rate $\leq 1\,500$ mg O_2/kg organic matter/hour ⁽⁵⁾ , and the product must have been composted
Paper mill biosolids (not contaminated by fecal matter)	<i>Salmonella</i> not detected (in 50 g weight) ⁽¹⁾ and written attestation from the paper mill's environmental officer that no municipal or domestic wastewater is discharged into the industrial wastewater treatment system.	Written attestation from the paper mill's environmental officer that no municipal or domestic wastewater is discharged into the industrial wastewater treatment system.
Other residuals (not contaminated by fecal matter)	Written attestation from the residual generator stating that the residuals are not contaminated with human fecal matter or manure.	Not applicable.

Note: (1) Until January 2007, it is permitted to use a different sample weight if the analysis permits detection.

(2) All residuals must have attained a pH of 12.

(3) MPN: most probable number. Use the geometric mean (not the arithmetic mean).

(4) The equipment used for soil incorporation must incorporate effectively. The chisel plough is not appropriate. Incorporation techniques allowing marked odour reduction are acceptable.

(5) When the O_2 uptake rate > 400 mg/kg organic matter/hour, the product is not mature.

2.1.2 Ontario's Environmental Protection Act and Regulation 347

Ontario has established regulations governing biosolids land application through the Regulation 347 of the Environmental Protection Act, and Regulation 267/03 under the Nutrient Management Act (NMA, 2002), administered by the Ontario Ministry of the Environment (MOE, 2005).

The Nutrient Management Act set out criteria for concentration of 11 elements of concern, amount, method and timing of application, separation distances from sensitive areas, and suitable soil types and topography. The regulations intend to ensure the biosolids land application safety. The keys to successful biosolids land application are proper application methods, best management practices, nutrient management planning (MOE, 2005).

2.1.3 Nova Scotia: Strict Regulations on Biosolids

Nova Scotia has passed tougher rules for biosolids uses and disposal since May 2004. The new guideline for biosolids land application addresses that “only stabilized biosolids could be land-applied” (Nova Scotia Environment and Labor, 2005). Pathogens criteria follow three categories: Class A, Class B, and Exceptional Quality biosolids. The criteria for metals and pathogens contents of biosolids quality are summarized in Tables 2-2 and 2-3. The guideline also includes the site selection criteria of biosolids land application, land application rates, and biosolids storage rules. This protective guideline facilitates land application while preventing people from adverse effects of biosolids, and “provide guidance as to apply for an Approval to land apply and/or store biosolids in Nova Scotia.” (Nova Scotia Environment and Labor, 2005).

Table 2-2 Maximum acceptable metal concentrations in biosolids (mg/kg of dry weight)
(Nova Scotia, Environment and Labor, 2005)

Metal	Exceptional Quality	Class A/Class B
Arsenic	13	75
Cadmium	3	20
Chromium	210	1060
Cobalt	34	150
Copper	400	760
Mercury	0.8	5
Molybdenum	5	20
Nickel	62	180
Lead	150	500
Selenium	2	14
Zinc	700	1850

Table 2-3 Pathogen reduction requirements (Nova Scotia, Environment and Labor, 2005)

Exceptional Quality	Class A	Class B
Fecal coliform: < 1000 MPN*/g total solids (dry weight) AND <i>Salmonella spp.</i> : <3 MPN*/4g total solids (dry weight)	Fecal coliform: < 1000 MPN*/g total solids (dry weight) OR <i>Salmonella spp.</i> : <3 MPN*/4g total solids (dry weight)	Fecal coliform: < 2,000,000 MPN*/g total solids (dry weight)

Note: * MPN (most probable number)

2.1.4 European Sewage Sludge Directive 86/278/EEC

In Europe, Sewage Sludge Directive 86/278/EEC has been enacted to regulate sewage sludge used in agriculture while protecting people from harmful effects of the pollutants in biosolids. Concentration limits values of heavy metals in the soil and sludge and the

maximum quantities of heavy metals which may be annually brought into the soil are established in the Directive.

To ensure the limit values are not exceeded by The Member States of Europe Community, they are obliged to take the necessary measurements to ensure these limit values are not exceeded through the use of sludge (European Council, 2005). It was not found that the Directive included any organic contaminants and pathogens in either original or revised Directive.

2.2 Pathogen Standards for Biosolids

The U.S. Environmental Protection Agency (EPA) has represented pathogen standards under the 40 Code of Federal Regulation (CFR) Part 503 Rule to ensure that land-applied biosolids do not threaten public health. The Part 503 rule sets forth a clear set of standards to regulate pathogens reduction and vector attraction control.

2.2.1 Class A Biosolids

The Part 503 rule categorizes biosolids into two groups as Class A and Class B regarding pathogens levels in biosolids. Class A pathogen requirement is stricter than Class B biosolids in that “Class A” designates that pathogenic organisms in biosolids are below detectable levels. Class A biosolids have undergone treatments to the point where the concentrations of pathogens are low enough that no additional restricts and limits are required by the Part 503 rule. Once biosolids meet “Exceptional Quality” requirements for metal contents, it can be bagged and marketed for sale as soil conditioner and fertilizer (EPA, 2000a).

EPA, 1994, defined pathogens as “disease - causing organisms, such as bacteria, viruses, and parasites”, and vectors as “organisms, such as rodents and insects that can spread diseases by carrying and transferring pathogens.” Pathogen reduction and vector attraction control could be achieved by special processes such as heating, composting, digestion and alkaline treatment. There are six alternatives designated by the Part 503 rule to get Class A biosolids. All six alternatives for Class A biosolids must meet the pathogen requirements. Either of the two conditions must be met as Class A biosolids: the density of Fecal coliform must be less than 1000 most probable number (MPN) per gram of total solids (dry - weight basis), or the density of *Salmonella spp.* bacteria in the biosolids must be less than 3 MPN per 4 grams of total solids as summarized in Table 2-1. The treatment alternatives and requirements for meeting indicator and pathogen reductions were outlined in Table 2-4.

Table 2-4 Part 503 pathogen density limits (Adapted from U.S.EPA, 2000)

Pathogen or indicator and class	Standard density limit (dry wt)
Class A	
<i>Salmonella</i>	< 3 MPN/4 g total solids or
Fecal coliforms.....	< 1,000 MPN/ gram and
Enteric viruses.....	< 1 PFU/ 4 g total solids and
Viable helminths ova	< 1 PFU/4 g total solids
Class B	
Fecal coliform density.....	< 2,000,000 MPN/g total solids
* MPN = Most Probable Number (MPN)	TS = Total Solids (dry weight basis)
PFU = Plaque Forming Unit	

Vector attraction reduction must take place together with pathogen reduction, except certain conditions are met (EPA, 1994).

2.2.2 Class B Biosolids

The requirements for Class B biosolids are less stringent than Class A biosolids. Class B biosolids have undergone treatment to the point where the disease – causing organisms are reduced certain degree, but there are still amounts of bacteria and pathogens remained in the biosolids. “Process to Significantly Reduce Pathogens” (PSRP) has been extensively used to produce Class B biosolids. The methods such as aerobic digestion, anaerobic digestion, air drying, and lime stabilization can effectively reduce pathogens but not eliminate pathogens. Therefore, precautionary measures are required by the Part 503 rule such as site and crop harvesting restrictions, grazing animals and public contact for all forms of Class B biosolids (EPA, 2000a). The requirement for Class B biosolids is that the density of Fecal coliform in biosolids is less than 2,000,000 MPN per gram total solid on dry weight basis (Meckes et al., 2004). The pathogens in Class B biosolids include bacteria, viruses, helminths, and protozoa. Precautions are advised to be taken by farmers and farm workers handling Class B biosolids to prevent direct contact or inhalation of dust. The neighbors could be exposed to pathogens through wind transport or water runoff during spreading process (EPA, 2004).

The handling and land application of Class B biosolids require special precaution to protect public from anticipated adverse effects. This fact has promoted a renewed interest in seeking various methods to enhance biosolids quality to Class A biosolids.

2.2.3 Conclusion

It can be concluded that:

- The objectives of these strict regulations on biosolids disposal and recycle are to protect the public from reasonably anticipated adverse effects of certain pollutants that might be present in sewage sludge and biosolids.
- The application of Class A biosolids is safe and environmentally friendly.
- Applicable methods which can efficiently upgrade Class B to Class A biosolids are highly demanded to relieve the constraint on biosolids beneficial uses.

2.3 Biosolids Management

Unit operation and processes are becoming more technologically advanced and efficient with increasing sludge generation and more complex sludge treatment processes (Santhanam et al., 1981). The handling and disposal of biosolids has gone through different stages with evolution, and the procedures of biosolids treatment are very comprehensive and cost – related processes.

2.3.1 Preliminary Operations

The preliminary operations are important at any wastewater treatment plant that recycles biosolids. The summary of preliminary treatment procedures are outlined in Table 2-5.

Table 2-5 Unit operations for sludge treatment (adapted from Metcalf and Eddy, 2003)

Screenings	Screenings include all types of organic and inorganic materials large enough to be removed by bar racks.
Grit	Grit is usually made up of the heavier inorganic solids that settle with relatively high velocities.
Scum and grease	Scum consists of the floatable materials skimmed from the surface of primary and secondary settling tanks and from the grit chambers and chlorine contact tanks
Primary sludge	Sludge from primary settling tanks is usually gray and slimy and, in most cases, has an extremely offensive odor.
Activated sludge	Generally has a brown flocculent appearance, inoffensive “earthy” odor, readily digested
Trickling-filter sludge	Brownish, flocculent, and relatively inoffensive when fresh. It generally undergoes decomposition more slowly than other undigested sludges. Digests readily.
Aerobically digested sludge	Brown to dark brown, and have a flocculent appearance. Not offensive odor, well – digested sludge dewateres easily on drying beds
Anaerobically digested sludge	Dark brown to black and contain an exceptionally large quantity of gas.
Compost	Dark brown to black, well – composted solids has inoffensive odor

Biosolids that are intended for land application should not have visible debris associated with solid wastes. Preliminary operation involves five major processes such as grinding - particle size reduction, screening – removal of fibrous materials, degritting – grit removal, blending – homogenization of solids streams, and storage – flow equalization.

2.3.2 Sludge Conditioning

The conditioning of sludge is an important pretreatment as to facilitate water removal from biosolids and reduce the volume of sludge. Chemical conditioning is typically achieved by adding chemical coagulants or polymers to flocculate the sludge particles to form larger aggregates (Lin and Shien, 2001). Commonly used conditioners are grouped into inorganic and organic conditioners. Ferric chloride (FeCl_3), ferric sulfate

($\text{Fe}_2(\text{SO}_4)_3$), and aluminum salts ($\text{Al}_2(\text{SO}_4)_3$) have been used for many years as inorganic chemical conditioners, whereas, polymers are employed as organic conditioners (Zhou, 2003, and Möller, 1979). Extensive research has been conducted on optimal chemical conditioner doses by Papavasiliopoulos and Markantonatos (2001). They showed that the optimal conditioner doses are related to various factors such as mixing speed, polymer distribution, viscosity measurements, and precipitation quantities in sludge (Papavasiliopoulos and Bache, 1998). Besides chemical conditioning, the applications of physical conditioning methods such as thermal treatment, freeze/thaw, elutriation applications have been reported frequently (Zheng et al., 1998, Lai et al., 2004, Lin et al., 2001).

However, the addition of polymers could be potential sources of strong odors of thickened biosolids (Chang et al., 2005). In addition, monitoring the toxicity of cationic polymer residuals could be a challenging task (Papavasiliopoulos and Markantonatos, 2001). The metal salts and other inorganic coagulants are generally harmful to plants. Moreover, the large costs of conditioning are somewhat offsetting the benefits achieved for the dewatering (Agarwal et al., 2005).

2.3.3 Thickening

Due to the large amount of water contained in the sewage sludge, thickening processes reduce the water content in the raw sludge and achieve volume reduction (Watanabe and Tanaka, 1999). The thickening procedures can affect the size and cost of equipment required to perform preceding and succeeding operations such as dewatering, digestion, and heat treatment. In addition, thickened biosolids makes the following procedures more

stable and economical. Various studies have been carried out for alternative methods of thickening, such as gravity sedimentation, flotation thickening, and centrifugal thickening, (Karl and Wells, 1999, Arnold et al., 1995, EPA, 2000c). Table 2-6 shows the typical solids content of sludge.

Table 2-6 Typical solids content of sludge (Adapted from Metcalf and Eddy, 2003)

Type of sludge	Solids concentration, % (w/w)	
	Range	Average
Primary	3 - 6	4.3
Waste activated	1 - 1.5	1.3
Anaerobically digested mixed	6 - 7	5.5
Septage	1 - 4.5	2.7

2.3.4 Sludge Dewatering

Sludge dewatering is a process intended to reduce the water content of biosolids, thus decrease the final volume of sludge to be transported and treated. It usually consists of 20 – 30% dry matter and 70–80% water, dewatered sludge, therefore, can minimize the energy consumption and potential runoff of biosolids in the succeeding treatment processes such as incineration and landfilling (Stasta et al., 2006). Commonly used dewatering technologies are briefly reviewed below.

Sand drying beds

Sand drying beds, a widely applied technology, dewater sludge on enclosed or open sand beds. Sand drying beds have advantages of the simple operation, little operator attention and maintenance, and less energy requirements. However, sand drying beds are affected by uncontrollable climatic conditions, raw sludge clogging problems, and odor problems. Therefore, sand drying beds are less favorable than mechanical dewatering technologies (Muzaini, 2003).

Lagoon drying

Lagoon drying is a relatively cost - effective sludge dewatering system, provided land is not expensive, and climate is relatively dry and hot (Idris et al., 2002). Theoretically, it is similar to sand drying beds, however, the odor problems is usually more serious than sand beds. It is reported that 40-45% solids content could be obtained from 5% primary solids content when placed in lagoon for 2-3 years (Santhanam et al., 1981).

Reed beds

Reed beds use common reed such as *Phragmites australis* to dewater biosolids in a confined area. The technique combines the conventional drying bed technology with wetland (Burgoon et al., 1997). Reed beds require low investment, simple operation and maintenance skills, and provide beneficial side – products. However, the technology is an empirical technology that requires large areas and long preparation period (Kim and Smith, 1997).

Belt filter press

Belt filter press dewater sludge by applying pressure to filtering belts between which the biosolids are sandwiched to squeeze out the water (EPA, 2000b). The cakes discharged continuously from the belt filter press normally reach the solid content of 15-25% (Chen et al., 2002). Belt filter requires simple maintenance, and produces less noise than

centrifuge facilities. However, the odor problems, intensive operation attention, and frequent washing process are the main disadvantages. Studies have shown that the dewatering effects depend primarily on the belt speed and belt tension and redesigning configuration has been discussed (Olivier and Vaxelaire, 2005, Day and Giles, 2002).

Vacuum filtration

The vacuum filtration achieves sludge dewatering by applying a vacuum to sludge-supporting filter medium, which typically rotate with a drum submerged in the reservoir of wet sludge (Santhanam et al., 1981). Cake filtration is the major mechanism of water removal (Wu et al., 2003). The continuous vacuum filtration has advanced from the other discontinuous counterparts. The major disadvantage is the frequency of medium washing.

Centrifugal dewatering

The centrifuge dewatering is a mechanical process that uses the centrifugal force from high speed rotating bowl to separate solids from liquid (EPA, 2000c). It has been applied for more than fifty years due to its simplicity of operation and the compactness of equipment. The solid content depends primarily on the sludge nature, the original sludge content, and the addition of polymers (Muzaini, 2004).

Basket, disc, and solid bowl conveyor are three most widely employed centrifuges for sludge dewatering with the last being used most commonly (Chen et al., 2002). The separation of solids and liquid by solid bowl conveyor is achieved by a rotating unit comprising a bowl and a conveyor joined through a gear system at different speeds (Santhanam et al., 1981). Chu and Lee (2001) have shown that the significant water removal occurs at the maximum moisture – removal rate when the filtration flows through a wet cake and the optimal rotation speed exists.

Centrifuge dewatering requires high-energy input to increase the centrifugal speed or to flocculate sludge at optimal dosage (Chu et al., 2005), and the addition of polymer or flocculants demands operational input. Meanwhile, the produced cake needs further treatment for disinfection. Belt press and centrifuge dewatering are broadly applied in Quebec province.

2.3.5 Electrokinetic Dewatering

Electrokinetic method has been demonstrated to be a cost – effective technology for sludge dewatering (Esmaeily et al., 2006). The water content is removed from sludge by electroosmosis and electrophoresis in the applied electrical field.

Literature demonstrates that electroosmosis causes the dewatering significantly, and the combination of electrokinetic method and conventional equipment such as a belt press has been applied at full scale which could obtain 17-24% dry solids content (Raats et al., 2002). The disadvantage is the anode corrosion in electrokinetic field. Typical dewatering processes normally have no effects on pathogen reduction and heavy metal removal. However, Esmaeily (2006) showed possibility of simultaneous dewatering, inactivation of pathogen, and heavy metal removal from combined sludge using EK and a conditioner. The comparison of different dewatering techniques is summarized in Table 2-7.

Table 2-7 Comparison of different dewatering methods

Dewatering method	Operation attention	Energy consumption	Total solids content	Odor problem	Advantages / disadvantages
Sand beds	Little	Low	25-40 %	Strong	Land requirements
Reed beds	Little	Low	20-40%	Strong	Climate, biomass generation
Lagoon drying	Little	Low	25-30%	Strong	Long term
Belt filter	High	High	15-25%	Moderate	Medium washing
Vacuum filtration	High	High	15-36%	Moderate	Frequent medium washing
Centrifuge	High	Very high	25-30%	Less	Less exposure to pathogens/noisy
Electrokinetic dewatering	High	Moderate	25-30%	Moderate	Metal removal

2.4 Stabilization

Stabilization of biosolids helps to reduce the pathogens, minimize odor potential, and eliminate vector attraction potential in biosolids, resulting in relatively stable end products. An extensive literature survey on biosolids stabilization processes in section 2.5.

2.5 Microbiological Characterization of Biosolids

Biosolids contain certain amount of pathogenic organisms originating from wastewater treatment processes. Extensive research has been conducted to identify pathogens in biosolids, and great efforts have been taken on the disinfection processes to effectively destroy pathogens. The major concerns of pathogenic microorganisms in biosolids include pathogenic bacteria, viruses, and parasites. This study focuses on the treatment of

enteric microorganism – Fecal coliforms, *Salmonella spp.* Major pathogens in municipal sewage and sludge are outlined in Table 2-8.

The survivability of pathogens differs from different species. Generally, factors which influence the survivability of pathogens include: pH, temperature, sunlight, nutrients, moisture, and competition from other microorganisms. Table 2-9 shows the survivability of bacteria, viruses, protozoa and helminths ova through different treatment processes (EPA, 1999b).

Table 2-8 Major pathogens in municipal wastewater and sludge (National Research Council, 1996)

Pathogen class	Examples	Diseases
Bacteria	<i>Shigella sp.</i> <i>Salmonella typhi</i> <i>Salmonella spp.</i> <i>Vibrio cholerae</i> <i>Enteropathogenic Escherichia coli</i> <i>Yersinia spp.</i> <i>Campylobacter jejuni</i>	Bacillary dysentery Typhoid fever Salmonellosis Cholera A variety of gastroenteritis diseases Campylobacteriosis (gastroenteritis)
Viruses	Hepatitis A virus Norwalk viruses Rotaviruses Polioviruses Coxsackie viruses Echoviruses	Infectious hepatitis Acute gastroenteritis Acute gastroenteritis Poliomyelitis “flu like” symptoms “flu like” symptoms
Protozoa	<i>Entamoeba histolytica</i> <i>Giardia lamblia</i> <i>Cryptosporidium sp.</i> <i>Balantidium coli</i>	Amebiasis (amoebic dysentery) Giardiasis (gastroenteritis) Cryptosporidiosis (gastroenteritis) Balantidiasis (gastroenteritis)
Helminths	<i>Ascaris sp.</i> <i>Taenia sp.</i> <i>Necator americanus</i> <i>Trichuris trichura</i>	Ascariasis (roundworm infection) Taeniasis (tapeworm infection) Ancylostomiasis Trichuriasis (whipworm infection)

Table 2-9 Log reduction of pathogens after sewage sludge treatment (EPA, 1999)

PSRP Treatment	Bacteria	Viruses	Parasites (Protozoa and helminths)
Anaerobic Digestion	0.5-4.0	0.5-2.0	0.5
Aerobic Digestion	0.5-4.0	0.5-2.0	0.5
Composting (PSRP)	2.0-4.0	2.0-4.0	2.0-4.0
Air Drying	0.5-4.0	0.5-4.0	0.5-4.0
Lime Stabilization	0.5-4.0	4.0	0.5

Note: A 1-log reduction (10-fold) is equal to a 90% reduction. Class B processes are based on a 2-log reduction.

2.5.1 Fecal Coliforms

Fecal coliform (FC) is the portion of the coliform bacteria group presenting in the intestinal tracts and feces of warm – blooded animals. Fecal coliforms are effective fecal indicators of enteric bacterial pathogens in biosolids because Fecal coliforms present large quantities in human feces, and they are generally not pathogenic under normal conditions (Nelson, 2003). In addition, the reduction rates of Fecal coliforms are comparable to many of the bacterial pathogens, but the initial concentrations of the former are usually many orders of magnitude higher. Coliforms are defined as “characteristically aerobic and facultatively anaerobic, gram-negative, non-spore-forming, and rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 35°C” (Buchino, 1970). Fecal coliforms are the most common indicator bacteria, living in the intestinal tract of warm-blooded animals and excreted in the feces. In addition, Fecal coliforms themselves are generally not pathogenic under normal conditions, which makes them favored for the determination of fecal contamination (Tallon et al., 2005). However, coliforms can cause diarrhea and opportunistic urinary tract infections (Tortora

et al., 1992). Fecal coliforms usually survive long enough outside human body in the water and biosolids, facilitating to be detected.

Jimenez et al. (2000) reported that the alkaline primary treatment was efficient to obtain Class B biosolids with Fecal coliforms less than 2 million MNP/ g TS. George, Crop, and Servais (2001) sampled and compared Fecal coliforms removal efficiency between various treatment methods. They concluded that activated sludge process and biofiltration with high retention time, and tertiary treatment like UV disinfection are the most efficient methods to eliminate FC densities in WWTP (George et al., 2001). Oropeza et al. (2001) found the anaerobic thermophilic digestion could achieve Fecal coliforms reduction to less than 1000 MPN / g TS - Class A biosolids (Oropeza et al., 2001). Hong et al. (2003) investigated the microwave irradiation was able to destroy Fecal coliforms membrane slowly up to 49 ± 3 °C, but rapidly above 60 ± 3 °C. Microwave irradiation appeared to be the method to kill Fecal coliforms with shorter time and lower pretreatment temperature. Meckes et al. (2003) who showed that the 3-log reduction (99.9%) of Fecal coliforms reduction was produced by lime treatment. However, the high investment costs and potential hazardous emissions make these methods difficult to be employed extensively. Therefore, the study for a better solution for the inactivation of Fecal coliforms in sludge is of most concern.

2.5.2 *Salmonella* spp. - Pathogenic Bacteria

Salmonella species are gram-negative, aerobic, rod-shaped, zoonotic bacteria that can infect humans and animals with a disease named Salmonellosis. *Salmonella* are ubiquitous pathogens causing food-borne diseases linked to red meat and poultry

products (Davies et al., 2000). Research shows that sludge is frequently contaminated with *Salmonella* (Sahlström et al., 2004). In Canada, it is estimated that about five thousand diagnosed cases of human Salmonellosis occur annually (Vanderpost et al., 1976). *Salmonella spp.* is easily transmitted by water and water disinfection is concerned as an important preventive mechanism, while increasing awareness has been brought to sludge disinfection (Espigares et al., 2006).

Salmonella spp. has been extensively studied over the past years and various methods for the reduction processes have been explored. Jepsen et al. (1997) investigated various conventional treatment methods for the reduction of *Salmonella spp.* in Denmark. They found that significant reduction of *Salmonella spp.* was obtained while storing biosolids at around 20 °C for about 1 year, which is very time-consuming. Sidhu et al. (2001) reported that the possibility of *Salmonella spp.* regrowth in biosolids was affected by the indigenous microflora, although the regrowth potential was very strong in composted sludge. The optimal growing pH for *Salmonella* is pH 6.2 - 7.2. Fukushi et al. (2003) revealed that in an organic acid environment, if the pH maintained below 5.5 at a retention time longer than 2 days, the number of *Salmonella spp.* was decreased to undetectable level. Zábranská et al. (2003) evaluated the efficiency of *Salmonella spp.* removal by autothermal thermophilic aerobic digestion and anaerobic digestion and found that both were effective to achieve Class A biosolids. Korolczuk et al. (2006) investigated the effects of pulsed electrical field on *Salmonella enteritidis* inactivation. They found that the reduction rate could be considered as linearly related to energy input, electrical field strength, and temperature.

The research group at Concordia University has performed investigations on coliform inactivation in biosolids (Esmaeily et al., 2006). The investigation concluded that complete Fecal coliform inactivation was achieved using EK system and a conditioner.

2.5.3 Conclusion

Recent research development has shown that the biosolids treatment processes with regard to the removal of the pathogenic microorganisms must meet the high standards of biosolids management. The efforts to seek for more comprehensive processes to reduce more pathogenic microorganisms need input further.

2.6 Pathogen Inactivation in Biosolids

Stabilization of biosolids is a sludge treatment process that reduces the pathogenic organisms in biosolids, eliminates the offensive odors, and inhibits the potential for putrefaction, thus enhances the quality of biosolids for the beneficial uses. The major stabilization processes include anaerobic digestion, aerobic digestion, alkaline stabilization, and composting.

2.6.1 Alkaline stabilization

Alkaline stabilization is a method which applies alkaline materials to render the sludge unsuitable for the growth of the microorganisms as to eliminate the nuisance condition in sludge. The high pH creates an environment that substantially retards the microbial reaction. The sludge will not putrefy so long as the pH is maintained at that level. The alkaline environment can also inactivate virus, bacteria, and other microorganisms

present. The disinfecting capabilities of lime are attributed to its ability to increase temperature, pH, and the free ammonia content in the biosolids (Abu-Orf et al., 2005).

The literature suggests that limed sludge can achieve pathogen reduction by pH increase and temperature rise (Mignotte-Cadiergues et al, 2001; Eriksen et al., 1995; Schuh et al., 1985). Capizzi-Banas et al. (2004) reported that the maintenance of good mixture of lime with pH higher than 12 can achieve the inactivation of *Ascaris* eggs removal. Lime is added into sludge to raise the pH to 12 or higher. Brewster et al. (2003) investigated the feasibility of inactivating *Ascaris suum* eggs spiked into digested and dewatered biosolids from Winnipeg, Manitoba to class A levels by storing the biosolids treated with lime (CaO) and (or) fly ash under anoxic conditions. They concluded that the inactivation time depended on the storage temperature and lime or fly ash dose. Lime treated sludge has a granular consistency which makes it easy to spread on land (Paulsrud and Nedland, 1997). Abu-Orf et al. (2004) investigated the feasibility of full-scale anoxic disinfection of dewatered and digested sludge with low lime doses and lagoon fly ash to produce class A biosolids for *Ascaris suum*, reoviruses, and Fecal coliforms.

Alkaline treatment has been demonstrated as an effective method to sludge stabilization. However, the odor problems remained unsolved. The lime dosage should be monitored as landfarming of biosolids with an excessive amount of Ca affects soil conditions.

2.6.2 Anaerobic Digestion

Anaerobic digestion of sewage sludge is a treatment process which involves the decomposition of organic materials by facultative and strictly anaerobic bacteria which can be placed into two domain, acetogenic bacteria and methanogens, in oxygen free

environment (Dearman et al., 2006). Anaerobic processes transform complex organic molecules to simple molecules and gases; reduce pathogens to a lower level, and convert biosolids to an innocuous sludge. Class B biosolids are typically produced through the process (EPA, 1992).

Anaerobic digestion has been extensively studied over the past years and various methods for process improvement have been explored. The sequential processes of microbial stabilization involve the hydrolysis of volatile solids to soluble organic compounds by facultative heterotrophic microorganisms. Followed by the fermentation process, the soluble organic compounds are transferred to volatile acids, carbon dioxide, and some hydrogen gas by acid – producing facultative bacteria. The volatile acids are primarily converted to methane gas. The growth rate of methane – producing bacteria as well as other factors such as temperature, pH, volatile acid, and alkalinity concentrations are the limiting factors for the whole process. Chauret et al., (1999) reported that 1-2 log reduction of Fecal coliforms and heterotrophic bacterial was achieved by anaerobic digestion of sludge.

Mesophilic and thermophilic anaerobic digestion are the most broadly applied anaerobic digestion technologies. Extensive research has been conducted on the issues for the pathogen removal. Oropeza et al. (2001) investigated the efficiency of thermophilic and mesophilic anaerobic digestion on the removal of pathogens and parasites from municipal sludge, and reported that anaerobic thermophilic digestion was close to complying with Class A biosolids (Oropeza et al., 2001). Song et al. (2004) demonstrated the performance of mesophilic and thermophilic co-phase anaerobic digestion for the destruction of Fecal coliforms and reduction of volatile solids was more stable, efficient,

and economical than single stage digester (Song et al., 2004). Smith et al. (2005) found the principal factors controlling the destruction of pathogens during mesophilic anaerobic digestion were microbial competition and substrate limitation. The advantages and disadvantages of anaerobic digestion are summarized in the Table 2-10.

Table 2-10 Advantages and disadvantages of anaerobic digestion

Advantages	Disadvantages
- the oxygen supply rate is not a limit factor for the overall process - loading rate can be much higher than for aerobic systems - the yield of highly valuable methane gas - lower net sludge production	- slow bacteria growth rate - toxic oxidizing agents - heat input for optimal temperature - complex knowledge of biochemical environment

2.6.2.1 Mesophilic Anaerobic Digestion

Mesophilic anaerobic digestion is a widely adopted biosolids stabilization treatment. During this process, biosolids undergo decomposition in the mesophilic temperature range from 25°C to 40°C. The goal of anaerobic digestion is to reduce the organic solids of raw sludge, remove or eliminate pathogens, and convert the sludge into a readily dewatering material. It is not primarily designed as a method to disinfect biosolids instead of sludge stabilization. However, reported by Gavala et al. (2003) through interacting operation conditions and variables, the method could achieve pathogen reduction.

2.6.2.2 Thermophilic Anaerobic Digestion

Anaerobic digestion in the temperature ranges from 50-55 °C has been applied over the past years in full – scale installation. The higher temperature stimulates more rapid reaction rate, superior dewatering properties, and better destruction of pathogens (Aitken et al., 2005). However, thermophilic anaerobic digestion requires more energy input, thus

more expensive the system is. Moreover, the liquid removed from the sludge contains higher organic and colloidal materials. Most importantly, the corrosive nature of liquid is easily forming a coat over the surface of the heat exchanger which causes more extra maintenance.

2.6.3 Aerobic Digestion

Aerobic digestion is a sludge stabilization process that utilizes aerobic microorganisms to degrade organic components in sludge (Bernard and Gray, 2000). It could achieve sludge volatile solids reduction and enhance the stability of yielding product. Aerobic digestion process has been developed as a stabilization method of sludge over the past years. During the aerobic process, sewage sludge or biosolids are biologically oxidized.

Aerobic digestion has been widely applied in many industrial and municipal treatment works. Bernard and Gray (2000) investigated the aerobic digestion for volatile solids reduction and found that full stabilization of sludge could be achieved. Tonkovic (1999) reported that continuous aeration achieved E.coli destruction greater than 95%, but the volatile solids reduction and odorous removal still required further treatment.

The aerobic digestion process has benefits in that it produces a biologically stable product with relatively simple construction and lower capital cost. The dewaterability of biosolids undergone aerobic digestion has been improved significantly, and volatile solids reduction is also very effective. However, the higher energy cost, the limiting oxygen uptake rate and the solid reduction efficiency are the major drawbacks of aerobic digestion system.

Thermophilic aerobic digestion

Thermophilic aerobic digestion has been practiced as an emerging alternative method for pathogen reduction and solids stabilization. In the thermophilic temperature range 50-55°C, the sludge degradation and pathogen reduction process have been accelerated. A number of researchers have exploited the application of thermophilic aerobic digestion. Kim et al. (2002) reported that certain pretreatment methods such as mechanical, ultrasonic, thermal, and alkaline treatment could help thermophilic aerobic digestion process achieve better pathogen reduction results.

2.6.4 Composting

Composting is the biological decomposition of organic materials under controlled conditions. In order to eliminate pathogens and reduce metal availability, sewage sludge is often composted prior to land application (Vaca-Paulín et al., 2006). Based on the oxygen use, temperature, and technology approaches, the composting technologies gradually developed into various choices such as aerobic or anaerobic, mesophilic or thermophilic, static pile or windrow, and mechanical or "enclosed" composting, respectively. Composting is a relatively simple and inexpensive process (Yamada and Kawase, 2005), but it may depend partly on the weather condition, and the odor complaints are usually the major drawback of the systems.

The advantages and disadvantages of different stabilization methods are summarized in the Table 2-11.

2.6.5 Conclusion

Biosolids management methods become increasingly interesting to researchers due to the great economical values. To upgrade the quality of biosolids, the removal the pathogens becomes the focus of recent researches. To date, however, most applied stabilization methods could not achieve both pathogen destruction and heavy metal removal (Yuan and Weng, 2006). Therefore, an economically attractive and environmentally feasible method needs to be pursued. Emphasis has been put on the emerging method – electrokinetic technology.

Table 2-11 Disadvantages and advantages of different stabilization methods (Adapted from Metcalf and Eddy, 2003)

Alkaline stabilization	Addition of an alkaline material, usually lime, to maintain a high pH level to effect the destruction of pathogenic organisms	Advantages: a rich soil-like product results with substantially reduced pathogens. Disadvantages: mass is increased by the addition of the alkaline material
Anaerobic digestion	The biological conversion of organic matter by fermentation in a heated reactor to produce methane gas and carbon dioxide. Fermentation occurs in the absence of oxygen	Methane gas can be used beneficially for the generation of heat or electricity. The resulting biosolids may be suitable for land application. The process requires skilled operation as it may be susceptible to upsets and recovery is slow
Aerobic digestion	The biological conversion of organic matter in the presence of oxygen or air, usually in an open – top tank	Process is much simpler to operate than an anaerobic digester, but no usable gas is produced. The process is energy – intensive because of the power requirements necessary for mixing and oxygen transfer
Autothermal thermophilic digestion	Process is similar to aerobic digestion except higher amounts of oxygen are added to accelerate the conversion of organic matter. Process operates at 40-80 °C, autothermally in an insulated tank.	Process is capable of producing class A biosolids. Skilled operators are required and the process is a high – energy user (O ₂ production)
Composting	The biological conversion of organic solids in an enclosed reactor or in windrows or piles	A variety of solids or biosolids can be composted. Composting requires the addition of bulking agent to provide an environment suitable for biological activity. Volume of compost produced is usually greater than the volume of wastewater solids being composted. Class A or B biosolids could be produced. Odor control is very important, as process is odorous.

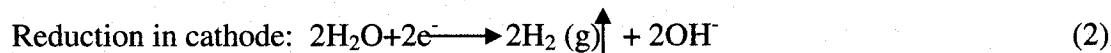
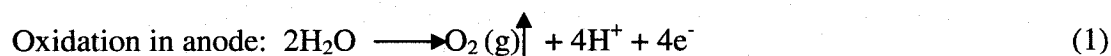
2.7 Electrokinetic Systems

An electrokinetic system consisting of electrodes connected to DC power supply generally refers to a system which involves electrokinetic phenomena including relative motions of species in an electric field (Chifrina, and Elektorowicz, 1998). The electrokinetic phenomena count for basic processes: electromigration, electrophoresis, and electroosmosis. In suspensions, additional phenomena (eg. electro-coagulation, electro-precipitation) might take place.

2.7.1 Electromigration

Electromigration in soil is defined as the migration of ionic species in void fluid under an electrical field (Reddy et al., 2003). Cations such as metals ions, ammonium ions, and anions such as chloride, cyanide, fluoride ions, move towards respective electrodes (Giannis et al., 2005). It has been found that in some cases significant removal of contaminants, especially in highly contaminated soils is due to electromigration (Li et al., 1997).

Electrochemical reactions are induced by the electrical current together with the mass flux of species that occurs in the electrical field. As a result, oxidation occurs at the anode while reduction occurs at the cathode. The reactions are shown in the following equations.



As a result, the hydrogen and hydroxyl ions migrating into each electrode causing the acidic conditions in the anode area, while an alkaline conditions at the cathode area.

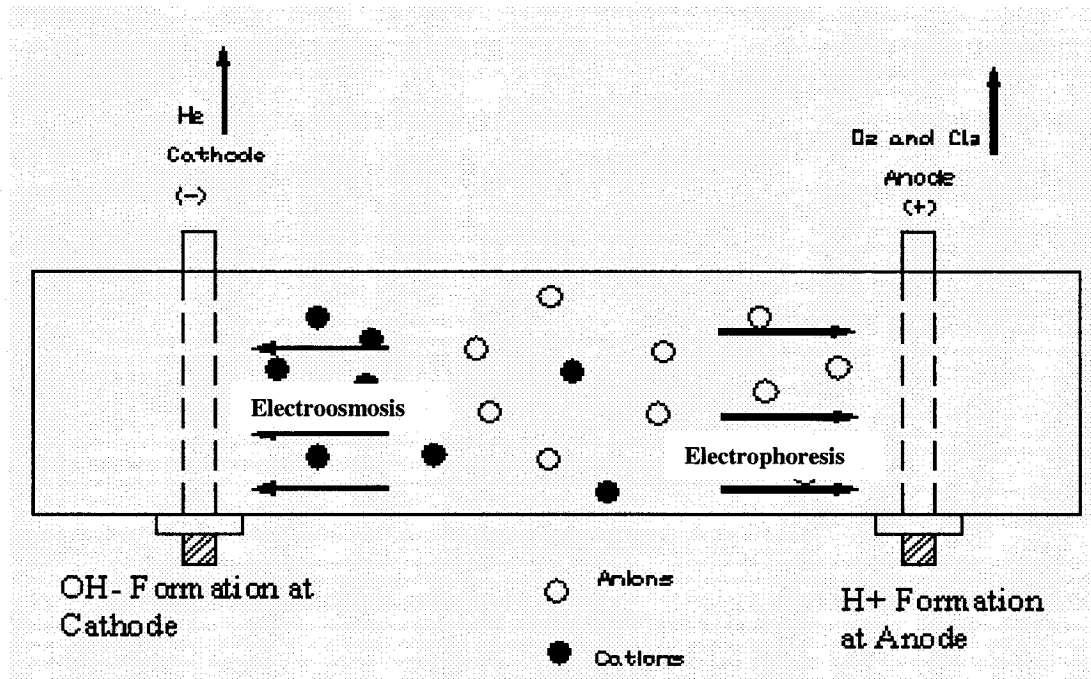


Figure 2-1 Typical electrokinetic system phenomena

2.7.2 Electroosmosis

Electroosmosis is the pore water movement in soil under an electric field. Based on diffuse double layer theory (Figure 2-2), a relatively immobile layer of cations will be held in the stern layer surrounding the negatively charged particle core, while in the diffuse layer, cations and some anions will be found as well as water molecules. The diffused layer charges migrate causing a flow. Depending on the relative mobility of opposite ions, a net flow is carried towards cathode (Banerjee and Law, 1998).

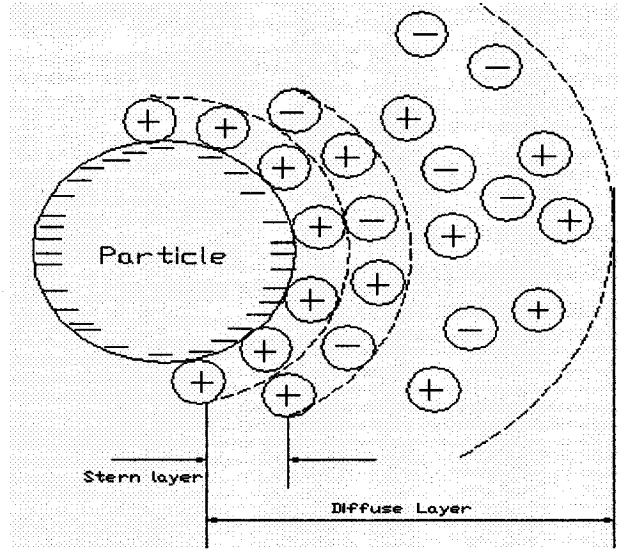


Figure 2-2 Diffuse double layer theory (Yong et al., 1992)

Electroosmotic permeability (k_e) is the volume rate of water flowing through a unit cross – sectional area due to unit electric gradient under constant conditions within a short duration. The driving force caused by electroosmosis (EO) flow is indicated by the coefficient, and the electroosmosis flow rate was estimated by Casagrande (Habibi, 2004) expressed as the equation (3):

$$q_e = k_e i_e A = k_i I \quad (3)$$

Where:

q_e = Electroosmosis flow rate [cm^3/s]

k_e = coefficient of EO permeability [$\text{cm}^2/\text{V.s}$]

i_e = potential gradient [V/cm]

A = cross – sectional area [cm^2]

k_i = coefficient of water transport efficiency [$\text{cm}^3/\text{A.s}$]

I = applied current [A]

2.7.3 Electrophoresis

Electrophoresis is the transport of charged particles or colloids under the influence of an electrical field (Virkutyte et al., 2002). All electrically charged particles like colloids, organic matters, and droplets are included in the definition.

2.7.4 Applications of Electrokinetic System

Electrokinetics is an emerging in-situ remediation technology for heavy metal and organic contaminant removal from unsaturated or saturated soil, sludges, and sediments. The first electrokinetic phenomenon was observed by Reuss at the beginning of 19th century. After that, many scientists explored the theories and mechanisms of electrokinetic system such as Helmholtz, Smoluchowski, and Pamukcu (Virkutyte et al., 2002). Electrokinetic system (EK) has been demonstrated as a cost - effective technology for soil remediation which has been applied broadly to separate and extract heavy metals and organic matter from contaminated soil and sludge (Yuan and Weng, 2003).

EK system has been demonstrated 85-95% efficiency in removing heavy metals such as arsenic, cadmium, chromium, lead, mercury, zinc, and nickel (Virkutyte et al., 2002). Amrate and Akretche (2005) investigated the EDTA enhanced electrokinetic remediation system for lead removal. Wang et al. (2005) reported the removal efficiencies of heavy metals were: 95% for Zn, 96% for Cu, 90% for Ni, 68% for Cr, 31% for As and 19% for Pb under experimental conditions. Jagannadh and Muralidhara (1996) investigated the electrokinetic system application on the control of membrane fouling.

Elektrokientic system have been applied into sludge dewatering and thickening (Raats et al., 2002; Yuan and Weng, 2003; Banerjee and Law, 1998). The application of electric

current into waste sludge had released the bound water in the sludge and increased solids content up to 65% (Eckenfelder et al., 1981).

The research group at Concordia University has conducted investigations for several years on electrokinetic application for heavy metal removal, oily sludge phase separation, and PAH and hydrocarbon removal (Habibi, 2004; Esmacily, 2002; Hakimipour, 2001; Hatem, 1999).

2.7.5 Conclusion

A great effort has been taken for the disinfection of biosolids, yet there is not an optimal one to disinfect biosolids while as the same time could facilitate dewatering, heavy metal removal, and eliminate a large spectrum of pathogens. The innovative electrokinetic technology appears both economically feasible and technical attractive for biosolids treatment. However, more study is needed.

CHAPTER 3 EXPERIMENTAL METHODOLOGY

As mentioned in previous chapters, electrokinetic method has been chosen for sludge disinfection due to its technical feasibility and economical attractiveness. In this study, effects of electrokinetic dewatering system (EK) on the reduction of pathogenic microorganisms in the biosolids have been investigated.

3.1 Experimental Procedure

The study was performed in Environmental Engineering Research Laboratory at Concordia University. The procedures of the lab work were composed of three major steps: sample characterization, electrokinetic system (EK) tests, and data analysis. The description of experimental procedures is displayed in the following flow chart in Figure 3-1.

The methodology involved the following stages:

1. EK system set - up;
2. Sample collection, sludge characterization prior to EK system application
3. Microbiological cultivation and incubation process
4. Microbiological spiking process
5. EK system application in pathogens removal
6. Sampling and analysis procedures after EK application
7. Results analysis and discussion

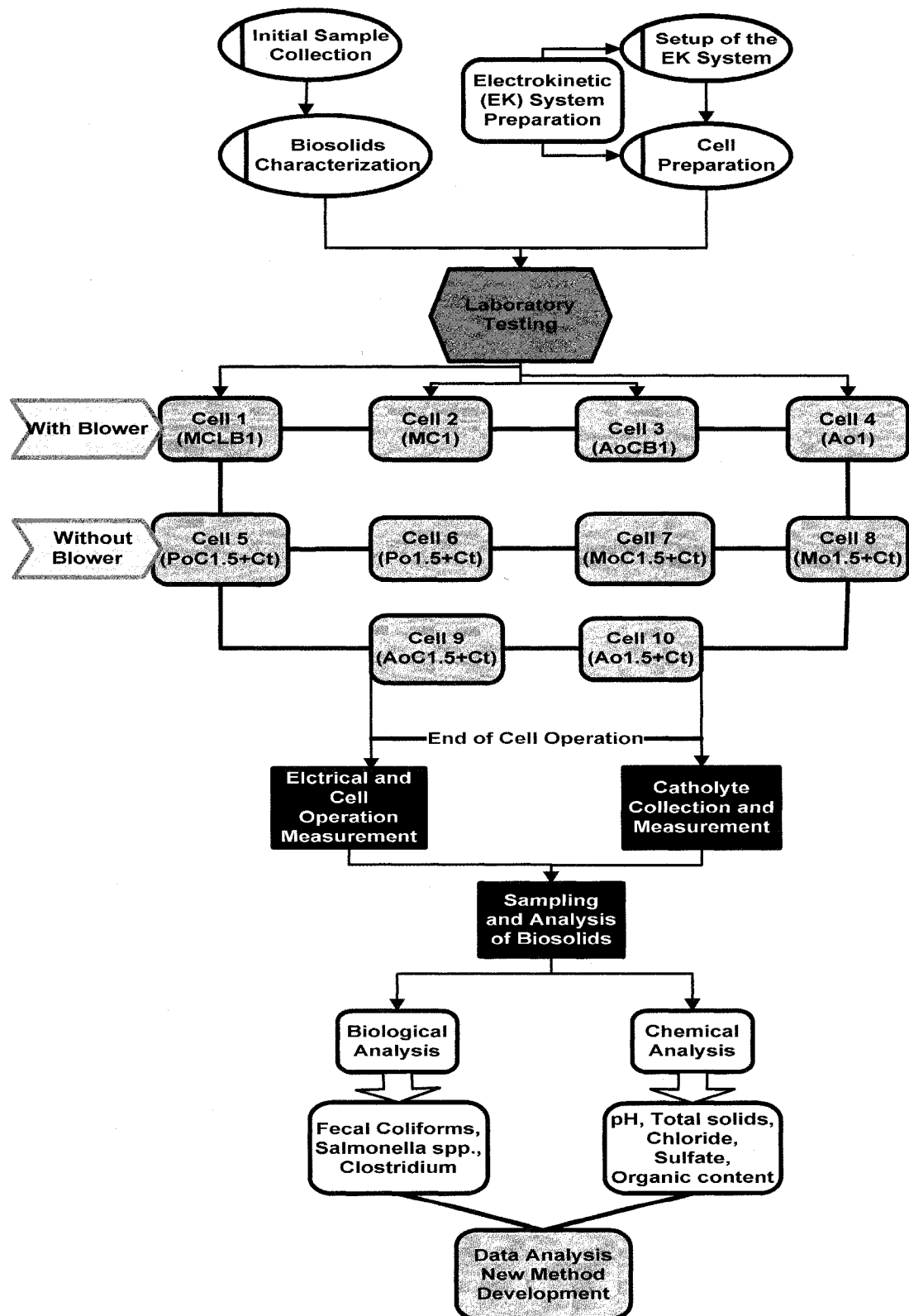


Figure 3-1 Flowchart of laboratory procedures

3.2 Sludge Characterization and Preparation

Biosolids samples were taken from both Auteuil Wastewater Treatment Plant (Laval, QC) and the Robert O. Pickard Environmental Centre (Ottawa, ON). The type of treatment in Auteuil Wastewater Treatment Plant includes biofiltration together with UV disinfection, with daily average flow rate of 38,305 m³/day, and maximum 65,000 m³/day. The major pollutants treated and efficiency of treatment is listed below in Table 3-1.

Table 3-1 Characteristics of the original wastewater sample from WWTP in Auteuil

Pollutants	Amount	Efficiency
BOD	3500 kg/d	80%
Suspended material	6208 kg/d	85%
Phosphorus (P)	91 kg/d	75%
Fecal coliforms	60,000 cfu/ml	99.9%

Note: cfu = colony forming unit

After preliminary treatment, sewage sludge is collected at the bottom of the primary clarifier. It enters secondary clarifier that applies an attached growth culture system. Biological treatment and chemical processes are employed for the secondary treatment by the attached growth culture system. Secondary sludge (attached growth culture) is transferred to thickening and dewatering unit at which polymers are added. After the dewatering processes, biosolids is conveyed to an incineration unit.

The general procedures of Auteuil Wastewater Treatment Plant are described in the following flowchart (Figure 3-2) from the Wastewater Treatment Plant, City of Laval. The mixture of primary and secondary sewage sludge sample from Laval was collected after the thickening procedure. The thickened sludge was placed in two 20-liter drums and two 4-liter plastic containers covered with ice during transportation. The sludge from

Robert O. Pickard Environmental Center in Ottawa was collected from four types of sludge processors which provided primary sludge, secondary sludge, anaerobic digestion sludge, and dewatered sludge cake.

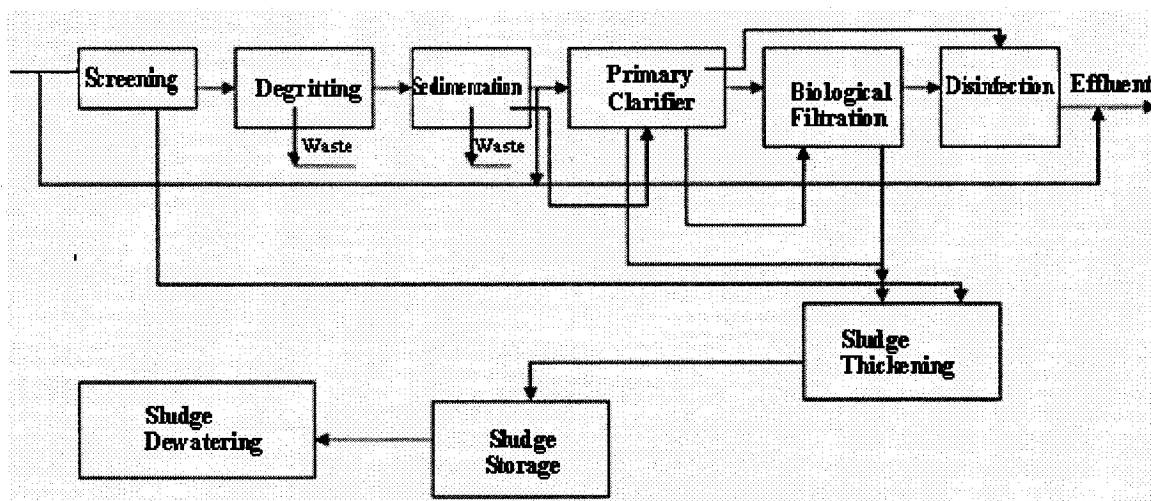


Figure 3-2 Treatment processes of Auteuil WWTP

The samples were stored in a refrigerator at 4°C in the Environmental Lab, where lab - scale experiments were conducted. Figure 3-3 illustrates the processes of wastewater treatment and sampling points in Robert O. Pickard Environmental Center in Ottawa.

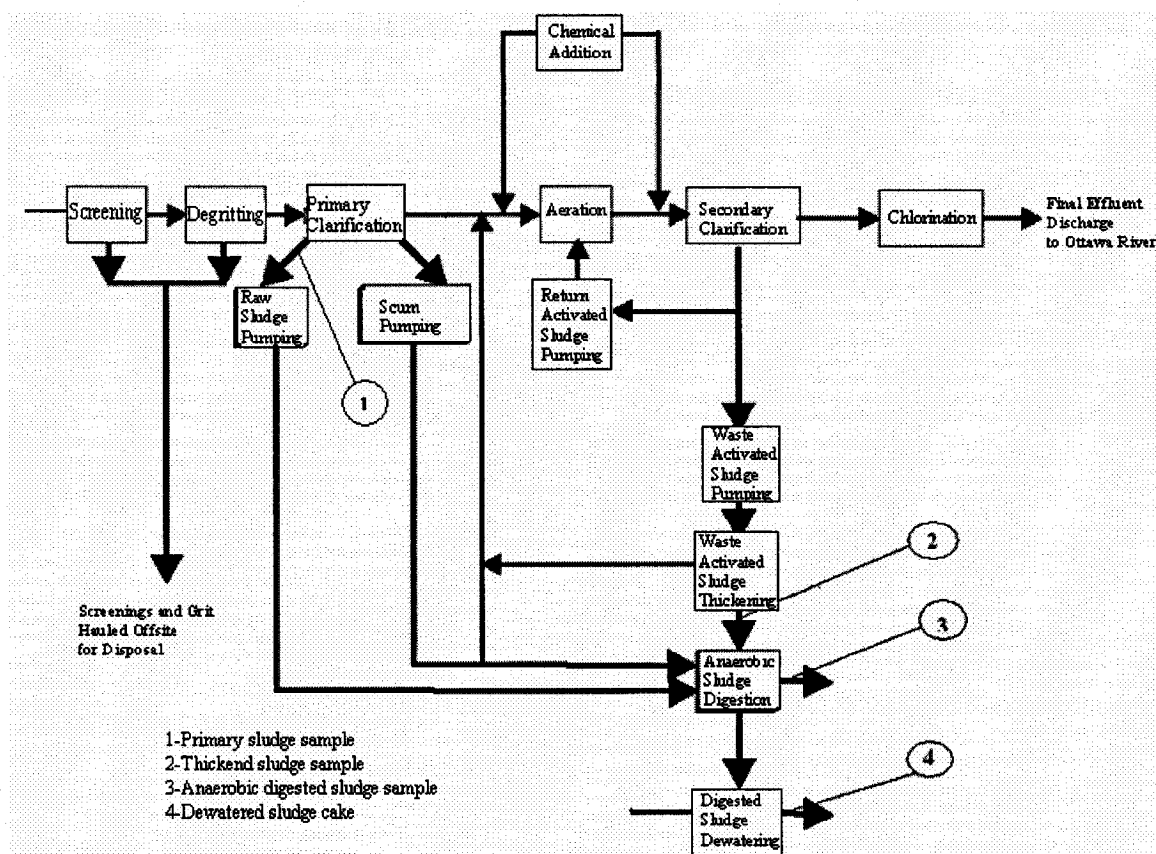


Figure 3-3 Schematic representation of wastewater treatment and sampling points in Robert O. Pickard Environmental Center

3.3 Initial Sludge Analysis

The characterization of biosolids is intended for obtaining the data of physical and chemical characteristics, and performing initial laboratory preparation. Standard methods have been applied for sludge characterization. The sludge source information is summarized in Table 3-1. The non-biological parameters of sludge characteristics are total solids, water content, fixed and volatile solids, and chloride ions concentration.

Apparatus and Reagents for Sludge Characterization

Muffle furnace for operation at 550⁰C (Isotemp, Fisher Scientific, 3000w)

Dry keeper, with a desiccant (Sanpla corp.)

Gravity oven, for operation at 103 to 105 °C (Lindberg/Blue M, 40-260°C)

Analytical balance (Denver Instrument, M-220, 10mg-220g)

Spectrophotometer (PerkinElmer, Lambda 40 UV/VIS spectrometer)

Graduated cylinder, 50 ~ 250-mL (Kimax)

Low-form beaker (class B or better) (Kimax)

Erlenmeyer flask, 250-ml

Buret, 50-mL

Stopwatch

Petri dishes, 100x20mm (diameter x height)

Low temperature incubator (Fisher Scientific)

Incubator (Hotpack, Watlow)

HPDE bottles, 250-mL (Nalgene)

Reagents

Potassium chromate indicator solution, 0.26 M

Standard silver nitrate titrant solution, 0.0141M

Standard sodium chloride solution, 0.0141M

Barium chloride, crystals, 20-30 mesh

Standard sulfate solution, 1.042 mM

M-FC medium:

Tryptose or biosate 10.0 g

Proteose peptone No.3 or polypeptone.....5.0g

Yeast extract.....3.0g

Sodium chloride, NaCl.....5.0g

Lactose.....	12.5g
Bile salts No.3 or bile salts mixture.....	1.5g
Aniline blue.....	0.1g
Agar (optional).....	15.0g
Reagent-grade water.....	1L

Notes*: M = mole/L, mM = mili mole/L

3.3.1 Total solids (TS), moisture (MO), volatile solids (VS) content

To determine the water content of biosolids, the standard method 2540-G (Clesceri, et al., 1998) was used. Biosolids sample was first placed in an evaporation dish in a water bath until dryness, and then placed in an oven at 103 °C for 1 hour. After that, the sample was placed in a desiccators cooled to room temperature and weighed. Repeat igniting (30 min), cooling, desiccating and weighing steps until weight change was less than 4% or 50 mg, whichever was less. The dried residue was cooled and weighed for further use. To determine fixed and volatile solids, firstly, the dried residue was transferred to a cool muffle furnace, and ignited at 550 °C for 1 h. Then it was cooled in a desiccator to balance temperature and the mass was determined. Repeat igniting (30 min), cooling, desiccating and weighing steps until weight change was less than 4% or 50 mg, whichever was less. Total solids, water content, and volatile solids content were calculated using the following equations:

$$\% \text{ TS} = (A-B)*100/(C-B)$$

$$\% \text{ VS} = (A-D)*100/(A-B)$$

$$\% \text{ MO} = 1 - \% \text{ TS}$$

Where: A = weight of dried residue + dish, mg

B = weight of dish, mg

C = weight of wet sample + dish, mg,

D = weight of residue + dish after ignition, mg

The results showed that the total solids content (TS) of sludge sample from Laval was about 2.5 % TS, while the TS contents of sludge samples from Ottawa varied from 2.45% TS of anaerobic digested sludge to 6.37% TS of secondary sludge. Accordingly, the water content varied from 93.63% to 97.55% in sludge samples from Ottawa. The TS and water content data of six sludge samples were summarized in Table 3-2.

3.3.2 Organic matter analysis

The organic matter content of biosolids samples were analyzed using the standard method 2540-G (Clesceri et al., 1998). The method is applicable to the determination fixed and volatile fractions in such solid and semisolid samples as sludge. Volatile solids content provides a rough approximation of organic matter present in sludge. The sludge sample had organic content varied from 16.6% of Ottawa primary sludge to 58.59% of Laval sludge. The organic matter data of six sludge samples were summarized in Table 3-2.

3.3.3 Chloride (Cl⁻)

Chloride concentration was determined by standard argentometric method 4500-Cl⁻ (Clesceri et al., 1998). Reagent potassium chromate was used as an indicator to determine the endpoint of the silver nitrate titration. Silver chloride was precipitated quantitatively before red silver chromate was formed. A 100-mL sample or a suitable portion of diluted

sample was prepared, and the pH was adjusted to 7-10 with NaOH. Then, 1.0 mL K_2CrO_4 indicator solution was added into the sample, following a titration process with standard $AgNO_3$ titrant (0.0141M) to a pinkish yellow end point. End-point recognition was consistent. The reagent blank volume was established by using distilled water instead of the sludge sample for the whole titration process. The concentration of chloride ion was calculated as follows:

$$\text{mg Cl}^-/\text{L} = (A-B) * N * 35450 / \text{mL sample}$$

Where: A = Consumed volume, mL

B = Blank, 0.3 mL

N = Normality of standard solution

The concentration of chloride ions in different sludge samples were summarized in Table 3-2.

3.3.4 Sulfate (SO_4^{2-})

Sulfate anion was determined using Turbidimetric method 4500- SO_4^{2-} E from standard method (Clescerl et al., 1998). The method is applicable in the range of sulfate concentration of 1-40 mg/L. Sulfate anions (SO_4^{2-}) form a suspension in the base of Barium Chloride ($BaCl_2$) – slight alkaline base. Light absorbance of the formation of milky-white suspension of barium sulfate ($BaSO_4$) was then measured by Lambda 20/40 UV/Vis spectrometer. Through the prepared calibration curve, sulfate concentration was then estimated. Reliability of calibration curve was measured by running a standard with every three or four samples. Correction for sample color and turbidity was made by running blanks to which $BaCl_2$ is not added. The calculation of concentration of sulfate

anions was used to plot standard curves. The concentrations of sulfate anions were summarized in Table 3-2.

3.3.5 Fecal Coliforms

Fecal coliform colony concentration was performed using the Standard method 9222D (Clesceri et al., 1998). Membrane filtration method was chosen for Fecal coliform colonies counting. The selection of sample volumes is to yield counts between 20 and 60 colonies per plate. M-FC medium was prepared for culturing. Petri dishes were submerged in a water bath at 44.5 ± 0.2 °C for 24 ± 2 hours. Fecal coliform colonies produced on M-FC medium are various shades of blue (Appendix Figure A-15). Pale yellow colonies may be atypical E.coli; nonfecal coliform colonies are gray to cream-colored. The colony density was calculated from the sample quantities that produced membrane Fecal coliform counts within the desired range of 20 to 60 Fecal coliform colonies. The following equation was used for Fecal coliform density.

Fecal coliforms per gram dry weight

$$= \text{colonies counted} / [(\text{dilution chosen}) * (\% \text{ dry solids})]$$

Table 3-2 Summary of sludge types and sampling locations

Location	Laval	Laval	Ottawa
Facility	Auteuil Wastewater Treatment Plant	Auteuil Wastewater Treatment Plant	Robert O. Pickard Environmental Center
Types of sludge sample	Combined thickened sewage sludge	Combined thickened sewage sludge	1. Primary sludge 2. Aerobic activated sludge 3. Anaerobic digested sludge 4. Dewatered sludge cake

Table 3-3 Initial characteristics of sludge parameters

Parameters	Total Solids (%)	Fixed Solids (%)	VS /OM (%)	Moisture Content (%)	Sulfate (mg/kg dry sludge)	Chloride (mg/kg dry sludge)	COD (mg/L)	pH	FC cfu/mL
Sample									
Combined sludge (Laval)	2.41	58.59	41.41	98.59	17399	10531	1864	6.65-7.23	2.9 E+7
Primary (Ottawa)	3.78	16.59	83.41	96.22	99682	2702	1866	6.47	0
Secondary (Ottawa)	6.37	29.79	70.21	93.63	588609	1443	1938	6.61	0
Anaerobic digested (Ottawa)	2.45	41.59	58.41	97.55	39564	6950	4388	6.71	0
Dewatered sludge cake (Ottawa)	28.76	47.98	52.02	71.24	---	---	---	---	---

3.4 Experimental Setup and Cell Configuration

The cells of electrokinetic system (EK) were designed to facilitate the analysis and measurement of EK parameters and sludge characteristics and to provide the simplicity, accuracy and convenience for system control and sampling process. All EK cells were uniform in the experiment.

3.4.1 Cells

Rectangular cells made from rigid polyethylene were placed above a wood frame. Experimental cells had the same dimensions (length = 22cm, width = 5.3 cm, depth = 5.0 cm). Cell volume was about 0.58 liter each. Cathodes and anodes were made from perforated stainless steel tubes. The distances between the centers of two electrodes were 18 cm. Each electrode was covered with stainless steel mesh (200). Configuration of one electrokinetic cell was displayed in Figure 3-4. Ten control cells without electrodes having length of 11cm, width of 5.3 cm, and depth of 5.0 cm were also prepared.

3.4.2 Catholyte Collection

250mL bottles were attached to the individual cathode of each cell in order to evaluate catholyte through the extension of each cathode. Bottles were made from high-density polyethylene (HPDE) from Nalgene and each bottle was narrow-mouthed. This system permitted to collect liquid transported due to gravity and electroosmosis from cathode area on a daily basis.

3.4.3 Power Supply

One direct current power supply was connected to each cell with electrical wires. Silver probe - electrodes were placed on the top of each cell connecting cathode and anode. Electrical parameters along the distance of cathodes and anodes were monitored by the silver probes.

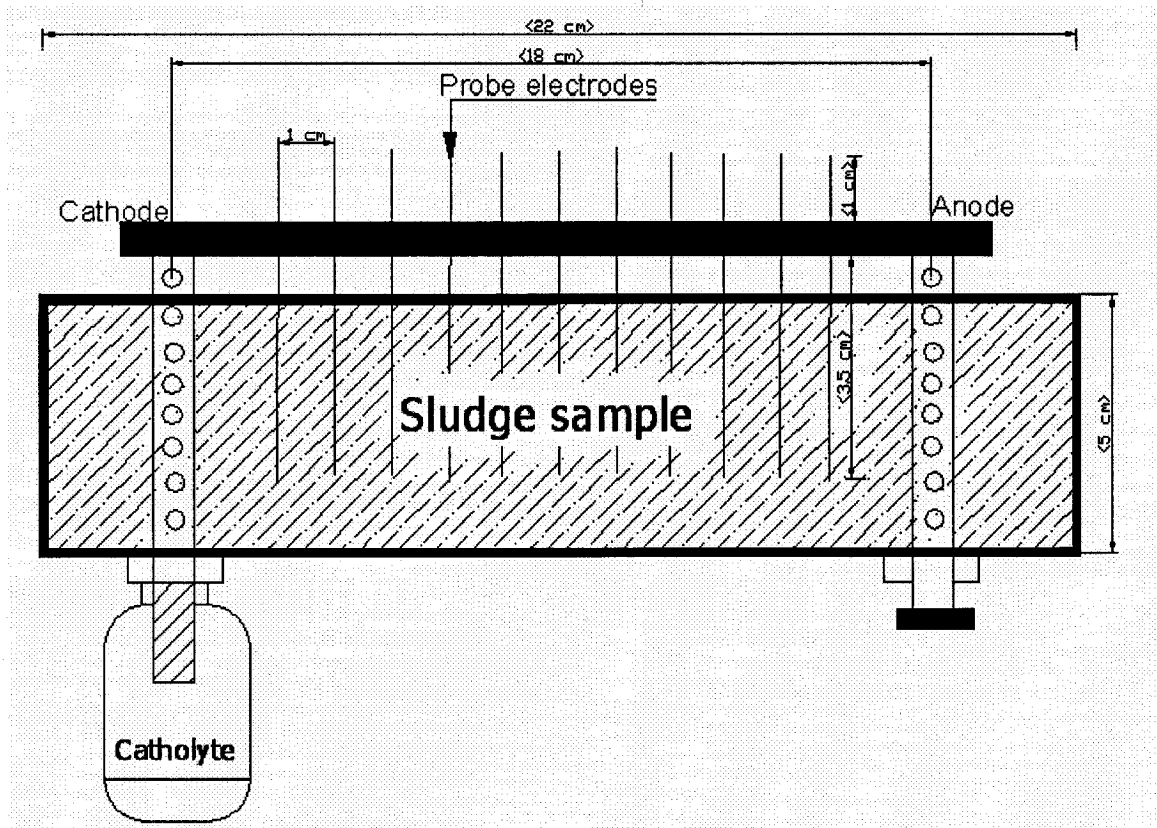


Figure 3-4 Configuration of electrokinetic cell

The probe was inserted into the cell to a depth of 4 cm. However, a 1-cm portion of probes remained above the cell surface. Silver probe-electrodes were lined vertically in a Plexiglas base on top of electrodes (Figure 3-4). Respective electrical potentials were applied to each cell to set the constant value of 1 V/cm or 1.5 V/cm. The longitudinal voltage distribution throughout the cell was monitored directly by daily measurements of

the potential difference between the electrodes and each probe-electrode. Potential measurements were carried out every 24 hours during an entire experimental procedure, around 9 days.

3.5 Apparatus, Reagents and Equipment

This section provides a summary of apparatus, reagents and equipment that were used in the experiment.

Cell configuration apparatus:

- Polyethylene cells, 10
- Stainless steel electrodes ($D_{\text{out}} = 1.0 \text{ cm}$, $D_{\text{in}} = 0.6 \text{ cm}$), covered with stainless steel mesh (200)
- Silver probe – electrodes
- 250-mL plastic bottles (Nalgene)
- DC power supply (Xantrex, XKW 40-25)
- DT-830B digital multimeter
- Sunbeam mixer (Mixmaster, stand mixer, 3.5L and 1.4L)

Microbiological measurement apparatus

- Incubator (Hotpack, watlow)
- Balance (Monobloc, 0.5-1510g)
- Rock'n Roller, 180 RPM
- Centrifuge (IEC, HN-SII)
- Vacuum filtration assembly (KNF Neuberger Vacuum pump)
- Automatic pipette, 1 ml tips

Reagents

- Material and culture media
- Buffered Peptone Water
 - 10 g of peptone, 5 g of sodium chloride, 9 g of disodium hydrophosphate ($\text{Na}_2\text{HPO}_4 \times 12 \text{ H}_2\text{O}$), 1.5 g potassium dihydrogen phosphate (KH_2PO_4) in 1 L sterile, deionized water and mix on magnetic stirrer unit until with the use of sterile, magnetic bar. Sterilize using a sterilization filter unit (cold sterilization) with a 0.2 μm membrane filter (Gelman TM brand or equivalent).
- Rappaport Vassiliadis (RV) broth
- Xylose-Lysine-Tergitol (Niaproof) 4(XLT 4) agar
- Brilliant Green Sulfa (BGS) agar
- Phosphorus buffer solution (1mM)
- Ammonia salts (13.4 g/L total sludge volume)

3.6 Electrokinetic System Testing Procedure

Electrokinetic system was applied using the experimental set-up with DC power supply. Physical, chemical and microbiological analyses were performed after the disconnection of the power supply for sludge sample. Chemical and biological parameters were analyzed for the catholyte on a daily basis. An entire experiment consisted of three steps. Four EK cells and four control cells were performed in the first, and six EK cells and six control cells were performed in the second and third batch. The conditions of ten EK cells were summarized in Table 3-4.

Table 3-4 Cell conditions of the experiments

Cell No.	Cell code	Sludge samples	Drying technique	Voltage gradient (V/cm)	Conditioner addition	Bacteria inoculation
1	MCLB1	Mixed sludge, (Primary + Secondary) Laval	EK + Blower	1	Yes	<i>Salmonella</i> spp.
Con 1	Con 1	Mixed sludge, (Primary + Secondary) Laval	Blower	0	Yes	<i>Salmonella</i> spp.
2	MLB1	Mixed sludge, (Primary + Secondary) Laval	EK + Blower	1	No	<i>Salmonella</i> spp.
Con 2	Con 2	Mixed sludge, (Primary + Secondary) Laval	Blower	0	No	<i>Salmonella</i> spp.
3	AoCB1	Anaerobic digested sludge, Ottawa	EK + Blower	1	Yes	<i>Salmonella</i> spp.
Con 3	Con 3	Anaerobic digested sludge, Ottawa	Blower	0	Yes	<i>Salmonella</i> spp.
4	AoB1	Anaerobic digested sludge, Ottawa	EK + Blower	1	No	<i>Salmonella</i> spp.
Con 4	Con 4	Anaerobic digested sludge, Ottawa	Blower	0	No	<i>Salmonella</i> spp.
5	PoC1.5+Ct	Primary sludge, Ottawa	Electrokinetics	1.5	Yes	<i>Salmonella</i> spp., <i>Clostridium</i>
Con 5	Con 5	Primary sludge, Ottawa	No	0	Yes	<i>Salmonella</i> spp., <i>Clostridium</i>
6	Po1.5+Ct	Primary sludge, Ottawa	Electrokinetics	1.5	No	<i>Salmonella</i> spp., <i>Clostridium</i>
Con 6	Con 6	Primary sludge, Ottawa	No	0	No	<i>Salmonella</i> spp., <i>Clostridium</i>

Table 3-4 Cell conditions of the experiments (cont'd)

7	PoC1.5+Ct	Mixed primary and secondary sludge, Ottawa	Electrokinetics	1.5	Yes	<i>Salmonella</i> spp., <i>Clostridium</i>
Con 7	Con 7	Mixed primary and secondary sludge, Ottawa	No	0	Yes	<i>Salmonella</i> spp., <i>Clostridium</i>
8	Mo1.5+Ct	Mixed primary and secondary sludge, Ottawa	Electrokinetics	1.5	No	<i>Salmonella</i> spp., <i>Clostridium</i>
Con 8	Con 8	Mixed primary and secondary sludge, Ottawa	No	0	No	<i>Salmonella</i> spp., <i>Clostridium</i>
9	AoC1.5+Ct	Anaerobic digested sludge, Ottawa	Electrokinetics	1.5	Yes	<i>Salmonella</i> spp., <i>Clostridium</i>
Con 9	Con 9	Anaerobic digested sludge, Ottawa	No	0	Yes	<i>Salmonella</i> spp., <i>Clostridium</i>
10	Ao1.5+Ct	Anaerobic digested sludge, Ottawa	Electrokinetics	1.5	No	<i>Salmonella</i> spp., <i>Clostridium</i>
Con 10	Con 10	Anaerobic digested sludge, Ottawa	No	0	No	<i>Salmonella</i> spp., <i>Clostridium</i>

Legend: Con – Control cell

3.6.1 Sampling Preparation and System Connection

The volume of 580 mL well-mixed sludge sample (using mechanic mixer) from the wastewater treatment plant with or without conditioner was poured into each cell. During the operation, the liquid from cathode area was collected from the connection of extended cathodes and the attached bottles. The electrodes were covered by the stainless steel mesh 200. The cell conditions were summarized in the next chapter.

After pouring the biosolids into the cells, the probe electrodes were inserted into the cell and the cover of the cells were placed on top of it. The DC power supply was connected to the cells and the desired voltage gradient was set as 1.0 or 1.5 V/cm.

3.6.2 Measurement of Electrical Parameters and Catholyte during the Experiment

The electrical potential along the distance between the cathode and anode was monitored during the experiment. Readings were obtained by using DT-830B Digital Multimeter. Each reading represents the electrical potential between the cathode and the subsequent probe electrode. The electrical current (I) and potential (V) at each cell probe electrode were measured daily. The resistance and its variation along with the distance from the cathode were calculated.

$$R = V/I$$

Where: R = resistance (Ohm)

V = electrical potential (V)

I = electrical current (A)

The catholyte collected from cathode in each cell was stored in 250-mL HDPE Nalgene bottles and kept in the refrigerator at the temperature of 4°C. The nature of catholyte in terms of pH, volume, color, and *Salmonella spp.* and Fecal coliforms concentration was recorded on a daily basis.

3.6.3 Sampling, Analyses, and Measurements after the EK Experiment

After EK tests, dewatered sludge was divided to sixteen or thirteen slices with around 1 cm width in each cell. The large numbers of the cell samples were necessary to provide

an accurate pH and the content of microorganism distribution between electrodes in each electrokinetic cell. Figure 3-7 shows the schematic representation of cell – contained biosolids sampling. Three samples from each Control Cell were randomly taken for further analyses.

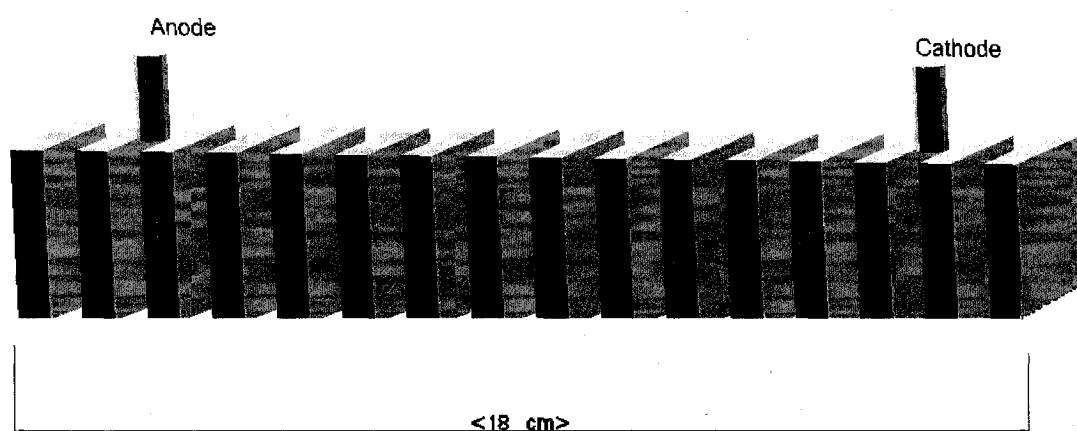


Figure 3-5 Scheme of the biosolids sampling

Each slide sample was separately wrapped in a plastic bag and sealed well. All samples were preserved in refrigerator at 4⁰C.

The middle portion of the sludge was used for the analysis of moisture content, organic matter content. The left and right portions of sludge sample were used for the analysis of pH, chloride and sulfate anion contents, Fecal coliforms, and *Salmonella spp.*

3.6.4 Measurement of Moisture Content

The standard method 2540-G (Clescerl et al., 1998) was applied to determine the total solids content of the biosolids. Biosolids samples were oven dried at 105⁰C for 24 hours, and placed into a desiccator to cool. After weighing, the total solids content (TS), volatile

solids content (VS), moisture content (MO) was calculated following formulas described in Chap 3.3.1.

3.6.5 Microbiological Test

At the beginning of the experiments, the enumeration of *Salmonella spp.* and Fecal coliforms tests were carried out to determine whether there were enough live bacteria cell in the original sludge sample or not. If there are not enough, the spiking procedures were taken into consideration.

3.6.5.1 Analysis of *Salmonella spp.* before the EK System

Detection and enumeration of *Salmonella spp.* in sludge were determined according to a trial procedure obtained from training in the Department of Food Science, University of Manitoba (Bujoczek, 1999). Two batch tests were conducted. One is with phosphate buffer solution; the other is with buffered peptone water, which is a pre-enrichment media to recovery the *Salmonella spp.*

Salmonella spp. enumeration was carried out on the inoculated mixture solution containing RV broth and sludge sample before and after experiment. Series of decimal dilutions were prepared in phosphate buffer solution and 0.1 or 0.3 mL sample of each dilution were plate out on Brilliant Green agar (BGA). After incubation at 37°C for 24 hours, the Colony Forming Units (cfus) were counted. *Salmonella spp.* colonies produced on the BGA surface were red-pink-white opaque coloured colonies with black center surrounded by brilliant red zones in the agar (Appendix Figure A-13).

The first batch was carried out with the following procedures:

1. 1mM buffer solution with $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$ was prepared and 9 mL of the solution was transferred into each of 10 culture tubes.
2. 1 mL sludge sample (Ottawa) was pipetted into first dilution tube, and then mixed with 9 mL phosphate buffer solution. The mixture was in vortex tube and shaken thoroughly, then 1 mL of the mixture was transferred from the vortex tube into the second dilution tube. Repeatedly vortex and mix tube thoroughly until it reached 10^6 -dilution.
3. 1 mL from 10^3 , 10^4 , 10^5 and 10^6 dilutions was pipetted into each plate, and a duplicate was made.
4. 0.1 or 0.3 mL of solution from each serial was spread on the surface of plate evenly using spreader.
5. The plates were incubated at 37°C for 24h.
6. CFU (colony forming unit) of *Salmonella spp.* was counted from each plate.
7. All wastes were autoclaved after finishing.

Results showed that there was no *Salmonella spp.* colony forming unit in those plates. It can be concluded that *Salmonella spp.* were inactivated in sludge sample.

The second batch used buffered peptone water, a non-selective pre-enrichment media to recover injured *Salmonella spp.* Three samples (primary sludge (OW), anaerobic digested sludge (OW), sludge (LA)) were pre-enriched in Buffered Peptone Water (BPW) for 24 hour at 37°C ; where after 1 mL of sludge sample were added to 249 mL Rappaport Vassiliadis Broth(RVB) in incubator at 42°C for 24 hours. RVB was inoculated on Xylose-Lysine-Tergitol 4 (XLT 4) agar and Brilliant green agar (BGA), and agar plates were incubated at 37°C for 24 hour. Red-pink-white opaque colored colonies surrounded

by brilliant red zones in the agar most probably *Salmonella spp.* (but not *Salmonella typhi*) were observed (Figure A-13). Then *Salmonella spp.* was verified biochemically. The results showed that there were enough *Salmonella spp.* colony forming unit detected in the plates which proved that the *Salmonella spp.* were recovered from sludge sample by non-selective and selective enrichment nutrient.

3.6.5.2 Analysis of *Salmonella spp.* after the EK System

After the disconnection of EK power supply system, the sludge sample slices divided from each EK cell were mixed with 30 mL distilled water in centrifuge tubes and shaken for 24 h. After shaking, the samples were centrifuged at 3000 RPM for 20 minutes. The supernatant was collected for the *Salmonella spp.* detection. A serial of decimal dilution was made with phosphorus buffer solution, following the spread plate method. *Salmonella spp.* was confirmed by agglutination test.

3.6.6 Measurements of Fecal Coliform after the EK System

The sludge sample slices divided from each EK cell were mixed with 30 mL distilled water in centrifuge tubes and shaken for 24 h. After shaking, the samples were centrifuged at 3000 RPM for 20 minutes. The supernatant was collected for the *Salmonella spp.* detection. A serial of decimal dilution was made with phosphorus buffer solution, following the membrane filtration method. Fecal coliform colony forming unit was counted on the surface of M-FC media.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the description of experimental results, analyses, and discussion. Ten electrokinetic (EK) cells were set up for the experiments. In order to assess efficiency of simultaneous dewatering, disinfection, and other applications of EK system, total solids contents (TS), Fecal coliforms (FC), pH, *Salmonella spp.*, and anions concentrations were analyzed. Generally, the cell content was divided into 16 sections between electrodes, and samples from combined sections were taken for analysis. The position of the combined sections in Cells #1 to #8 is shown in Table 4-1. Note that Cells #9 and #10 were divided into 12 sections.

Table 4–1 Distribution and description of sections in Cells #1 to #8

Number of section	Position
0-1	Back anode
1	Anode
1-3	Near anode area
3-6	Middle anode area
6-8	Middle anode area
8-10	Middle of the cell
10-12	Middle cathode area
12-14	Near cathode area
14-16	Cathode area
16	Cathode

4.1 Total Solids Content

The moisture and total solids contents were analyzed in each EK cell and each control cell. The analysis of the total solids content in control cells permitted assessing the impact of a blower on the EK dewatering of sludge; and subsequently on the moisture content. The analyses were performed following the method described in Chapter 3.6.4.

In Cell #1 (MCLB1), the total solid (TS) content was much higher than that of the original sample. Figure 4-1 shows the trend of solid content that increases toward the anode.

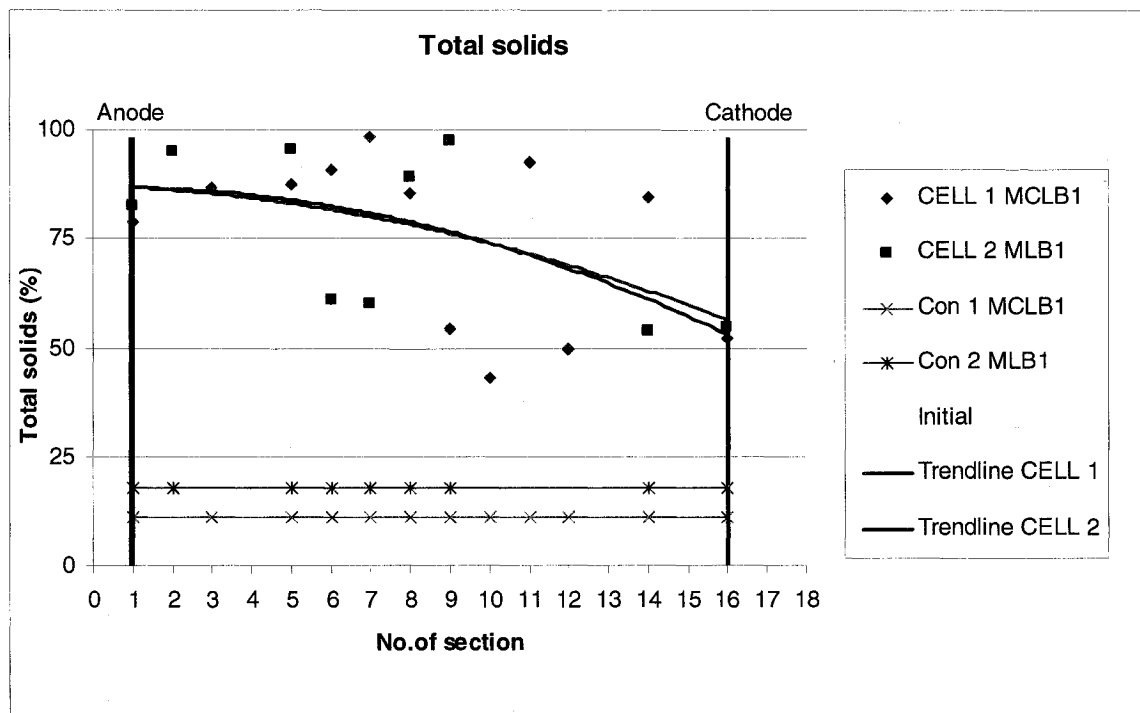


Figure 4-1 Total solids content in Cells #1 and #2

The highest total solids content of 98.5% was in the middle of the cell. The total solids content was about 28% higher at the anode area than that at the cathode area. The uneven

distribution of total solids was due to the crack formation in the cell after EK treatment illustrated in Figure 4-2.

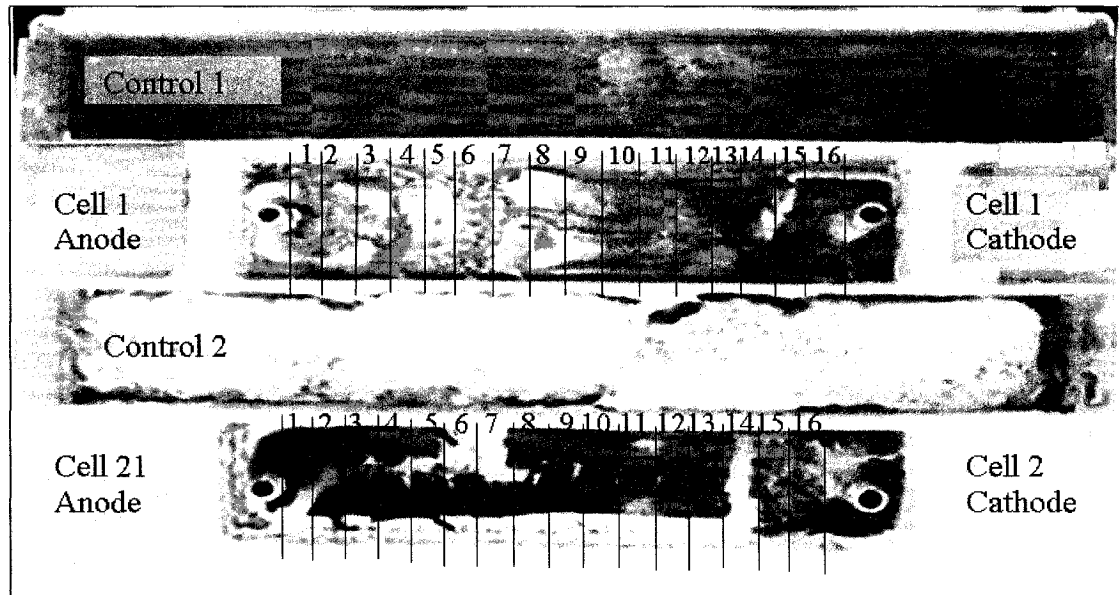


Figure 4-2 Crack formation in Cells #1 and #2

In Cell #2 (MLB1), the TS content distribution between electrodes had a similar trend as that in Cell #1. At the anode area, the highest value reached 94.8%. The TS content in the cathode was as high as 55%. The maximum and minimum solids content in Cell #2 were 97.5% and 54.1%, respectively. Due to the crack formation along the cell (Fig. 4-2), the electroosmotic flow was not uniform in the entire mass of sludge, subsequently a variation of the TS contents was observed in both cells.

The analyses showed that Control #1 and Control #2 had 11.04% and 18.01% of total solids, respectively. Since the initial TS content was 2.4%, both control cells increased the TS content between 4.5 and 7 times due to using the blower system; while the application of electrokinetics combined with blower system increased the TS content almost 50 times. Comparison of the solids content between Cells #1 (MCLB1) and #2

(MLB1) and the Control Cells shows that the electrokinetic process with conditioner has an effect on the dewatering of biosolids, particularly in cathode area. The total solids content was higher at the anode than at the cathode.

Figure 4-3 illustrates the total solids content in Cells #3 (AoCB1) and #4 (AoB1). In Cell #3 (AoCB1), the average solids content was much higher than that of the original sample. In general, the TS content increased toward the anode. At the anode and cathode, the TS content were 75.8% and 33.3%, respectively. In Cell #4 (AoB1), the variation of solids content was in the similar trend of Cell #3 (AoCB1). The crack formation in Cells #3 and #4 caused the variance of the total solids content in cells (Figure 4-4).

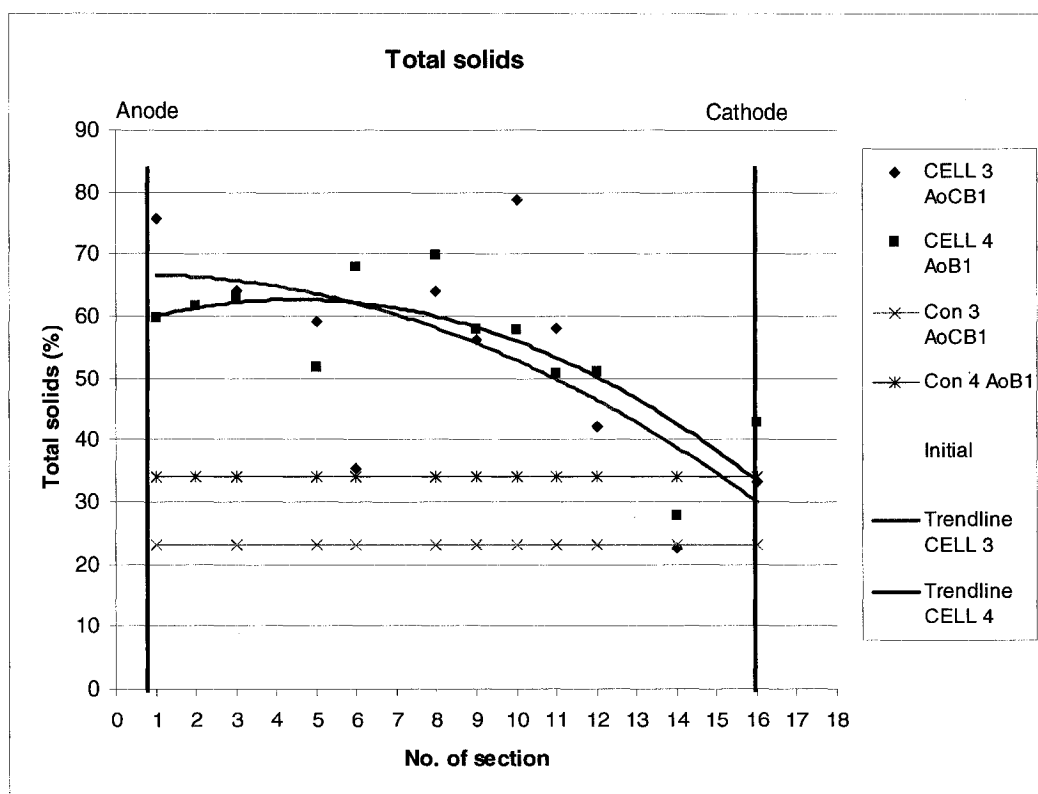


Figure 4-3 Total solids content of Cells #3 and #4

The Control #3 and #4 had 23.3 % and 34.1% TS, respectively. Both Control Cells contained higher total solids content than the original sample, which had only 2.45% total solids. It was due to the use of the blower system. Comparison of the solids content between Cells #3 (AoCB1) and #4 (AoB1) shows that the conditioner has an impact on electrokinetic process in the area of cathode.

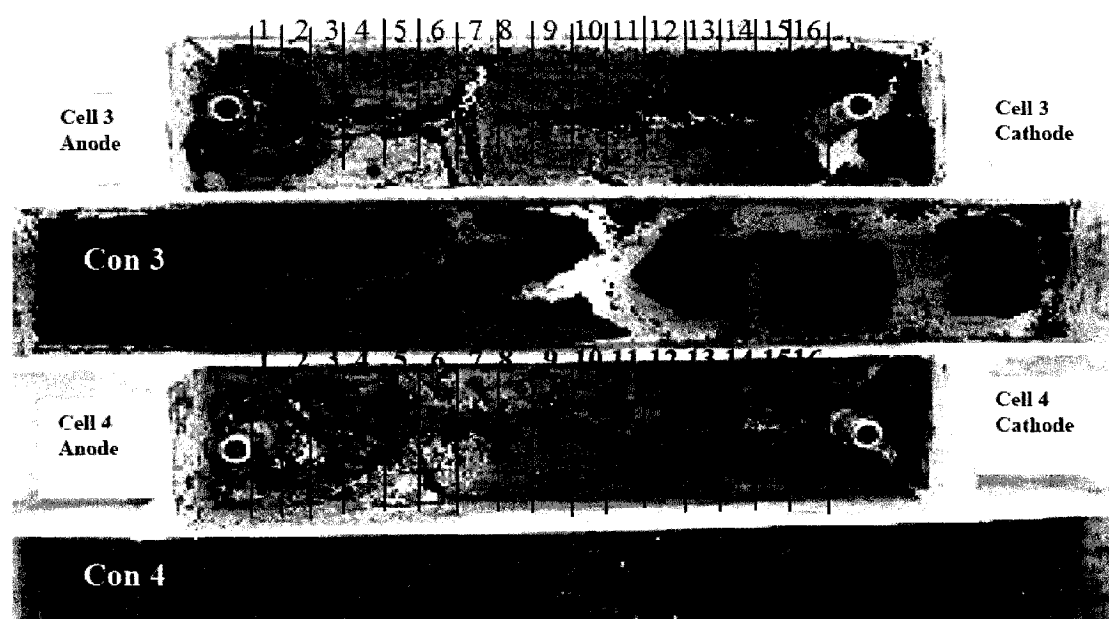


Figure 4-4 Crack formation in Cells #3 and #4

Figure 4-5 illustrates the total solids content in Cells #5 and #6. In Cell #5 (PoC1.5+Ct), the maximum and minimum solids content were 86.1% (at near anode area) and 61.7% (at middle cathode area). In Cell #6 (Po1.5+Ct), the variation of total solids content was on the similar trend with Cell #5. The maximum and minimum solids content were 86.1% at near anode area and 64.6% at middle cathode area. No crack formation was observed in both cells.

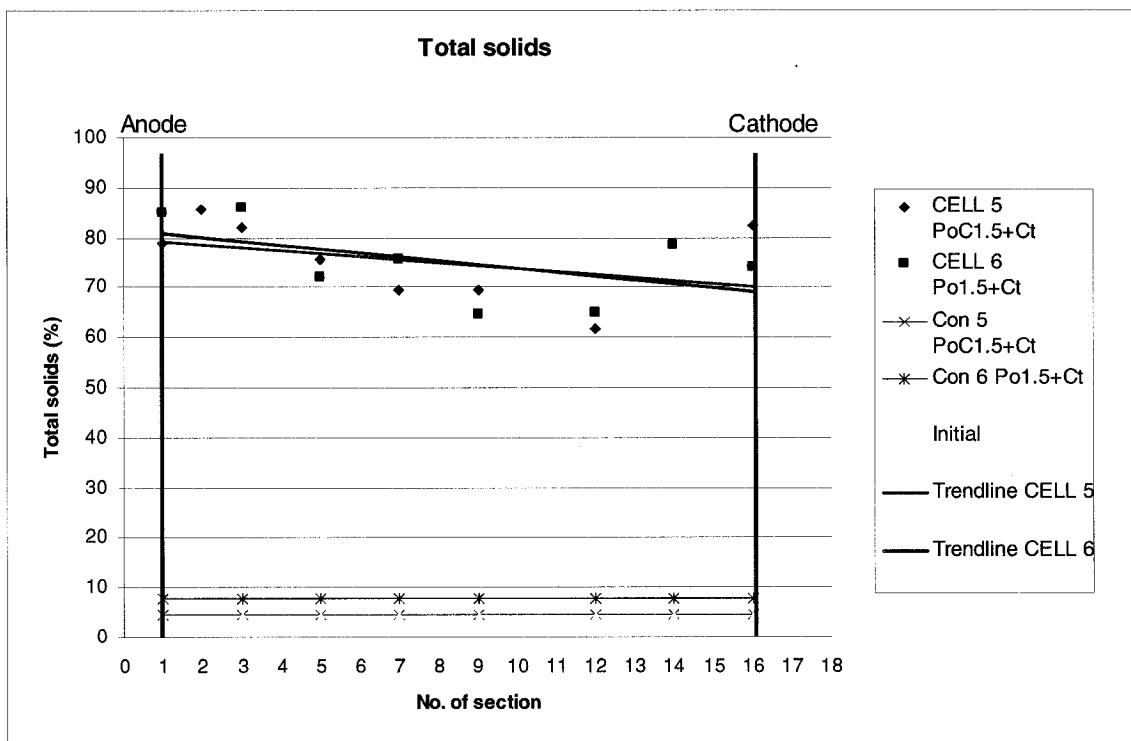


Figure 4-5 Total solids content of Cells #5 and #6

The Control #5 and #6 cells had 4.66 % and 7.85 % total solids, respectively. Both of the two control cells contained higher TS content than the original sample, which had only 3.78% TS. It was due to the presence of the ventilation system in the fume-hood.

Figure 4-6 illustrates the total solids content in Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct). In Cell #7 (MoC1.5+Ct), the total solids content increased from cathode

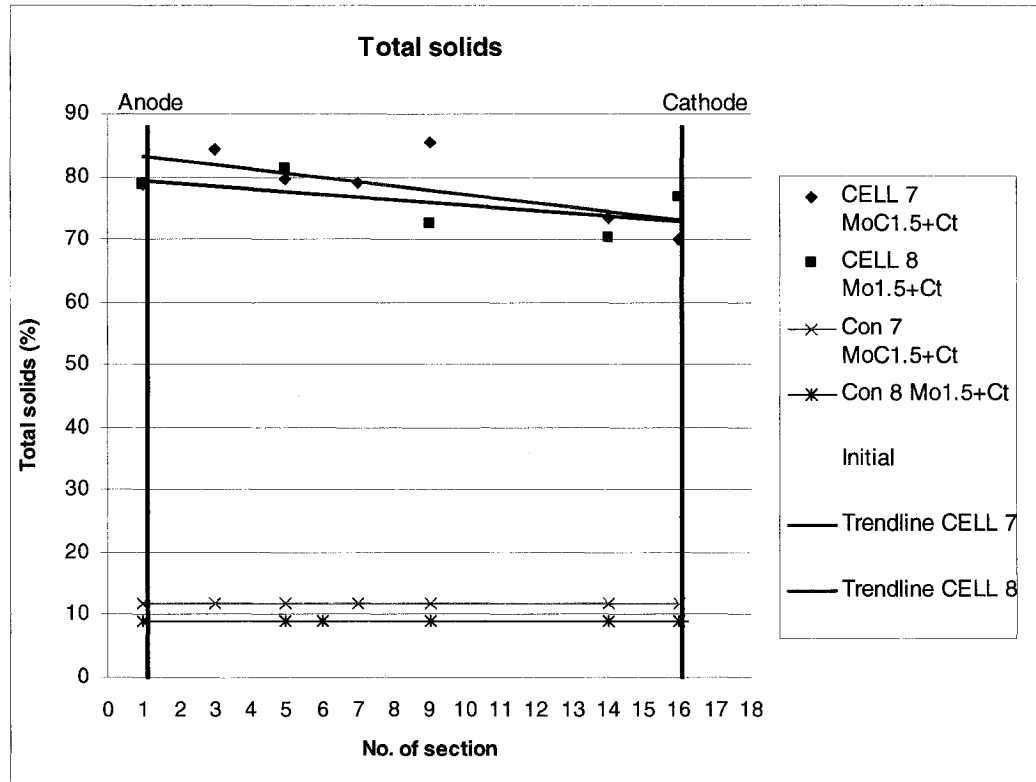


Figure 4-6 Total solids content of Cells #7 and #8

toward the anode. Highest total solids content was in the middle section with 85.4% TS. In Cell #8 (Po1.5+Ct), the total solids content was increased toward the anode. The maximum and minimum solids content were 81.2% at near anode and 70.4% at cathode area.

The Control #7 and #8 cells had 11.8 % and 8.9 % total solids, respectively. Both control cells contained higher total solids content than the original sample, which had 5.45% total solids. It was due to the presence of the ventilation system in the fume hood.

Comparison of the solids content between Cells #7 (PoC1.5+Ct) and #8 (Po1.5+Ct) shows that the electrokinetic process with conditioner had higher efficiency in biosolids dewatering. The total solids content was higher in the anode than in the cathode area.

Figure 4-7 illustrates the total solids content in Cells #9 and #10.

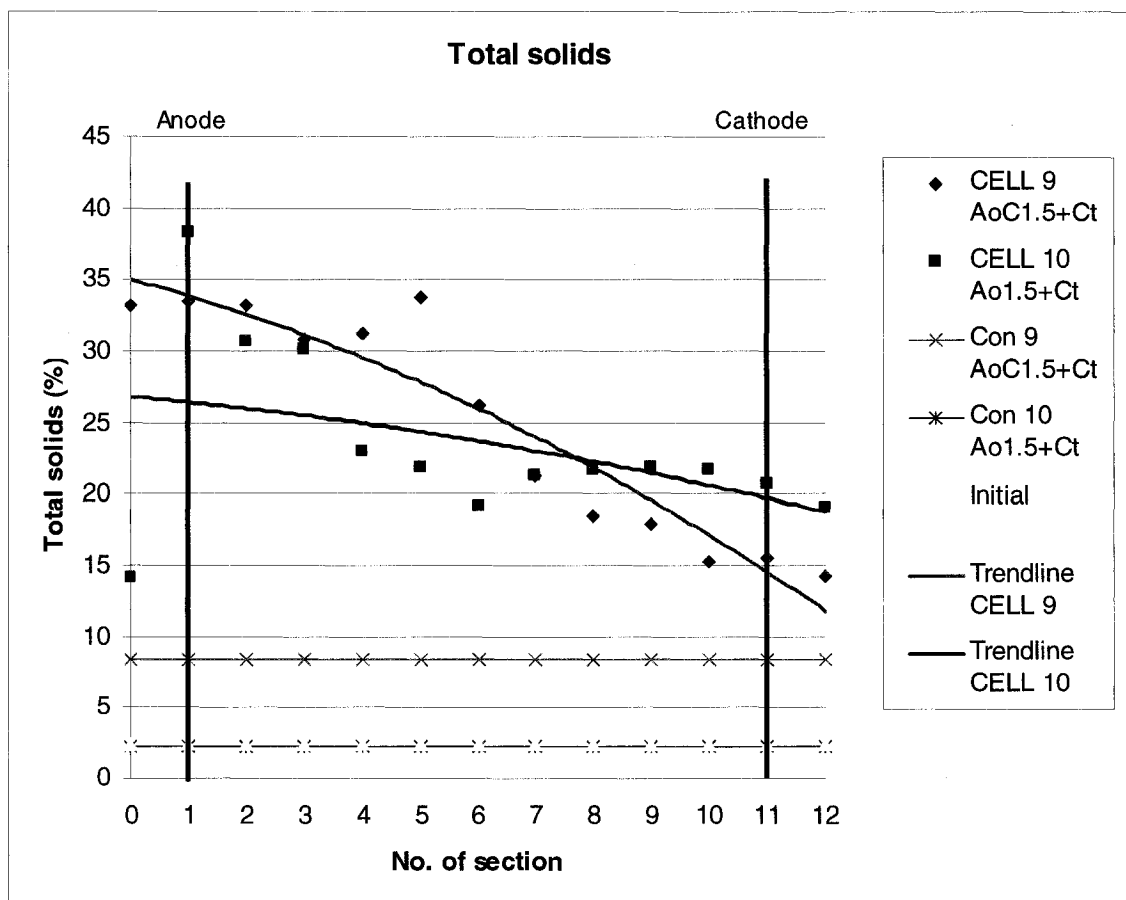


Figure 4-7 Total solids content of Cells #9 and #10

In Cell #9 (AoC1.5+Ct), the sample was anaerobically digested sludge with addition of conditioner. The total solids content was higher at the anode with 33.5% TS than at cathode with 15.5% TS. It decreased gradually toward cathode area to the lowest point at the back of cathode with 14.3% TS. In Cell #10 (Ao1.5+Ct), the total solids content decreased toward cathode gradually. The highest TS was at the anode with 38.3% and the lowest was at the cathode with 20.8%.

The Control #9 and #10 cell had 8.40 % and 2.45 % total solids, respectively. Control #9 contained higher total solids content than the original sample, which had only 2.45% total solids. It was due to use of a conditioner.

4.2 pH Value

Figures 4-8 to 4-12 illustrate the pH variation from anode to cathode after the electrokinetic treatment. The pH value increased along the cell from anode toward cathode area. The lowest pH value was at the anode area and the highest pH value at the cathode area in all ten cells. Acidic front was observed extending from anode to the middle of cells. The mixed sludge had more extended acidic front than the primary sludge. A more expanded acidic front was observed in the case of anaerobic sludge. The acidic front also was bigger when a higher voltage gradient was applied. The acidic front was less significant where the conditioner was used. All Control Cells showed the pH value close to neutral or slightly above neutral. Corrosion at the anode area was evidently observed in Cells #1, 3, 5, 7, 9 within the acidic front. No impact of the corrosion on the disinfection and dewatering efficiency was expected.

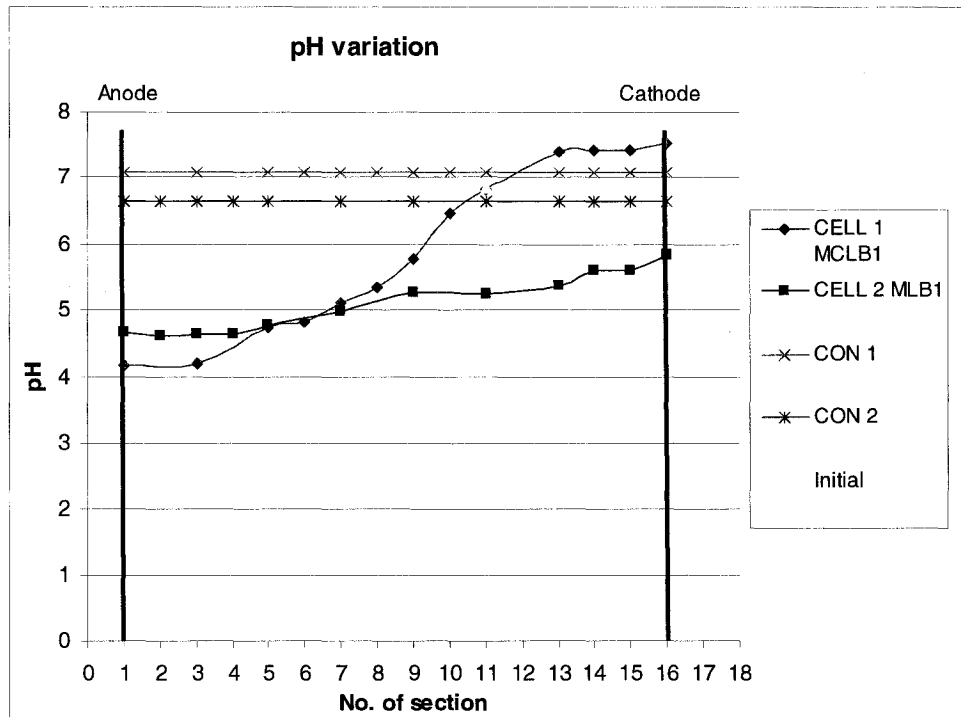


Figure 4-8 pH variation in Cells #1 and #2

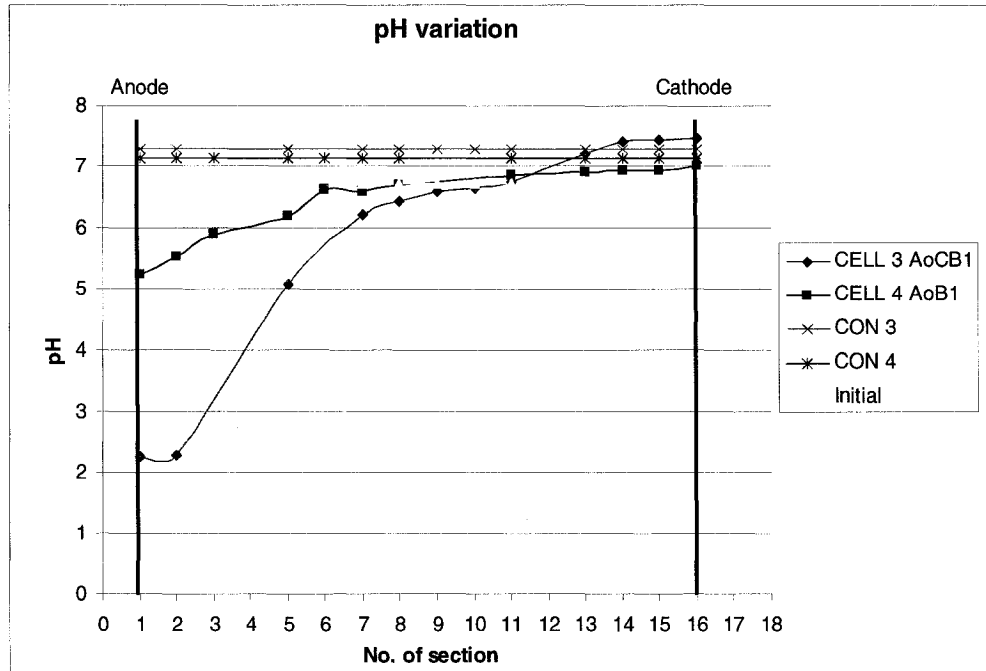


Figure 4-9 pH variation in Cells #3 and #4

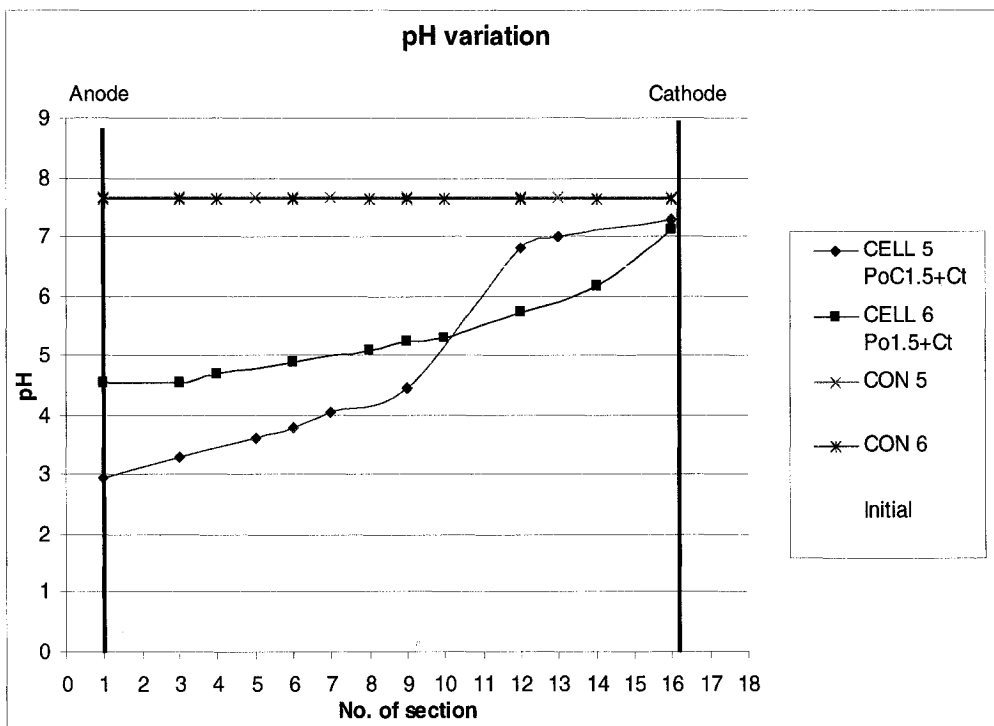


Figure 4-10 pH variation in Cells #5 and #6

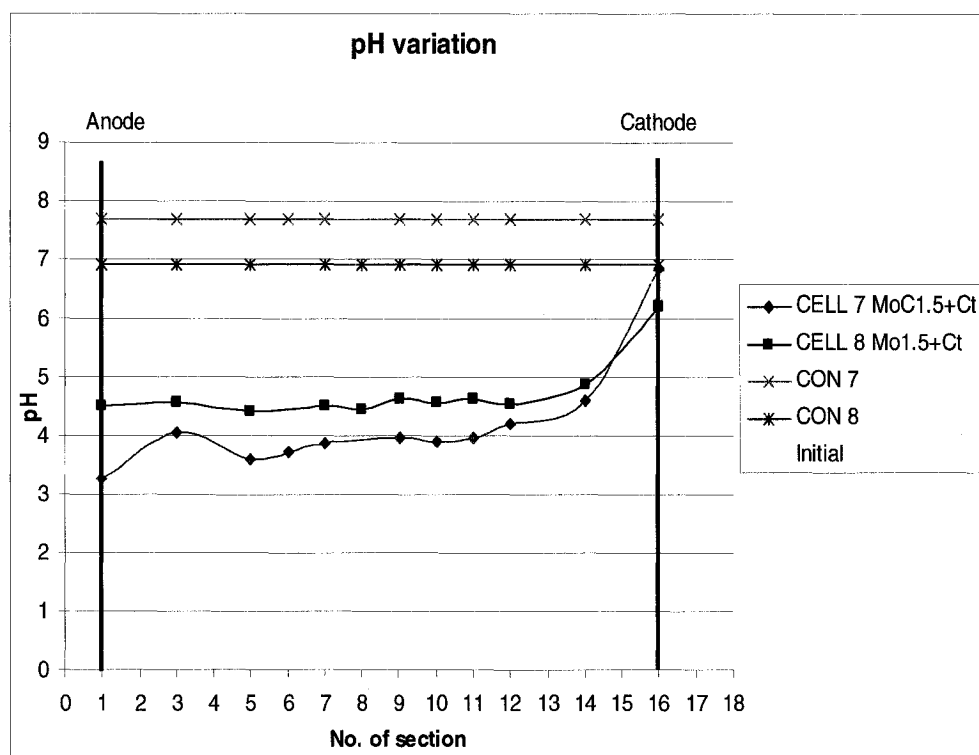


Figure 4-11 pH variation in Cells #7 and #8

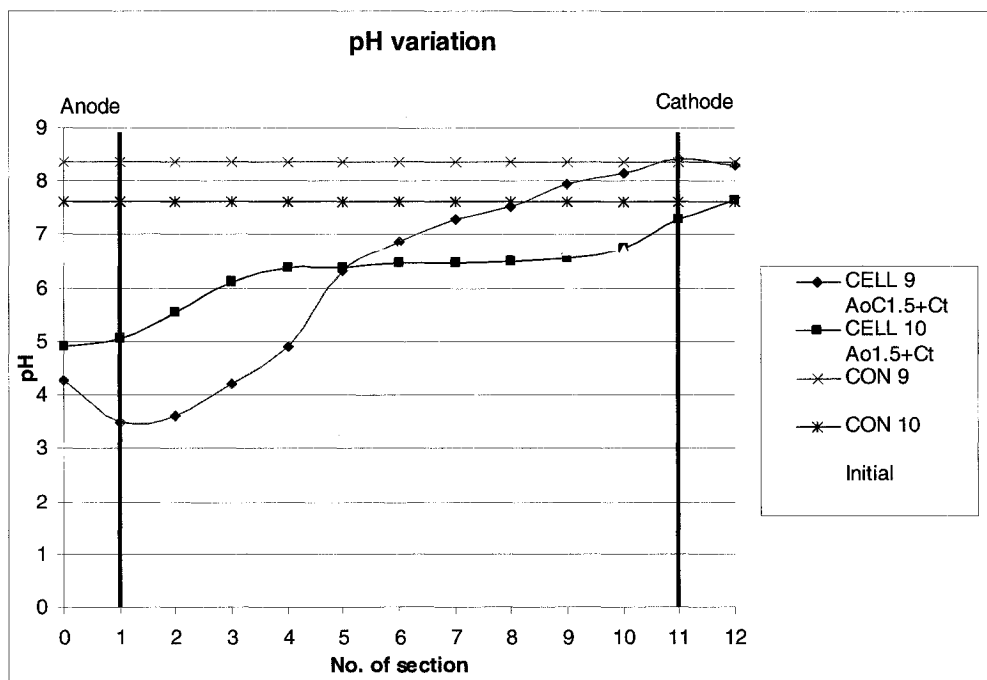


Figure 4-12 pH variation in Cells #9 and #10

4.3 Volatile Solids Contents

The volatile solids (VS) content represents the approximate organic matter content in the sludge. Figure 4-13 illustrates the volatile solids distribution in Cells #1 (MCLB1) and #2 (MLB1) after EK treatment.

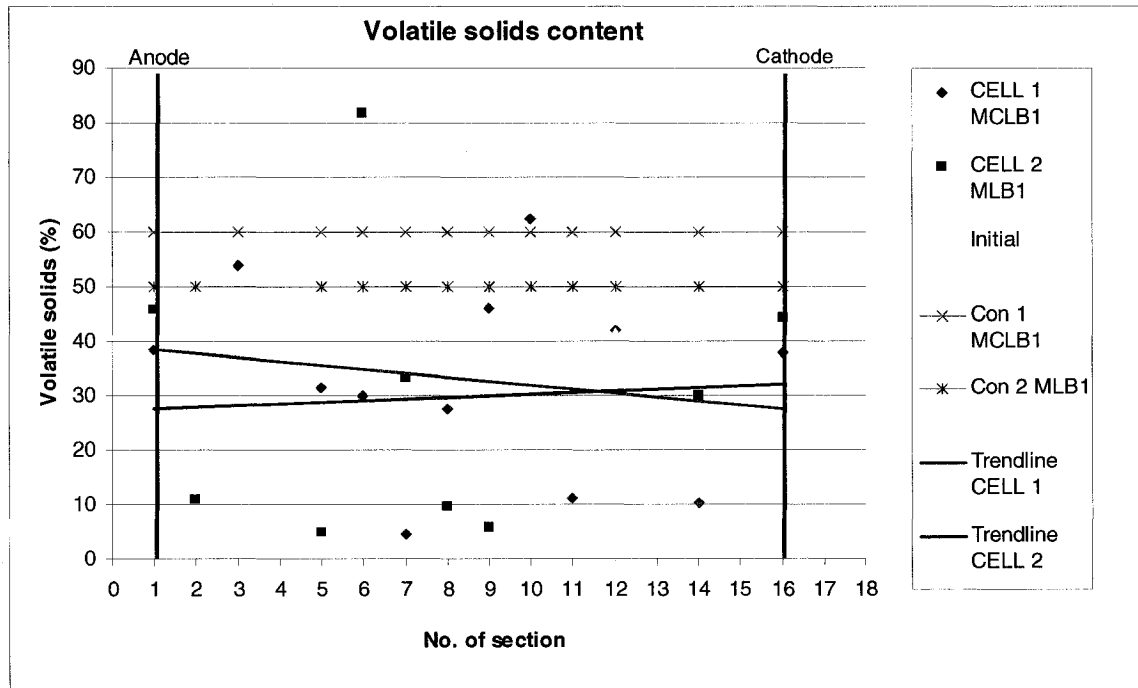


Figure 4-13 Volatile solids content in Cells #1 and #2

In Cell #1 (MCLB1), the volatile solids content decreased in trend from anode area toward cathode area. The VS content differed slightly at anode and cathode, and they were 38.5% and 37.8% respectively. In Cell #2 (MLB1), the volatile solids contents increased a little from anode toward cathode in trend. The lowest VS content value was found to be 5.8% in the middle section. The variation of volatile solids content may be caused by the crack formation in cells after EK treatment as illustrated in Figure 4-2.

In Control #1 and #2 and the initial sample, the volatile solids content were 60%, 50%, and 41.4%, respectively. It was speculated that biological activity took place and produced biomass and other organic matters in the cells. Therefore, VS contents were higher than initial value in most of samples in Cell #1 and #2.

Figure 4-14 illustrates the volatile solids distribution in Cells #3 (AoCB1) and #4 (AoB1) after EK treatment.

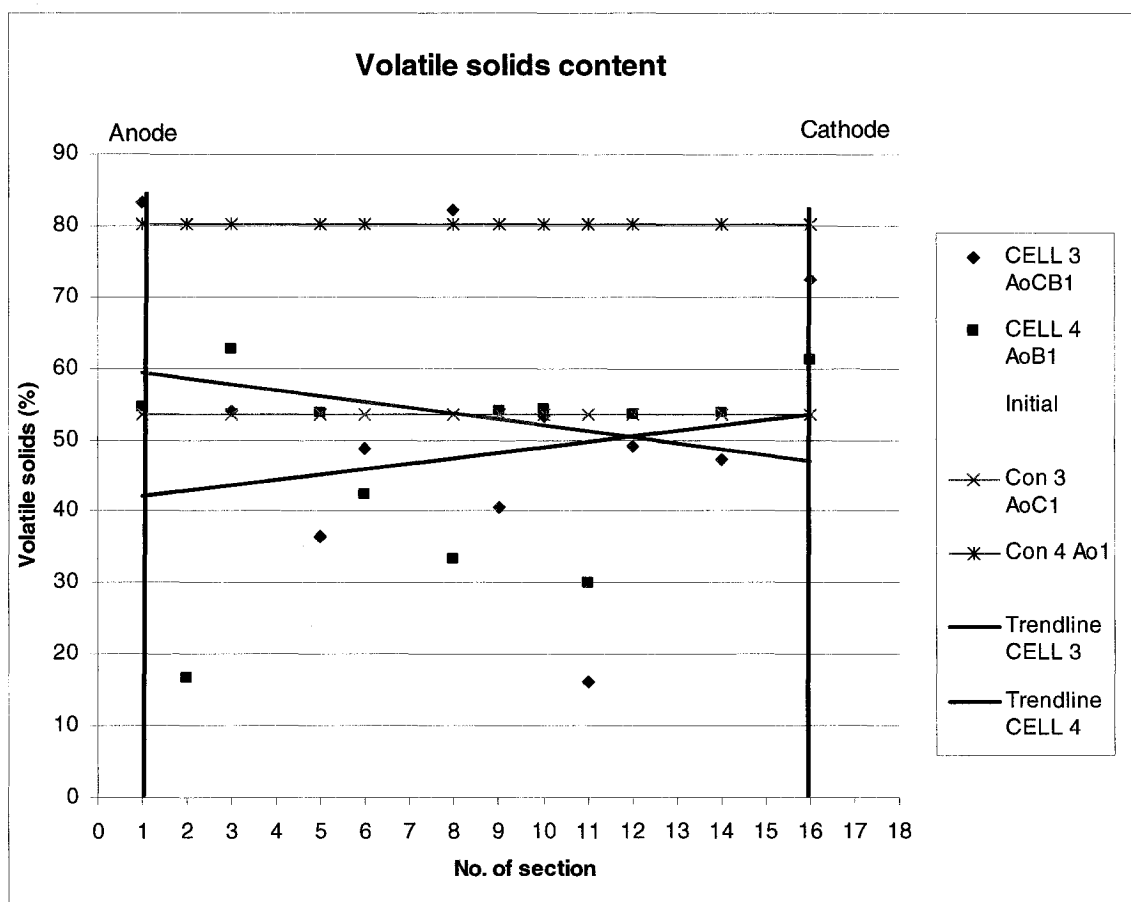


Figure 4-14 Volatile solids content variation in Cells #3 and #4

In Cell #3 (AoCB1), the volatile solids contents decreased in trend from anode toward cathode. The lowest VS content was 16.3% in the middle of the cell. In Cell #4 (AoB1), the volatile solids contents decreased from cathode toward anode in trend. The lowest VS

content was 16.8% in the anode area. The variation of volatile solids content may be caused by the crack formation in cells after EK treatment as illustrated in Figure 4-4.

In Control #3 and #4 and the initial sample, the volatile solids content were 53.4%, 80.11%, and 58.41%, respectively.

Figure 4-15 illustrates the volatile solids distribution in Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct) after EK treatment.

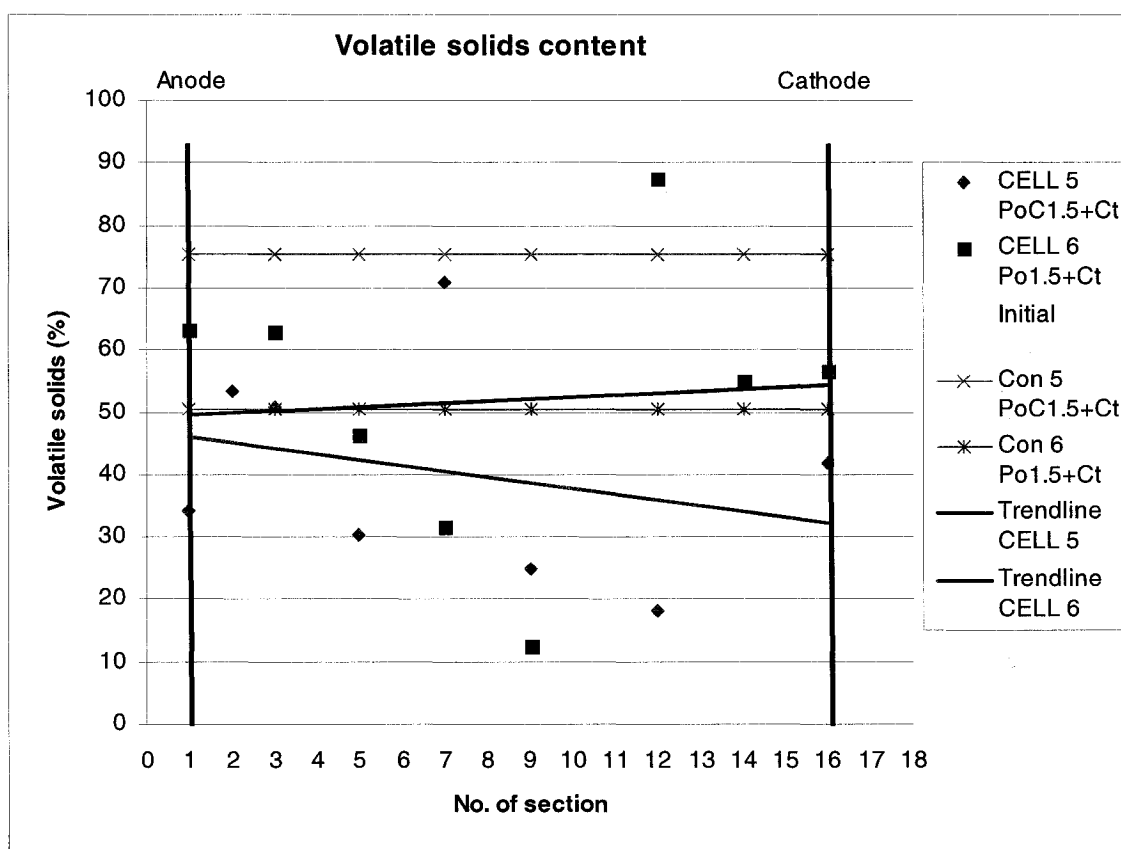


Figure 4-15 Volatile solids content variation in Cells #5 and #6

In Cell #5 (PoC1.5+Ct), the volatile solids contents decreased in trend from anode toward cathode. The lowest VS content was 18.2% in the middle of the cell. In Cell #6 (Po1.5+Ct), the volatile solids contents increased slightly from cathode toward anode in trend. The lowest VS content was 12.6% in middle of the cell.

In Control #5 and #6 and the initial sample, the volatile solids content were 75.6%, 50.4%, and 83.4 %, respectively. It was speculated that biological activity took place and produced biomass and other organic matters in the cells. Therefore, VS content were higher than the initial value and samples in Cell #5 and #6. The use of the conditioner led to less VS content in cells with addition of conditioner.

Figure 4-16 illustrates the volatile solids distribution in Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct) after EK treatment.

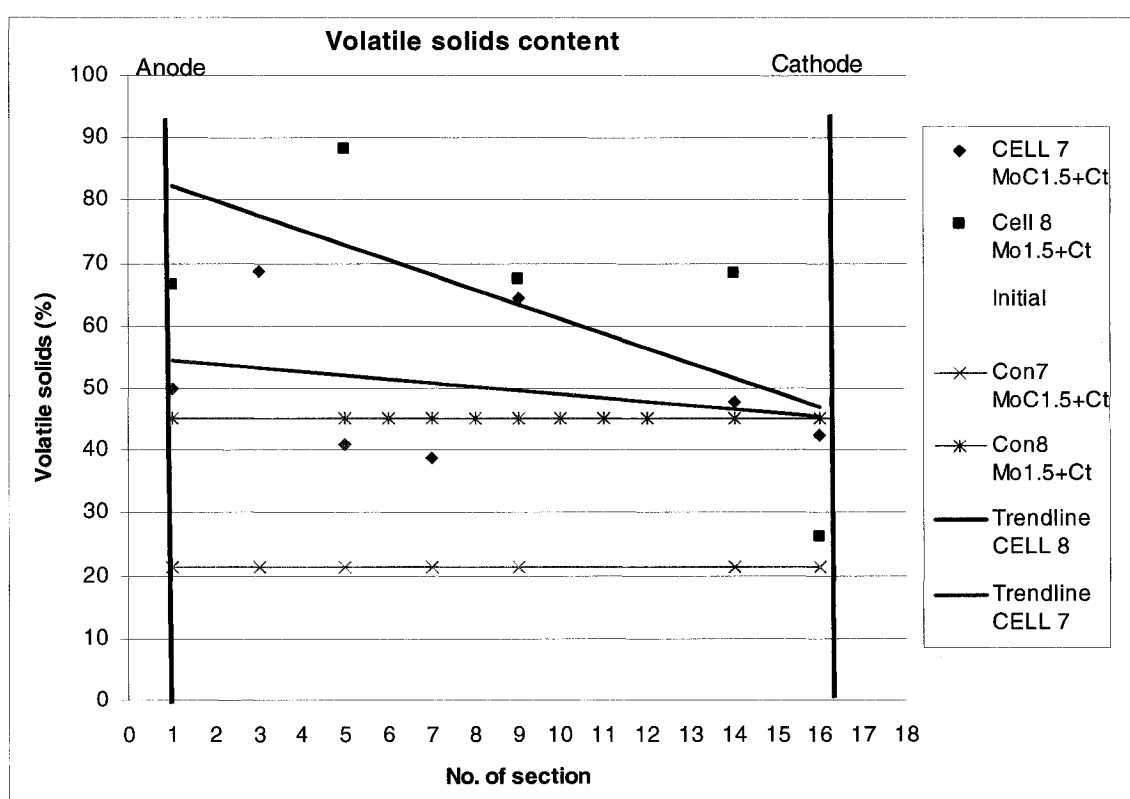


Figure 4-16 Volatile solids content variation in Cells #7 and #8

In Cell #7(MoC1.5+Ct), the volatile solids contents decreased from anode to cathode. The lowest VS content was 38.75% in the middle anode area. Generally, in Cell #8

(Mo1.5+Ct), the volatile solids contents decreased from anode to cathode. The lowest volatile solids content was 26.0% at the cathode.

In Control #7 and #8 and the initial sample, the volatile solids content were 21.3%, 45.1%, and 78.3 % respectively. The use of the conditioner, led to the less VS content.

Figure 4-17 illustrates the volatile solids distribution in Cells #9 (AoC1.5+Ct) and #8 (Ao1.5+Ct) after EK treatment.

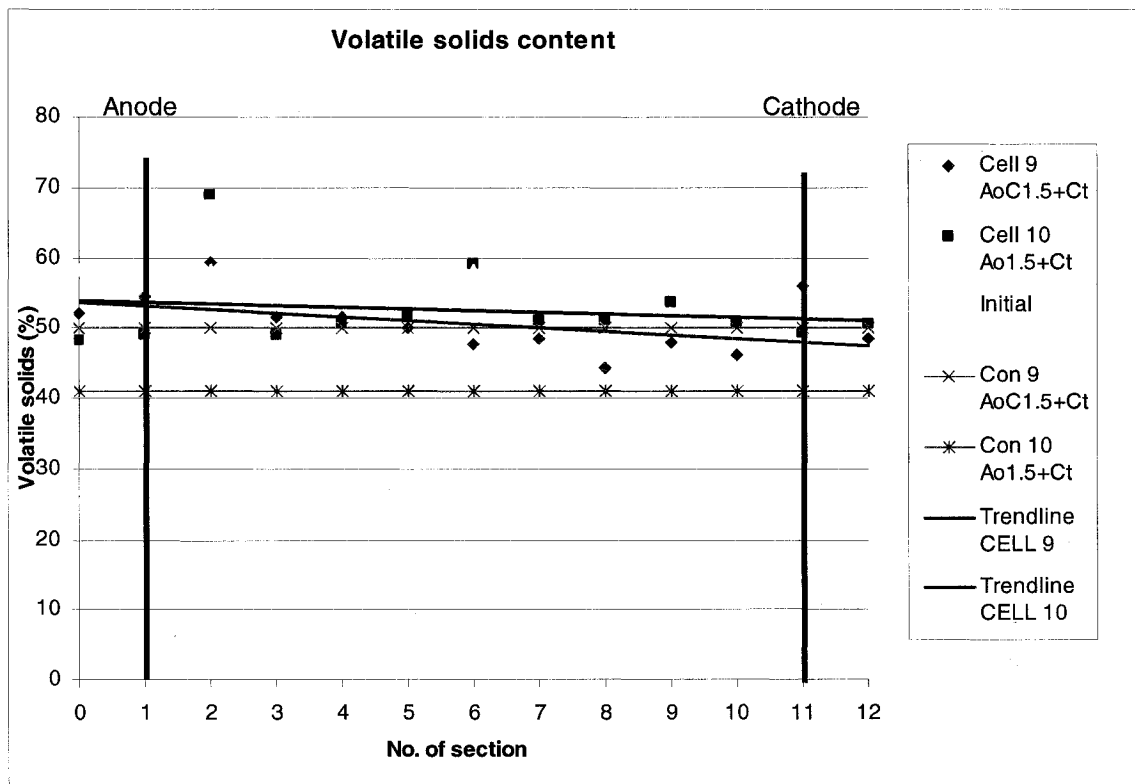


Figure 4-17 Volatile solids content variation in Cells #9 and #10

In Cell #9 (AoC1.5+Ct), the volatile solids contents decreased from anode to cathode in trend. The lowest volatile solids content was 44.3% at middle cathode area. The back anode and the back cathode had lower volatile solids content than that at anode and cathode. In Cell #10 (Ao1.5+Ct), the distribution of volatile solids contents was in the similar trend as Cell #9. The lowest VS content was 50% at cathode.

4.4 Chloride Contents

Figure 4-18 illustrates the chloride distribution in Cells #1 (MCLB1) and #2 (MLB1).

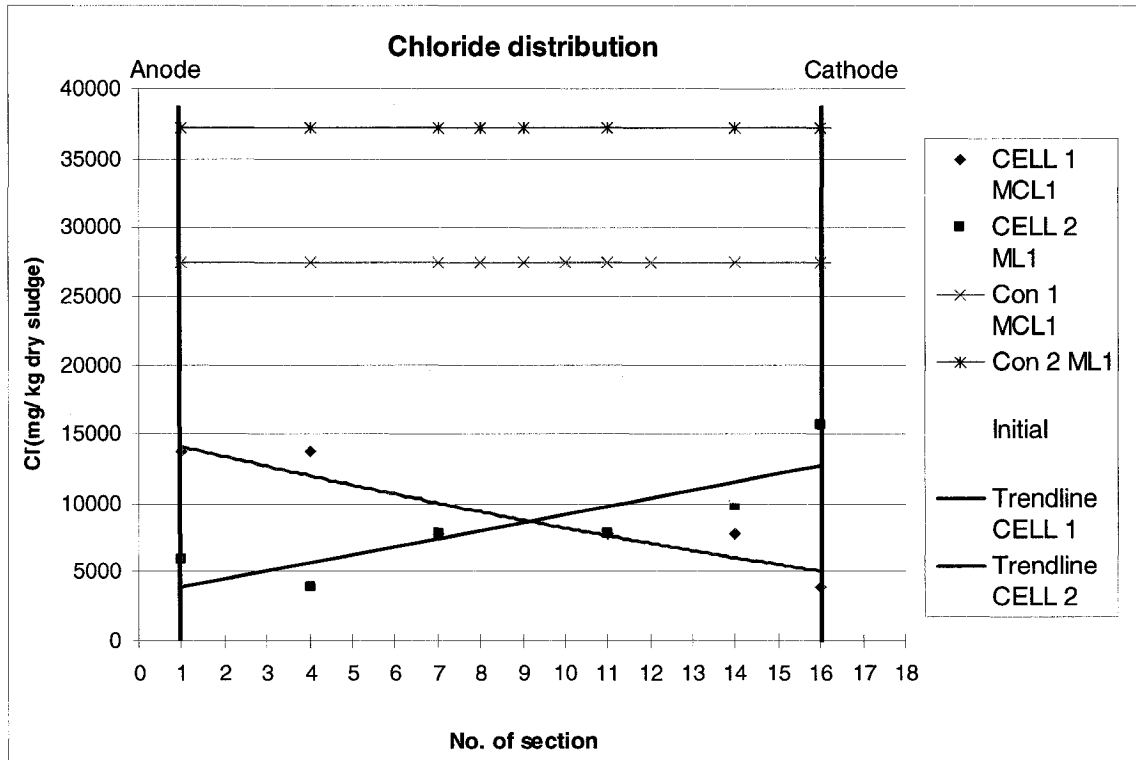


Figure 4-18 Chloride contents distribution for Cells #1 and #2

In Cell #1 (MCLB1) and Cell #2 (MLB1), the variation of chloride concentration was on the opposite trend, but the distribution of chloride contents was similar in Cells #1 and #2. In Cell #1 (MCLB1), the chloride content decreased from anode to cathode. The minimum chloride concentration was 3922 mg/kg dry sludge at cathode. In Cell #2 (MLB1), the chloride content decreased from cathode to anode, and the minimum chloride contents was 3922 mg/kg at middle anode area.

The Control #1 and #2 and initial sample had chloride content of 27457, 37264, and 10531 mg/kg dry sludge, respectively. The control cells had much higher chloride

contents than the EK cells. It was speculated that the abiotic reactions (e.g. dissociation) took place in control cells and they caused the higher chloride concentration than initial.

Figure 4-19 illustrates the chloride distribution in Cells #3 (AoCB1) and #4 (AoB1).

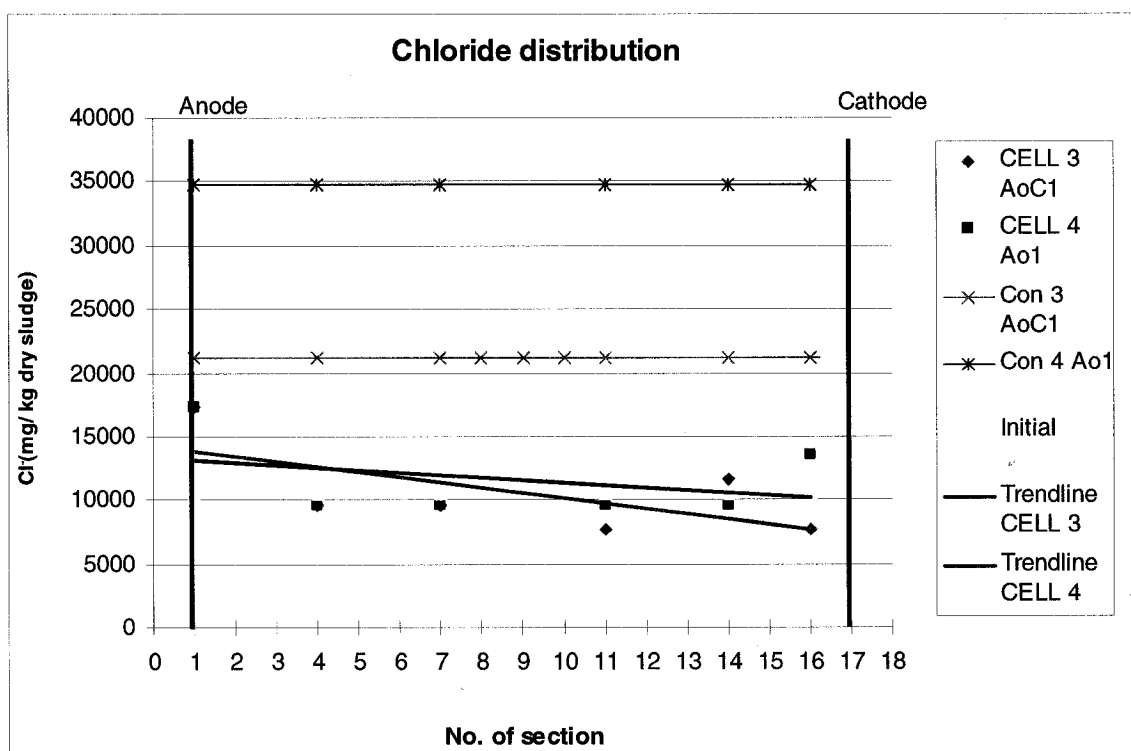


Figure 4-19 Chloride contents distribution for Cells #3 and #4

In Cell #3 (AoCB1) and Cell #4 (AoB1), the chloride decreased from anode toward cathode. In Cell #3 (AoCB1), the minimum chloride concentration was 7717 mg/kg dry sludge at middle cathode area. In Cell #4 (AoB1), the concentration at cathode was lower than that at anode, with 13504 mg/kg dry sludge.

The Control #3 and #4 and initial sample had chloride content of 21221, 34726, and 10531 mg/kg dry sludge, respectively. The control cells had much higher chloride contents than the EK cells.

Figure 4-20 illustrates the chloride distribution in Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct).

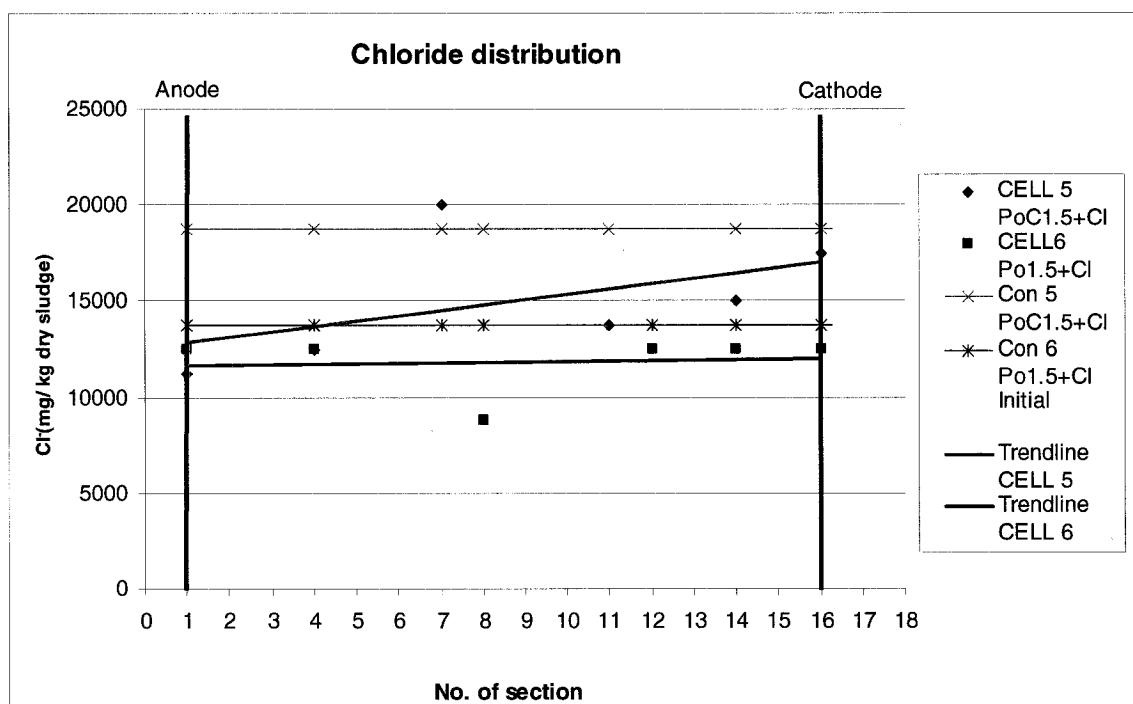


Figure 4-20 Chloride contents distribution for Cells #5 and #6

In Cell #5 (PoC1.5+Ct), the chloride content was lower at anode area than cathode area. The minimum chloride concentration was 11254 mg/kg dry sludge at anode. In Cell #6 (Po1.5+Ct), the chloride content variation was not significant along the cell. The chloride concentration at anode and cathode were both 12504 mg/kg dry sludge.

The Control #5 and #6 and initial sample had chloride content of 18756, 13754, and 2702 mg/kg dry sludge, respectively. The control cells had much higher chloride contents than most of the cell samples. Figure 4-21 illustrates the chloride distribution in Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct).

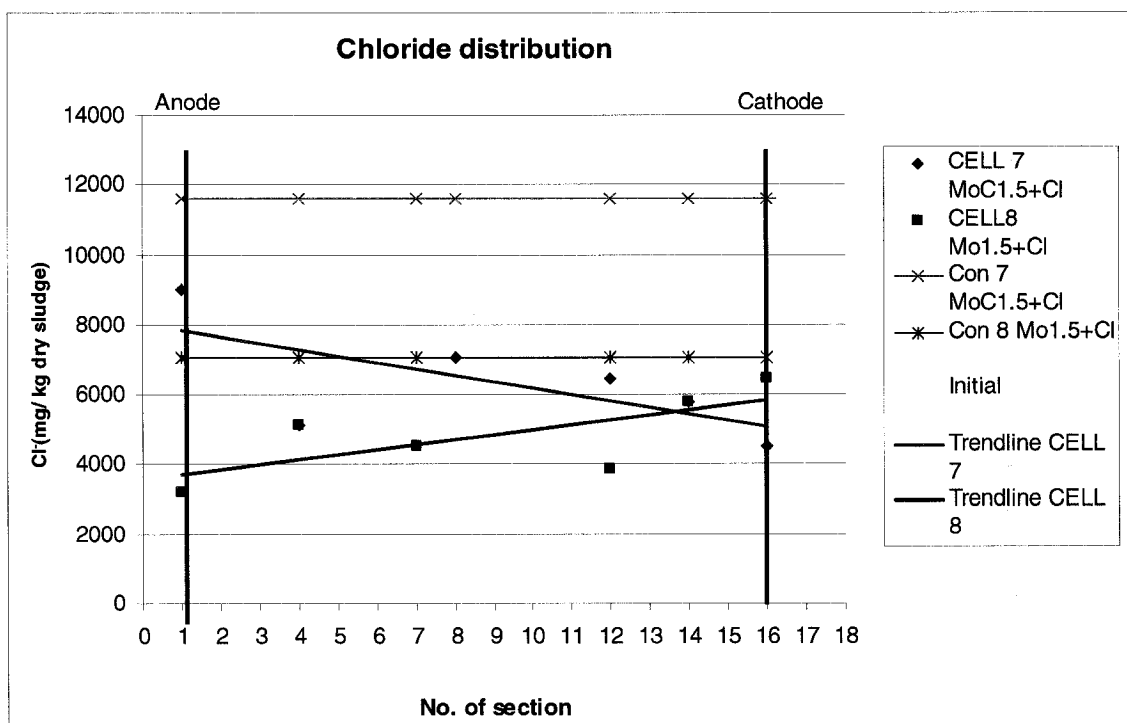


Figure 4-21 Chloride contents distribution for Cells #7 and #8

In Cell #7 (MoC1.5+Ct) and Cell #8 (Mo1.5+Ct), the distribution of chloride concentration was an opposite trend. In Cell #7 (MoC1.5+Ct), the chloride content decreased from anode to cathode. The minimum chloride concentration was at the cathode, with 4511 mg/kg dry sludge. In Cell #8 (Mo1.5+Ct), the chloride content increased from anode to cathode, with the minimum chloride contents 3222.7 mg/kg dry sludge at the anode.

The Control #7 and #8 and initial sample had chloride content of 11601, 7090, and 2500 mg/kg dry sludge, respectively. The control cells had much higher chloride contents than EK cells. It was speculated that the abiotic reaction took place in control cells leading to the higher chloride concentrations.

Figure 4-22 illustrates the chloride distribution in Cells #9 (AoC1.5+Ct) and #10 (Ao1.5+Ct).

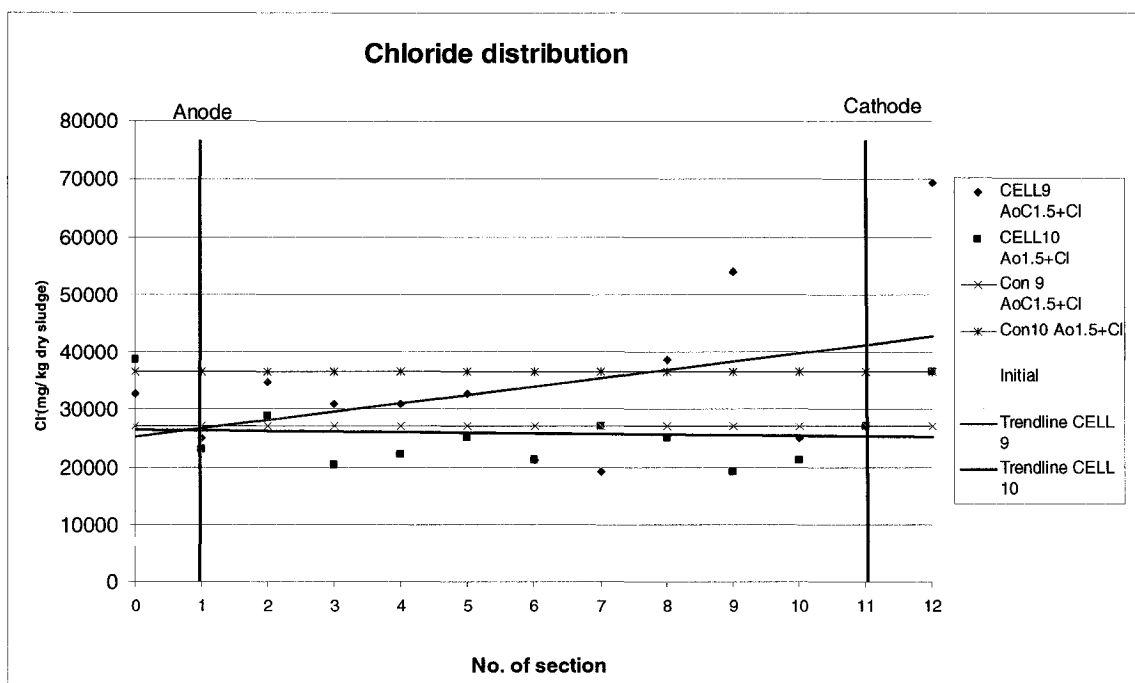


Figure 4-22 Chloride contents distribution for Cells #9 and #10

In Cell #9 (AoC1.5+Ct) and Cell #10 (Ao1.5+Ct), the distribution of chloride concentration was very similar. In Cell #9, chloride concentration decreased from cathode to anode in trend. The minimum chloride concentration was 32797 mg/kg dry sludge at anode. In Cell #10, the variation of chloride concentration was not significant. The minimum concentration was at middle cathode area with 19292 mg/kg dry sludge. The Control #9 and #10 and initial sample had chloride content of 27009, 36655, and 6950 mg/kg dry sludge, respectively.

4.5 Sulfate Contents

Figure 4-23 illustrates the sulfate distribution along the Cells #1 (MCBL1) and #2 (MBL1).

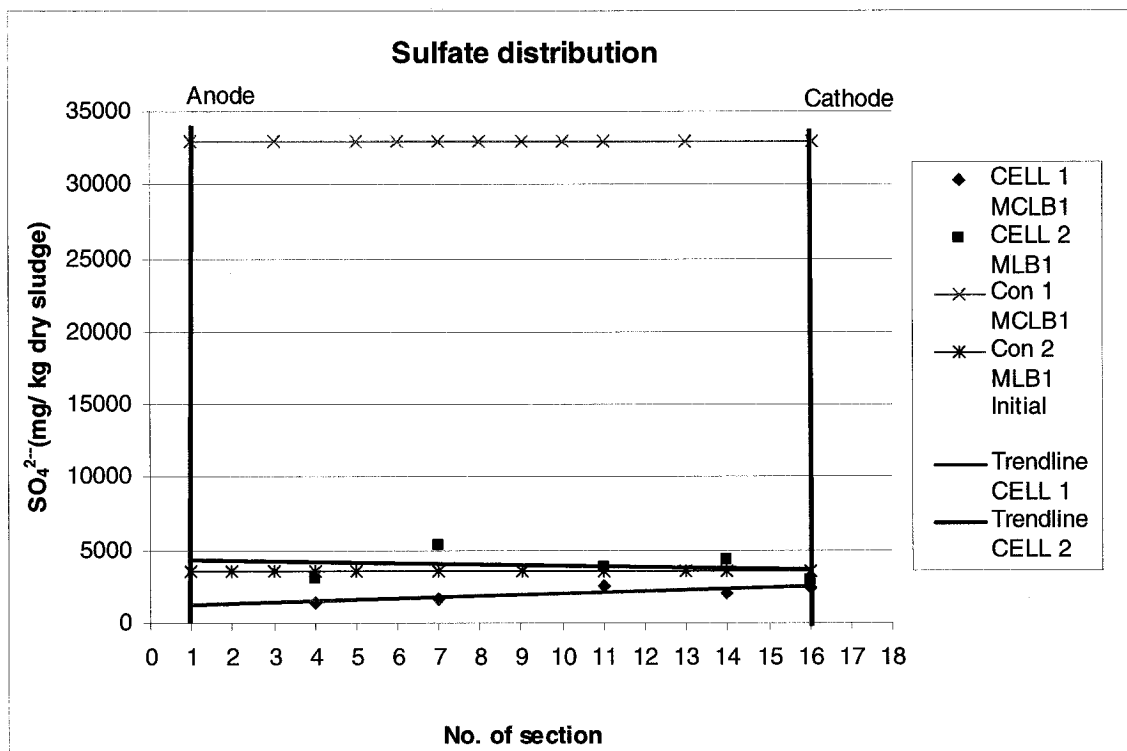


Figure 4-23 Sulfate concentration in Cells #1 and #2

In Cells #1 (MCLB1) and #2 (MLB1), the sulfate content variation along the cell was not significant. In Cell #1, the sulfate concentration decreased from cathode to anode in trend. The lowest concentration was 1445 mg/kg dry sludge at anode. In Cell #2, the variation curve was very flat. The lowest concentration was 2869 mg/kg dry sludge at near cathode area.

In Control #1 and #2 and initial sample, the sulfate concentration was higher than that of the EK cells. Figure 4-24 illustrates the sulfate distribution along the Cells #3 (AoCB1) and #4 (AoB1).

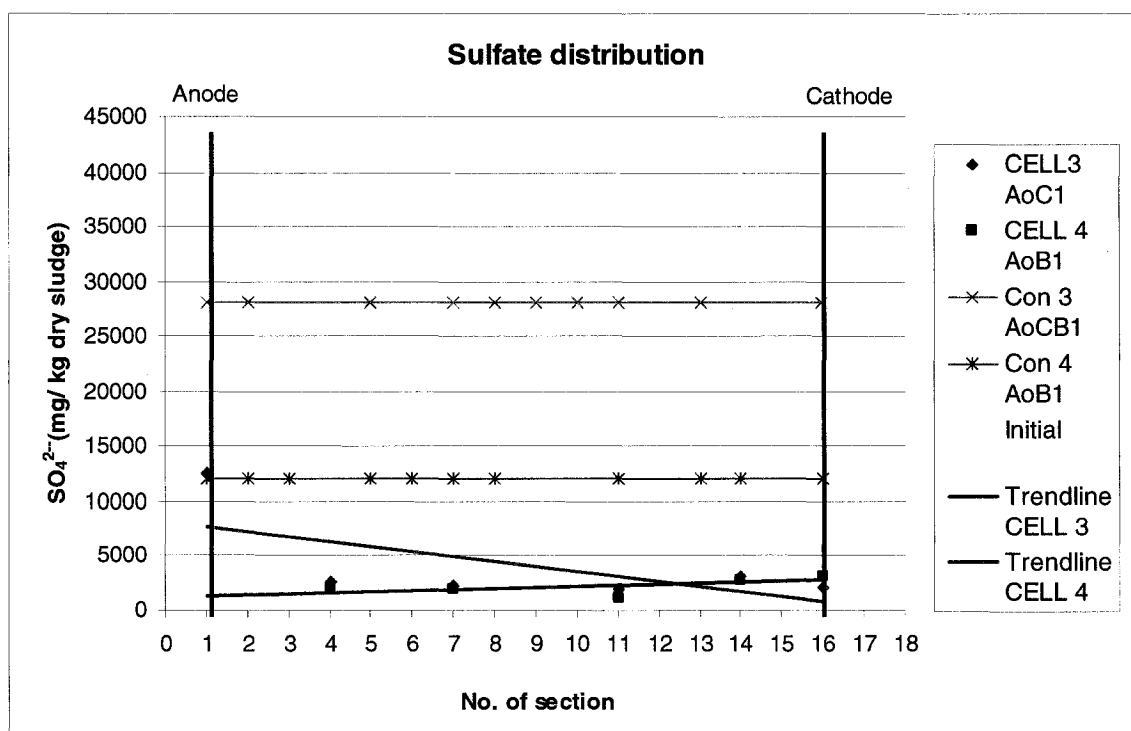


Figure 4-24 Sulfate concentration in Cells #3 and #4

In Cells #3 (AoCB1) and #4 (AoB1), the variation of sulfate concentration was in similar trend. In Cell #3, the sulfate decreased from anode to cathode. The minimum sulfate content was 1908 mg/kg dry sludge at middle cathode. In Cell #4, the minimum sulfate content was 1177 mg/kg dry sludge at middle anode area. In Control #3 and #4 and initial sample, the sulfate concentration was much higher than that of EK cells..

Figure 4-25 illustrates the sulfate distribution along the Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct). In Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct), the sulfate content variation was in similar trend and not significant. In Cell #5, the minimum sulfate content was 2645 mg/kg dry sludge at near anode area. In Cell #6, the minimum sulfate content was 868 mg/kg dry sludge in the middle area.

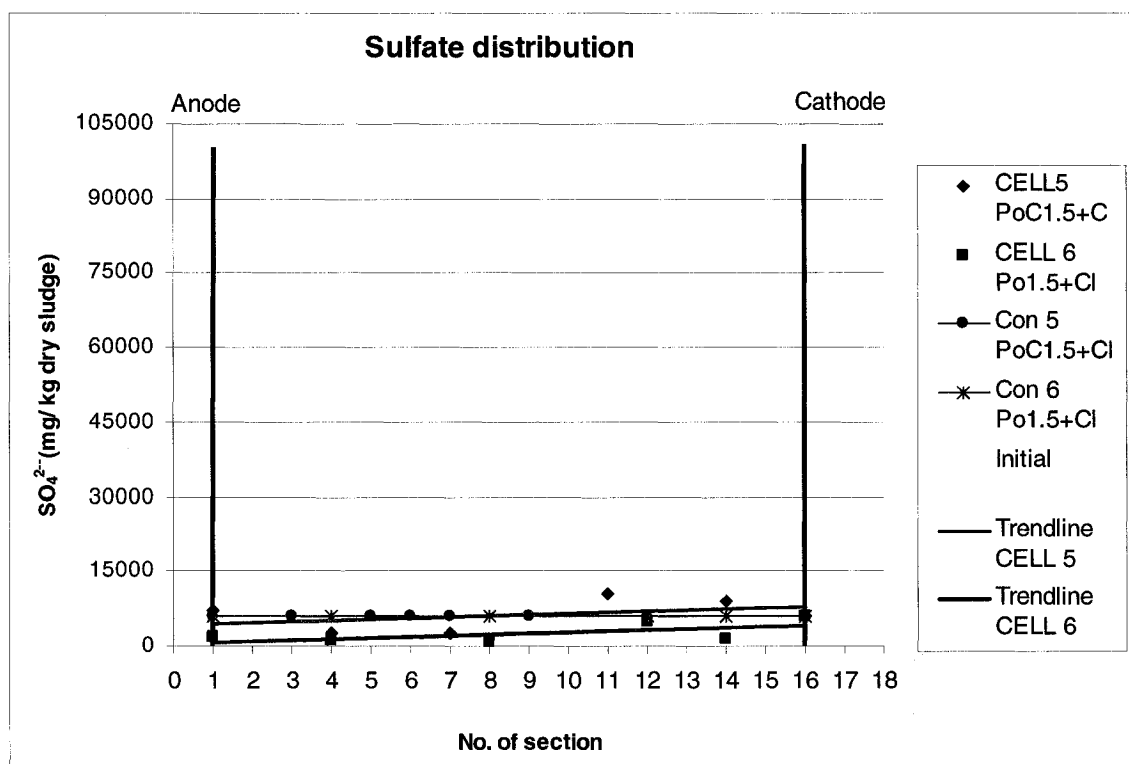


Figure 4-25 Sulfate concentration in Cells #5 and #6

In Control #5 and #6, and initial sample, the sulfate concentration was higher than most of the samples in EK cells.

Figure 4-26 illustrates the sulfate distribution along the Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct). In Cell #7 (MoC1.5+Ct), the sulfate concentration decreased slightly from cathode to anode. The minimum sulfate concentration was 373 mg/kg dry sludge at middle section. In Cell #8 (Mo1.5+Ct), the sulfate content decreased from anode to cathode. The minimum sulfate concentration was 332 mg/kg dry sludge at cathode. In Control #7 and #8 and initial sample, the sulfate content was much higher than that in the EK cells #7 and #8.

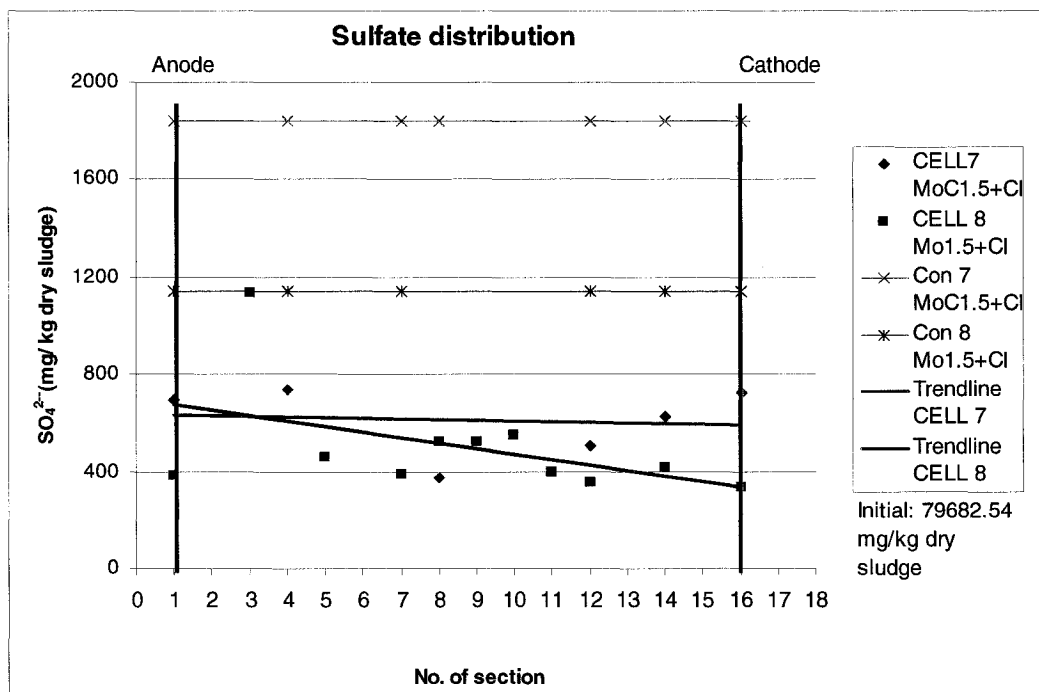


Figure 4-26 Sulfate concentration in Cells #7 and #8

Figure 4-27 illustrates the sulfate distribution along the Cells #9 (AoC1.5+Ct) and #10 (Ao1.5+Ct).

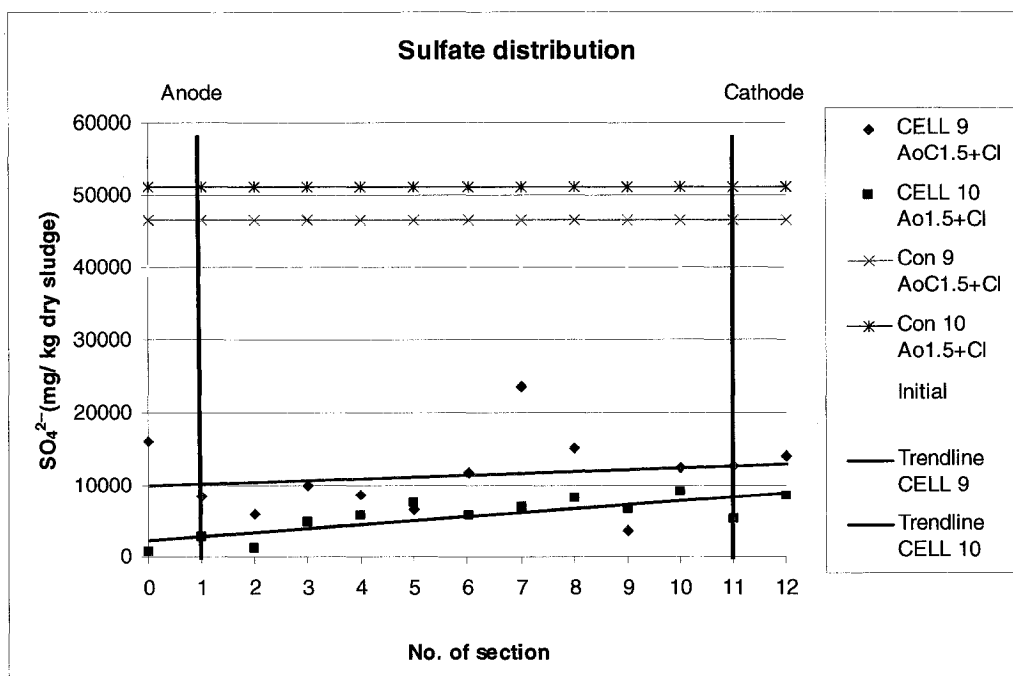


Figure 4-27 Sulfate concentration in Cells #9 and #10

In Cells #9 (AoC1.5+Cl) and #10 (Ao1.5+Cl), the sulfate concentration variation along the cell was not significant. In Cell #9, the maximum and minimum sulfate content was 54019 and 19292 mg/kg dry sludge, at middle anode and at near cathode area, respectively. In Cell #10, the maximum and minimum sulfate content was 771.7 and 8508.5 mg/kg dry sludge, at the anode and at the cathode, respectively.

In Control #9 and #10, and initial sample, the sulfate concentration was much higher than most of the samples in EK Cells #9 and #10. It was speculated that the biotic and abiotic reaction took place in control cells, which caused the higher sulfate concentration.

4.6 Resistance

The variation of resistance in the cells from the anode to the cathode, displayed in Figures 4–28 to 4–37, was measured on a daily basis. In all cells the resistance tended to decrease from anode to cathode. In cells with mixed sludge, Cells #1 (MCLB1) and #2 (MLB1), Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct), the first day's resistance difference between electrodes was 222, 275, 231, and 145 Ω , respectively. In cells with primary sludge, Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct), the first day's resistance difference between electrodes was 260 and 183 Ω , respectively. In cells with anaerobic digested sludge, Cells #3 (AoCB1) and #4 (AoB1), and Cells #9 (AoC1.5+Ct) and (Ao1.5+Ct), the first day's resistance difference between electrodes was 251, 123, 258, and 164 Ω , respectively.

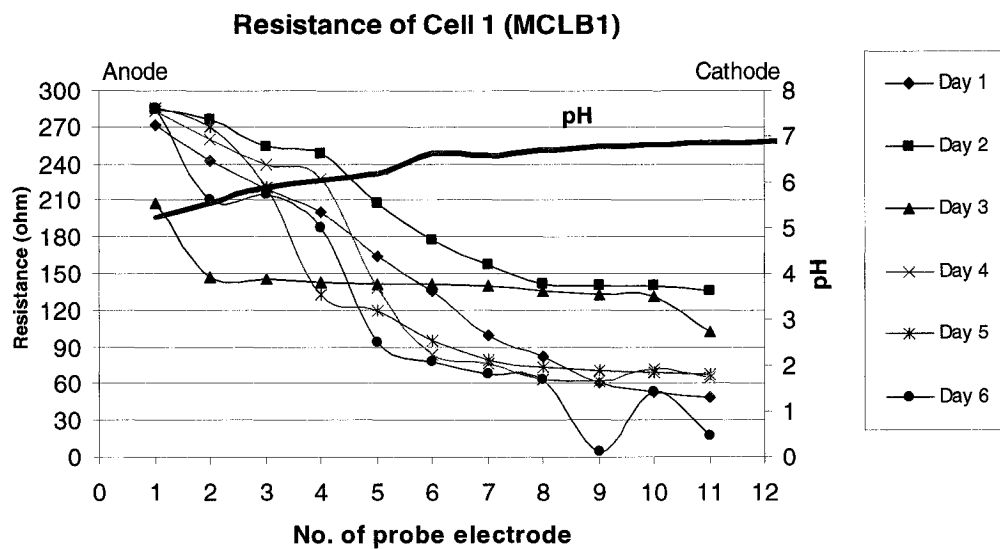


Figure 4-28 Resistance distribution in Cell #1 (MCLB1)

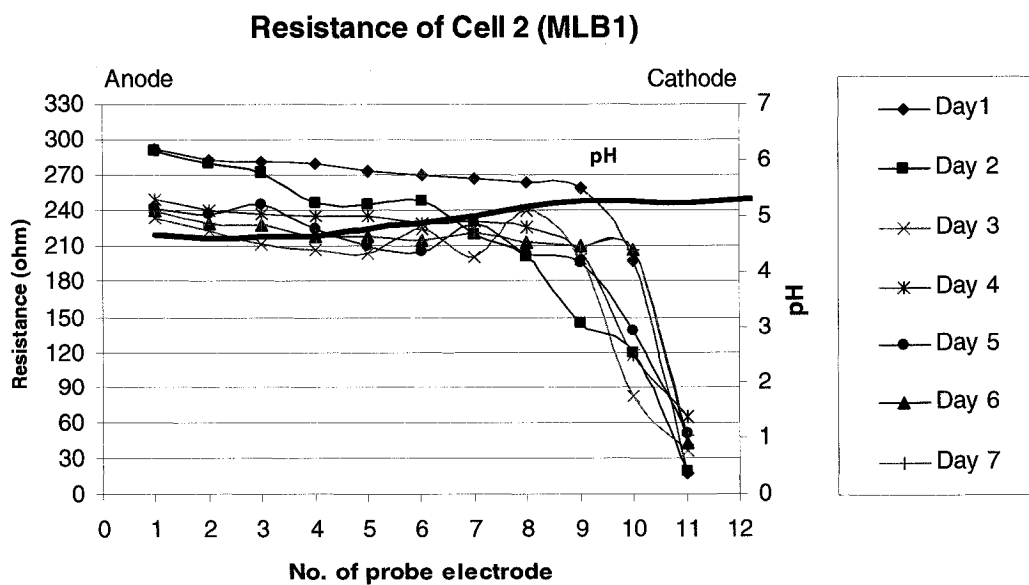


Figure 4-29 Resistance distribution in Cell #2 (MLB1)

Resistance of Cell 3 (AoCB1)

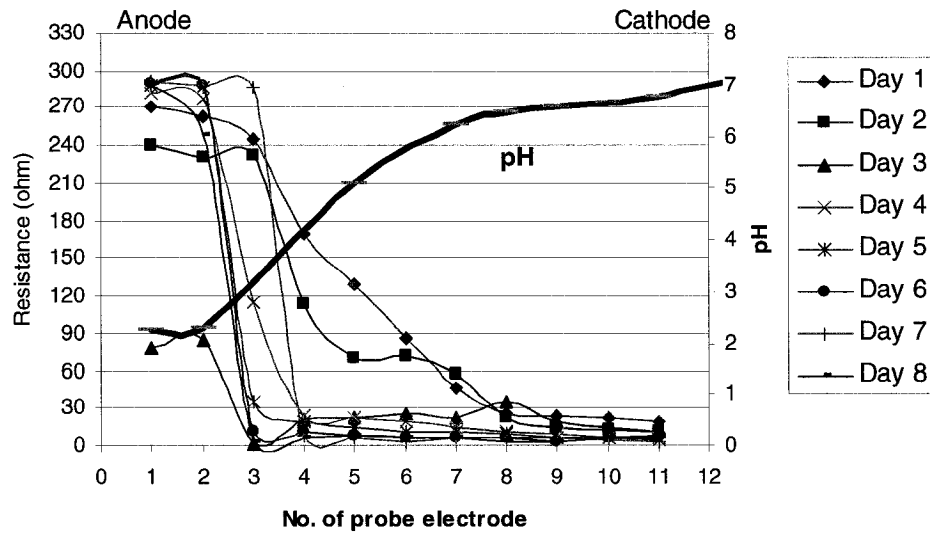


Figure 4-30 Resistance distribution in Cell #3 (AoCB1)

Resistance of Cell 4 (AoB1)

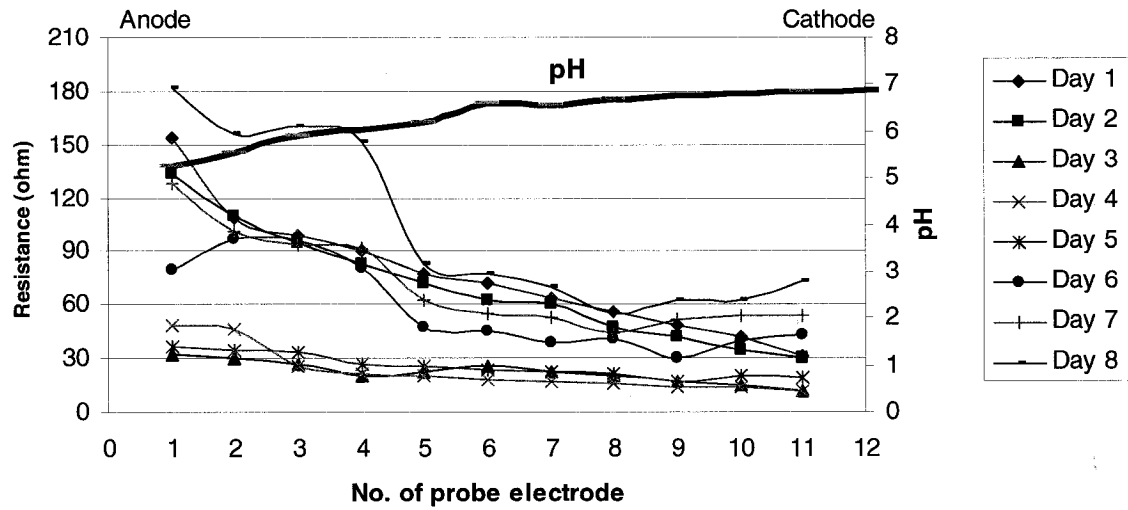


Figure 4-31 Resistance distribution in Cell #4 (AoB1)

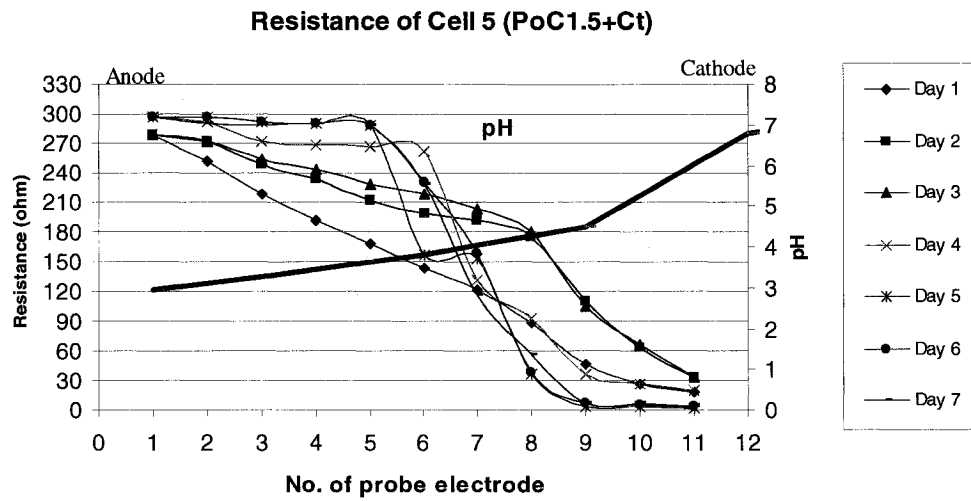


Figure 4-32 Resistance distribution in Cell #5 (PoC1.5+Ct)

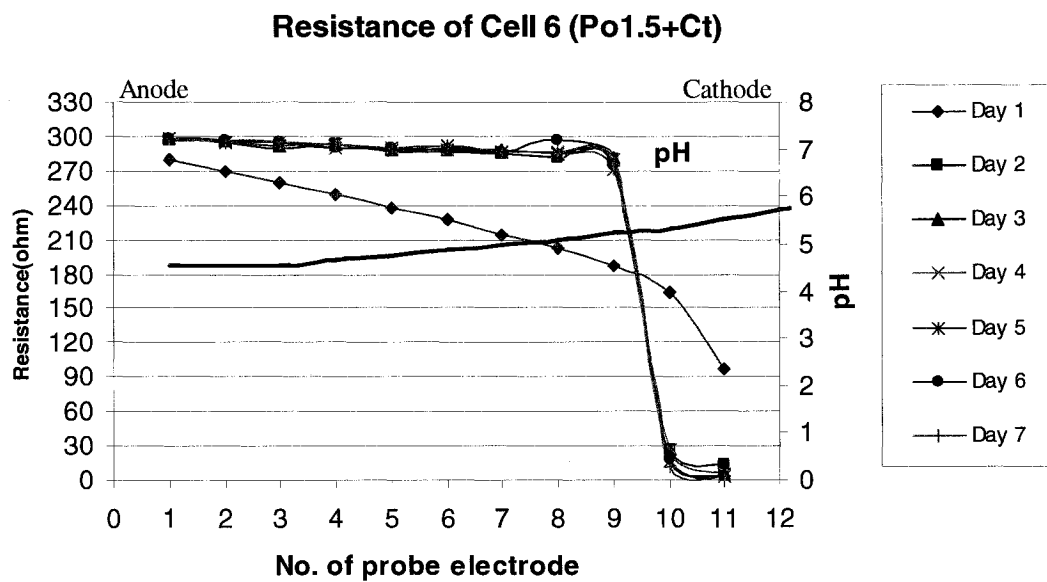


Figure 4-33 Resistance distribution in Cell #6 (Po1.5+Ct)

Resistance of Cell 7 (MoC1.5+Ct)

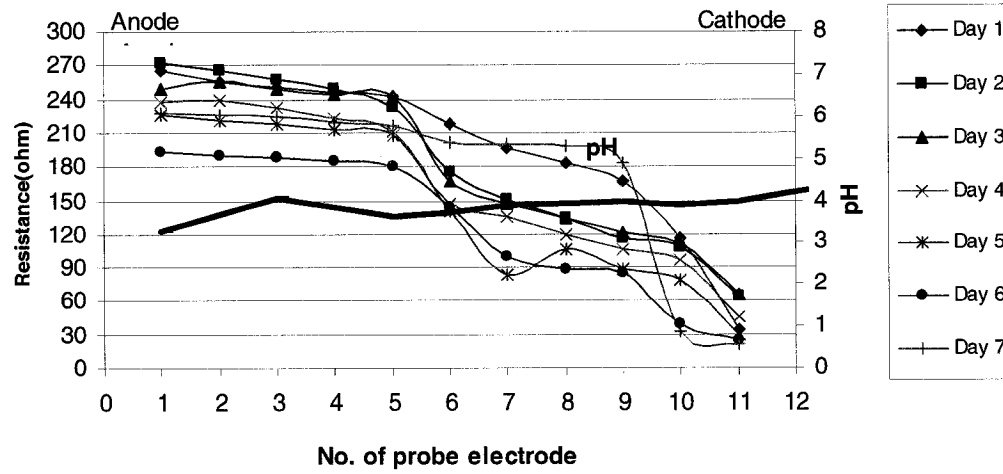


Figure 4-34 Resistance distribution in Cell #7 (MoC1.5+Ct)

Resistance of Cell 8 (Mo1.5+Ct)

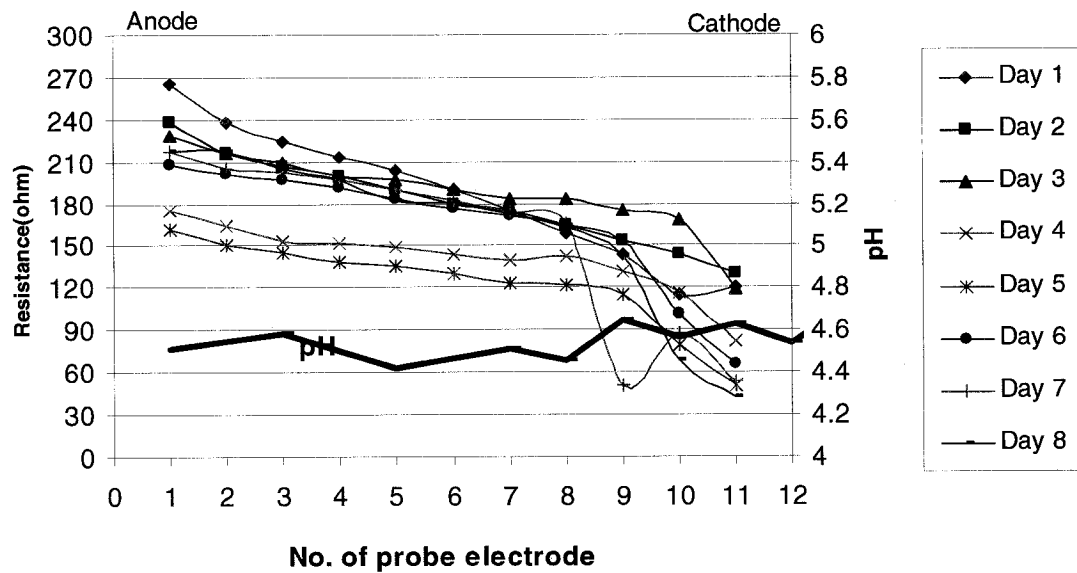


Figure 4-35 Resistance distribution in Cell #8 (Mo1.5+Ct)

Resistance of Cell 9 (AoC1.5+Ct)

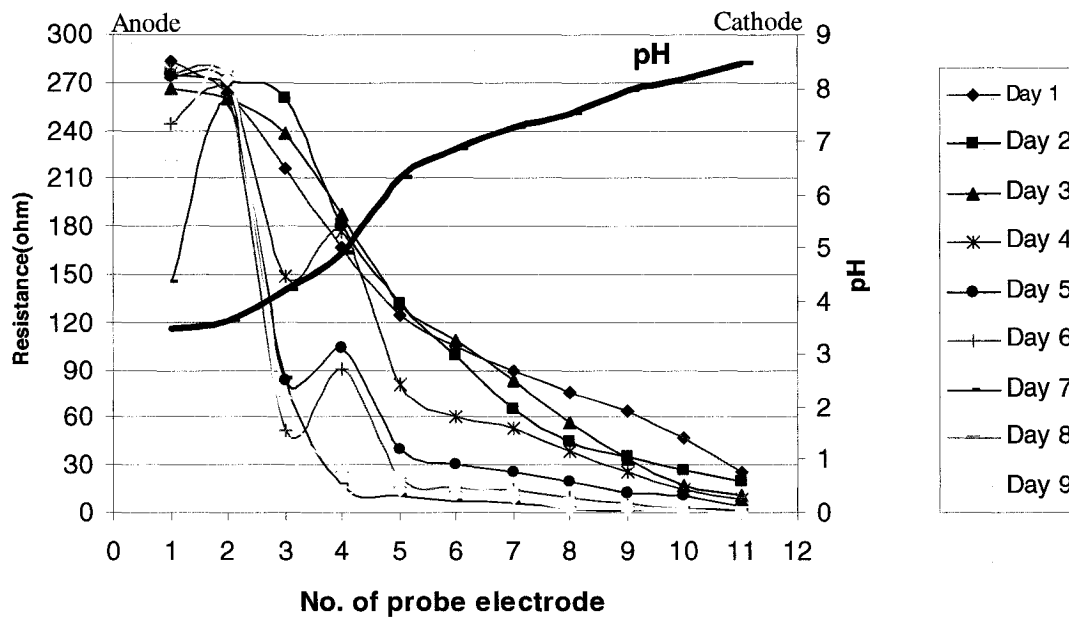


Figure 4-36 Resistance distribution in Cell #9 (AoC1.5+Ct)

Resistance of Cell 10 (Ao1.5+Ct)

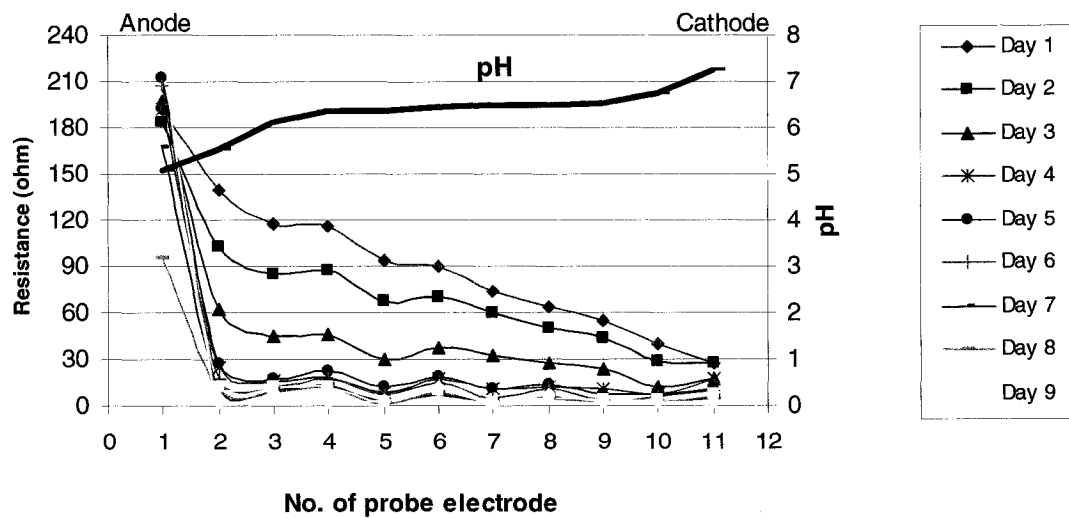


Figure 4-37 Resistance distribution in Cell # 10 (Ao1.5+Ct)

In all cells, the initial resistance at anode area slightly varied between 270 and 300 Ohms within the type of sludge. Anaerobic sludge without conditioner was an exception; its initial resistance was found to be below 200 Ohms. The resistant curve pattern provides information about development of electrokinetic processes inside the cell including indications regarding the day when the electroosmotic flow is less efficient for removal. These data are consistent with electrolyte collections described in Chap. 4.8. The application of DC field creates acidic and reduced zones due to electrokinetic phenomena. The expansion of these zones depends on voltage gradient, types of sludge and application of a conditioner. The Figures 4-29 to 4-38 illustrate that the pattern of pH distribution is a mirror reflection of the resistance distribution in all cells. It can be concluded that the manipulation of electrical field parameters can control expansion of both oxidation (acid) and reduced (alkaline) zones in order to enhance biotic and abiotic processes in biosolids.

4.7 Inactivation of Pathogens

4.7.1 Fecal Coliforms

The analysis of Fecal coliforms (FC) was done following the protocol described in Chapter 3.3.5. The concentration of Fecal coliforms in control cells and the initial sample was at thousands cfu/mL. Fecal coliforms were not detected after treatment in all EK cells with exception of Cell #3 (AoC1). In Cell #3, the Fecal coliforms were detected at the middle of the cell, and the concentration was reduced to 200 cfu/mL, which was 3267 cfu/mL lower than the original sample, and 585 cfu/mL lower than the Control #3.

4.7.2 *Salmonella spp.*

The *Salmonella spp.* concentration was analyzed for all ten cells following methodology described in Chapter 3.6.5. In all cells a decrease of *Salmonella spp.* was observed. In Cell #1 (MCLB1), the *Salmonella spp.* was detected at anode area, and the concentration was at 34 cfu/mL only. It was much less than the original concentration $1.9E + 09$ cfu/mL. From middle anode area to the cathode, there was no detectable *Salmonella spp.*. In Cell #2 (MLB1), the *Salmonella spp.* was detected at only cathode area. The *Salmonella spp.* concentration at cathode area was in the range from 67 to 267 cfu/mL. It was much less than the original concentration $1.9E + 09$ cfu/mL.

The control cells had much higher *Salmonella spp.* concentration with $5.2E+07$ and $4.87E+07$ cfu/mL in Control #1 and #2 respectively. However, the initial sample contained much higher ($1.9E + 09$ cfu/mL) *Salmonella spp.* concentration. Figure 4-38 illustrates the *Salmonella spp.* concentration in Cells #1 and #2, compared with the original and control samples.

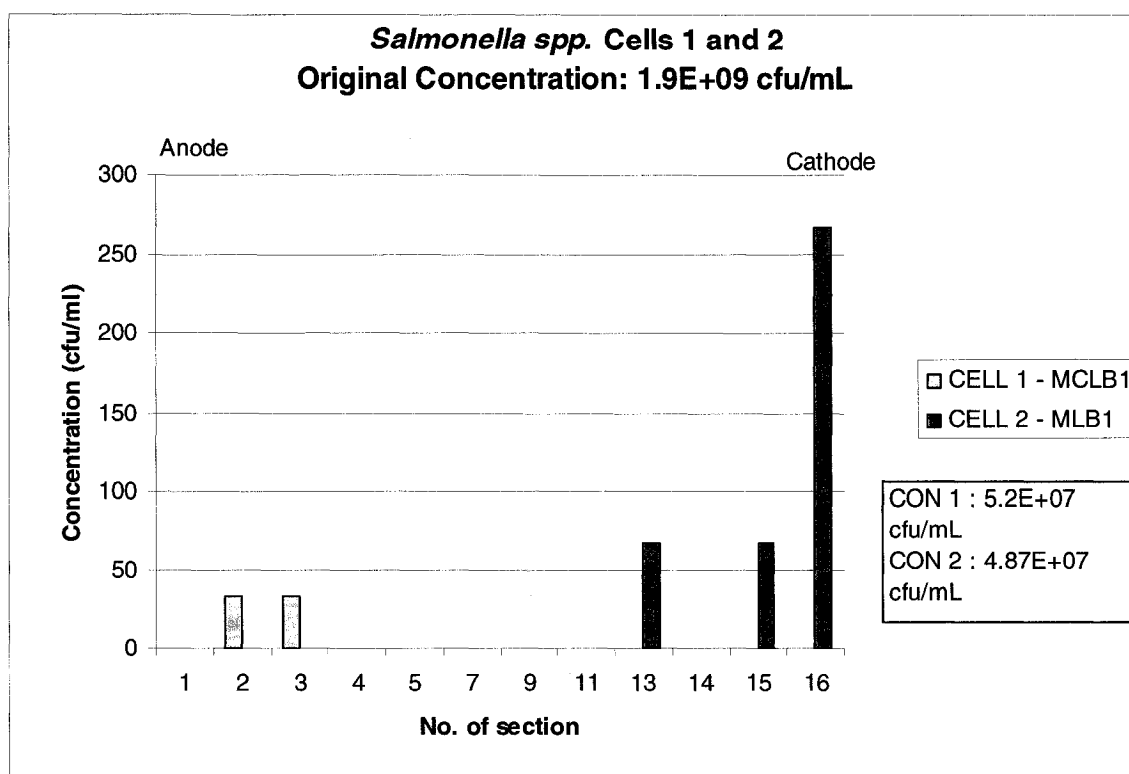


Figure 4-38 *Salmonella* spp. concentration in Cells #1 and #2

In Cell #3 (AoCB1), the *Salmonella* spp. concentration was detected at the middle anode area. The concentration was 200 cfu/mL, which was much lower than the original concentration of 1.9E+11 cfu/mL. There was no *Salmonella* spp. detected in other areas) There was no detected *Salmonella* spp. in the whole Cell #4 (AoB1). The original sample and Control #3 and #4 had much higher *Salmonella* spp. concentrations than the EK cells. Figure 4-39 illustrates the *Salmonella* spp. concentration in Cells # 3 and #4.

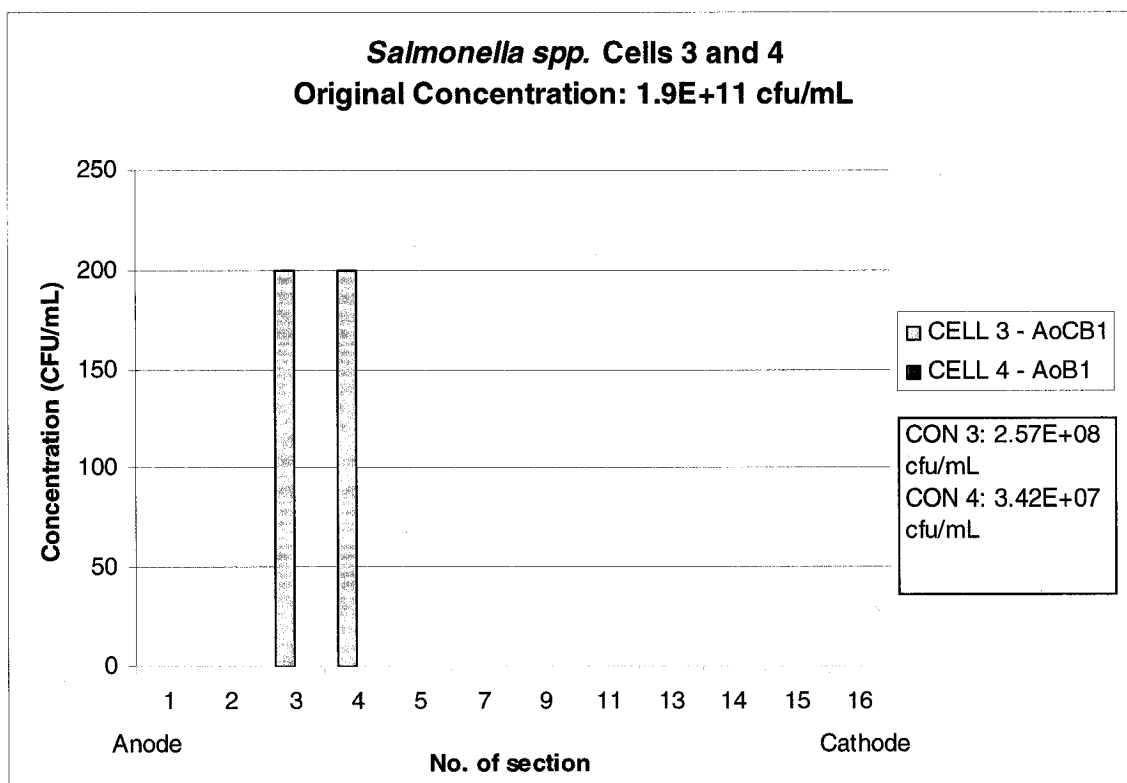


Figure 4-39 *Salmonella spp.* concentration in Cells #3 and #4

In Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct), there was no detected *Salmonella spp.* The original sample and the control Cells #5 and #6 had much higher *Salmonella spp.* concentration. They were 1.6E+10, 2.56E + 06, and 3.45E+06 cfu/mL, respectively.

In Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct), there was no detected *Salmonella spp.* The original sample and the control cells #7 and #8 had much higher *Salmonella spp.* concentration. They were 2.0E+09, 1.50E + 08, and 3.90E+07 cfu/mL, respectively.

In Cell #9 (AoC1.5+Ct), the *Salmonella spp.* was not detected from the anode to the middle anode area. From the middle section to the cathode area, the range of concentration of *Salmonella spp.* was from 3.3E+04 to 1.2E+05 cfu/mL, which was much lower than the concentration of original and the control samples. The original and

the control concentration were $1.87\text{E}+11$ cfu/mL and $2.60\text{E}+07$ cfu/mL, respectively. Figure 4-40 illustrates the *Salmonella spp.* concentration in Cell #9. A thin layer of film material was observed covering the Control #9. It was speculated that it was the results of the biological activities (Appendix Figure A-5). Also, the growth of a biological film was observed in Cells #9 and #10 (Appendix Figure A-14). The identification analysis showed that species forming biofilm are *Bacillus amiloliquefaciens*.

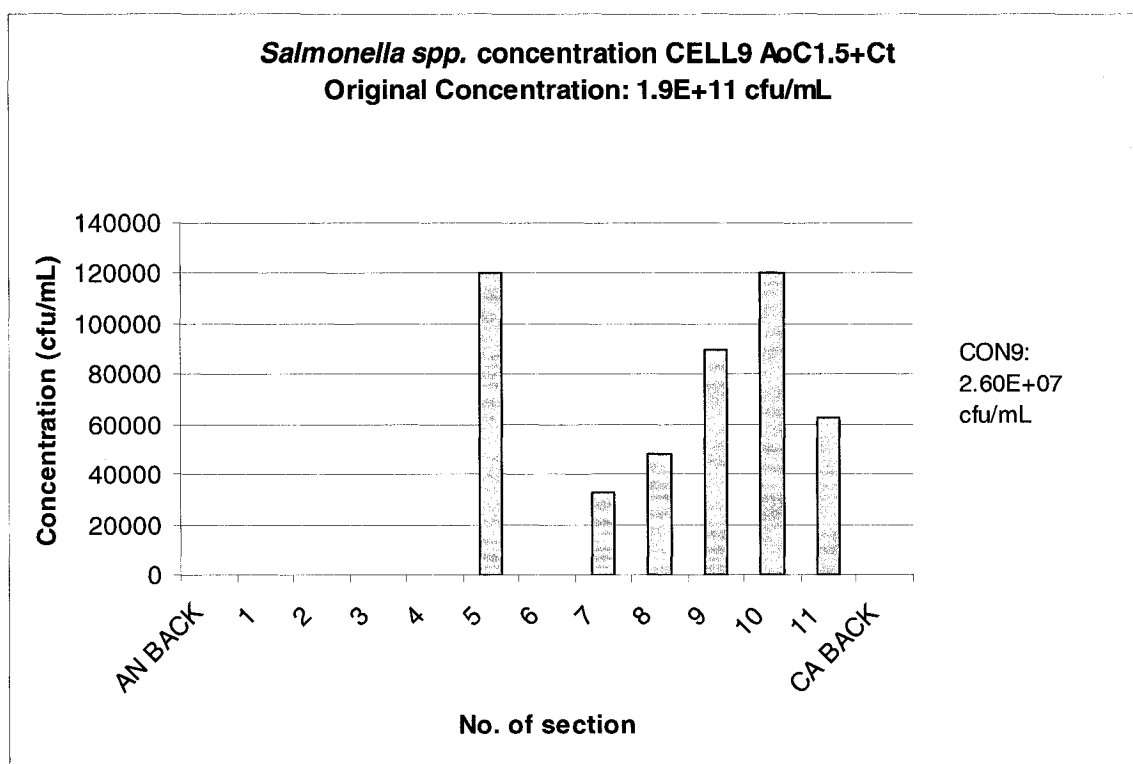


Figure 4-40 *Salmonella spp.* concentration in Cell #9

In Cell# 10 (Ao1.5+Ct), the *Salmonella spp.* was not detectable at the anode and near anode area. From the middle anode area to the cathode, the *Salmonella spp.* concentration ranged from $7.8\text{E}+04$ cfu/mL to $2.4\text{E}+05$ cfu/mL. The original concentration and the control sample were $1.87\text{E}+11$ cfu/mL and $3.80\text{E}+08$ cfu/mL, respectively, which was much higher than the EK cell concentration. Figure 4-41 illustrates the *Salmonella spp.*

concentration in Cell #10. Bubbles were observed in Control #10 suggested for anaerobic processes taken place in Control #10 (Figure A-5).

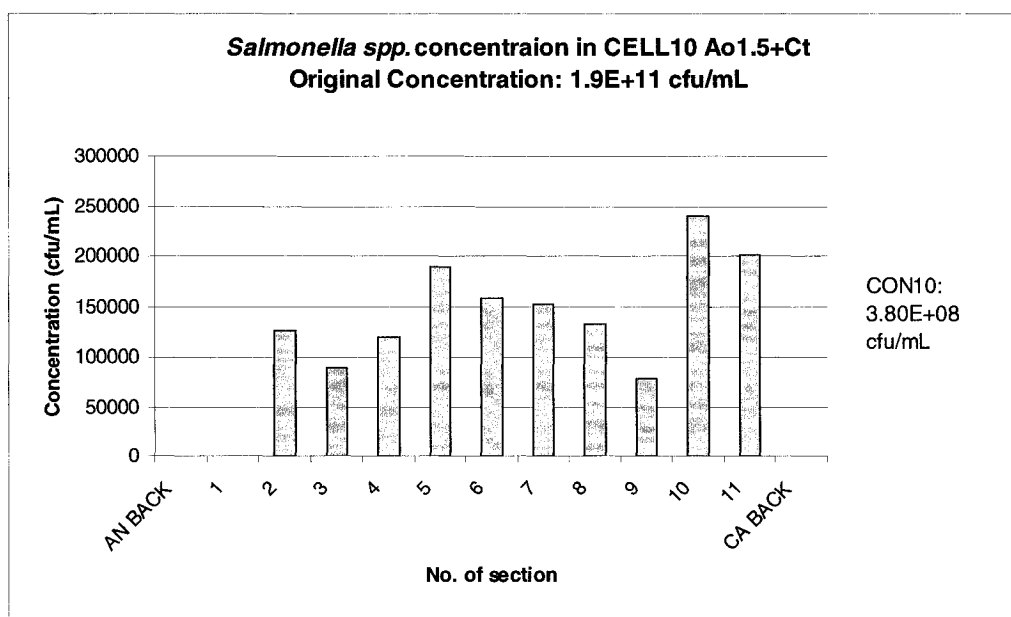


Figure 4-41 *Salmonella* spp. concentration in Cell #10

The average log reduction of *Salmonella* spp. was plotted in Figure 4 – 42.

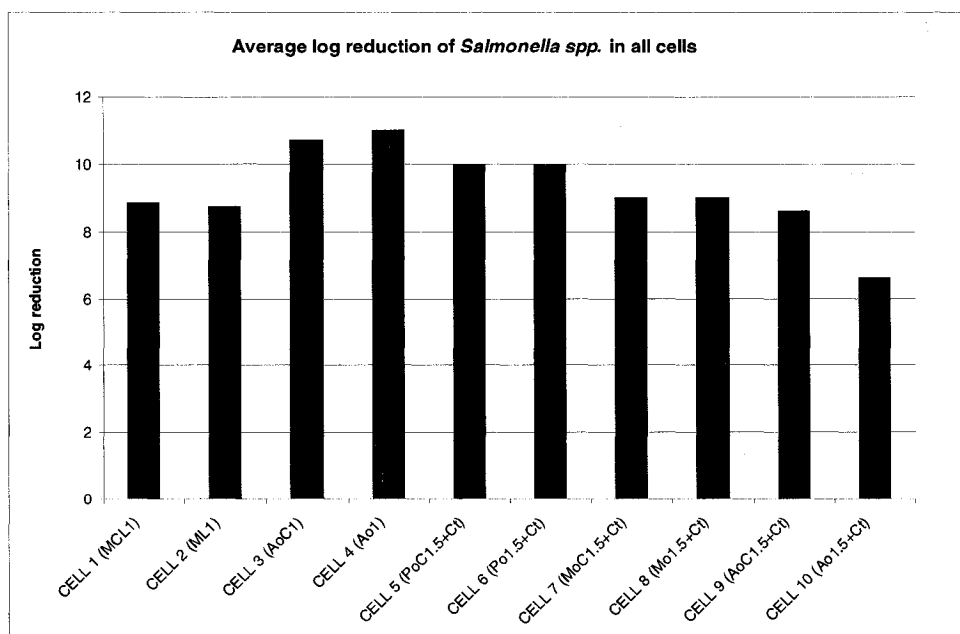


Figure 4-42 The average log – reduction of *Salmonella* spp. in all cells

4.7.3 *Clostridium*

Clostridia were spiked into Cells #5 to #10 prior to the EK testing. Analysis of *Clostridium* was done by another researcher. The results showed that no *Clostridium* was detected in cells and catholyte after EK treatment.

4.8 Catholyte

Catholyte was collected, and the pH and volume were measured for each cell on a daily basis. In Cell #1 (MCLB1), the catholyte was collected only on the first day of the experiment and the volume of the catholyte was 295 mL. The pH of the catholyte was 9.2. There was no *Salmonella spp.* and Fecal coliform in the catholyte. Table 4-2 displayed the results of catholyte measurements and analyses for Cell #1.

Table 4-2 Catholyte measurements for Cell # 1

Cell #1 (MCLB1)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total.
Volume of catholyte (mL)	295	0	0	0	0	0	0	295ml
pH of catholyte	9.2	N/A	N/A	N/A	N/A	N/A	N/A	
Color of catholyte	brownish yellow	N/A	N/A	N/A	N/A	N/A	N/A	
Temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella spp.</i> (cfu/ml)	0	N/A	N/A	N/A	N/A	N/A	N/A	0
Fecal coliform (cfu/ml)	0	N/A	N/A	N/A	N/A	N/A	N/A	

In Cell #2 (MLB1), the catholyte was collected on the first day with 260 mL totally. There was no *Salmonella spp.* and Fecal coliform in the catholyte. Table 4–3 illustrates the catholyte measurements of Cell #2.

Table 4–3 Catholyte measurements for Cell # 2

Cell #2 (MLB1)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte (mL)	260	0	0	0	0	0	0	260
pH of catholyte	10.66	N/A	N/A	N/A	N/A	N/A	N/A	
Color of catholyte	transparent yellowish	N/A	N/A	N/A	N/A	N/A	N/A	
Temperature of cell (°C)	25	25	25	24	24	24	24	
<i>Salmonella</i> <i>spp.</i> (cfu/ml)	0	N/A	N/A	N/A	N/A	N/A	N/A	0
Fecal coliform (cfu/ml)	0	N/A	N/A	N/A	N/A	N/A	N/A	

In Cell #3 (AoCB1), the catholyte was collected on the first three days of the experiment.

The volume of the catholyte decreased from 260 mL on the first day to 3.2 mL on the third day. The *Salmonella spp.* was detected on the first three days of the experiment.

Table 4–4 displayed the results of catholyte measurements for Cell #3.

In Cell #4 (AoB1), the catholyte was collected in the first three days. The pH was above 11 of all the catholyte. *Salmonella spp.* was detected in the first three days' catholyte. There was no Fecal coliform in the catholyte. Table 4–5 illustrates the catholyte measurements of the Cell # 4.

Table 4–4 Catholyte measurements for Cell # 3

Cell #3 (AoCB1)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte (mL)	260	5.2	3.2	0	0	0	0	268.2
pH of catholyte	9.96	11	11.46	N/A	N/A	N/A	N/A	
Color of catholyte	brown and black	trans-parent	trans-parent	N/A	N/A	N/A	N/A	
Temperature of cell (°C)	24	24	24	23	25	25	25	
<i>Salmonella</i> spp. (cfu/ml)	2167	460	230	N/A	N/A	N/A	N/A	2857
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

Table 4–5 Catholyte measurements for Cell # 4

Cell #4 (AoB1)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte	145	8	6	0	0	0	0	159
pH of catholyte	11.46	11.5	11.8	N/A	N/A	N/A	N/A	
Color of catholyte	yellow-ish	trans-parent	trans-parent	N/A	N/A	N/A	N/A	
Temperature of cell (°C)	24	24	24	23	24	24	24	
<i>Salmonella</i> spp. (cfu/ml)	980	870	267	0	0	0	0	2117
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

In Cell #5 (PoC1.5+Ct), the catholyte was collected on the first seven days of the experiment. The pH range was from 11.35 to 8.17. The *Salmonella* spp. was detected in

the first three days' catholyte. The concentration of *Salmonella spp.* in the catholyte decreased daily. Table 4–6 illustrates the catholyte measurements of Cell #5.

Table 4–6 Catholyte measurements of Cell # 5

Cell # 5 (PoC1.5+Ct)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume (mL)	100	40	35	17.5	8.8	4.8	1.4	207.5
pH of catholyte	11.35	10.62	10.15	10.05	9.14	8.24	8.17	
Color of catholyte	light brown	light brown	light yellow	yellow	greenish	yellow -ish	yellow- ish	
Temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella</i> <i>spp.</i> (cfu/ml)	1133	1200	167	0	0	0	0	2500
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

In Cell #6 (Po1.5+Ct), the catholyte was collected from day one to day five. The volume of catholyte decreased daily. *Salmonella spp.* was detected in the first three days' catholyte. Table 4–7 illustrates the catholyte measurements in Cell #6.

Table 4–7 Catholyte measurements for Cell # 6

Cell # 6 (Po1.5+Ct)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume (mL)	155	40	2.5	4.3	1.3	0	0	203.1
pH of catholyte	11.84	11.69	8.78	8.92	9.03	N/A	N/A	
Color of catholyte	dark yellow	yellow- ish	light yellow	yellow- ish	trans- parent	N/A	N/A	
Temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella</i> <i>spp.</i> (cfu/ml)	600	67	667	0	0	0	0	1334
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

In Cell #7 (MoC1.5+Ct), the catholyte was collected from day 1 to day 7. The volume of catholyte decreased significantly from day 1 to day 2. The pH of the catholyte was above 8.54. *Salmonella spp.* was detected on the first two days. Table 4 – 8 illustrates the catholyte measurements for Cell #7.

Table 4–8 Catholyte measurements for Cell # 7

Cell # 7 (MoC1.5+Ct)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte	202	69	30.5	8.1	7.2	8.85	4.8	330.5
pH of catholyte	10.35	11.71	11.22	9.6	9.63	9.53	8.54	
Color of catholyte	dark brown	light yellow	trans-parent	bluish	bluish	trans-parent	trans-parent	
Temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella spp.</i> (cfu/ml)	333	200	0	0	0	0	0	533
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

In Cell #8 (Mo1.5+Ct), the catholyte was collected in seven days of the experiment. The volume decreased daily. The concentration of *Salmonella spp.* also decreased daily. No Fecal coliform was detected in the catholyte. Table 4–9 illustrates the catholyte conditions for Cell # 8.

Table 4 –9 Catholyte measurements for Cell # 8

Cell # 8 (Mo1.5+Ct)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte	149	15	16.8	3.2	6.5	7.7	4.8	203
pH of catholyte	11.76	11.62	10.97	9.15	8.94	8.5	8.33	
Color of catholyte	light yellow	yellow	trans-parent	trans-parent	trans-parent	trans-parent	trans-parent	
Temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella</i> spp. (cfu/ml)	1033	333	167	67	0	0	0	1600
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

In Cell #9 (AoC1.5+Ct), the catholyte was collected in seven days. *Salmonella* spp. was detected in the first three days' catholyte. No Fecal coliform was detected in the seven days of the experiment. Table 4–10 illustrates the catholyte measurements for Cell #9.

Table 4–10 Catholyte measurements for Cell # 9

Cell # 9 (AoC1.5+C)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte	211.3	25	23	18	8	8	1	294.3
pH of catholyte	10.19	11.46	10.93	10.35	9.73	9.5	9.2	
Color of catholyte	orange	yellow-ish	yellow-ish	yellow	light yellow	yellow	yellow	
Temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella</i> spp. (cfu/ml)	1067	833	800	0	0	0	0	2700
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

In Cell #10 (Ao1.5+Ct), the catholyte was collected on the first four days of the experiment. The concentration of *Salmonella spp.* and Fecal coliforms was measured on a daily basis. *Salmonella spp.* was detected on the first four days of the experiment. No Fecal coliform was detected in catholyte. Table 4–11 illustrates the catholyte measurements for Cell # 10.

Table 4–11 Catholyte measurements for Cell #10

Cell #10 (Ao1.5+Ct)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Volume of catholyte	230	1.25	1	0.8	0	0	0	233.05
pH of catholyte	10.38	10.27	9.56	9.65	N/A	N/A	N/A	
color of catholyte	dark brown	trans-parent	trans-parent	trans-parent	trans-parent	trans-parent	trans-parent	
temperature of cell (°C)	25	25	25	25	25	25	25	
<i>Salmonella spp.</i> (cfu/ml)	2066	666	67	67	0	0	0	2866
Fecal coliform (cfu/ml)	0	0	0	0	0	0	0	

The volume of catholyte collected in each EK cells during the experimental period was plotted in Figure 4-43.

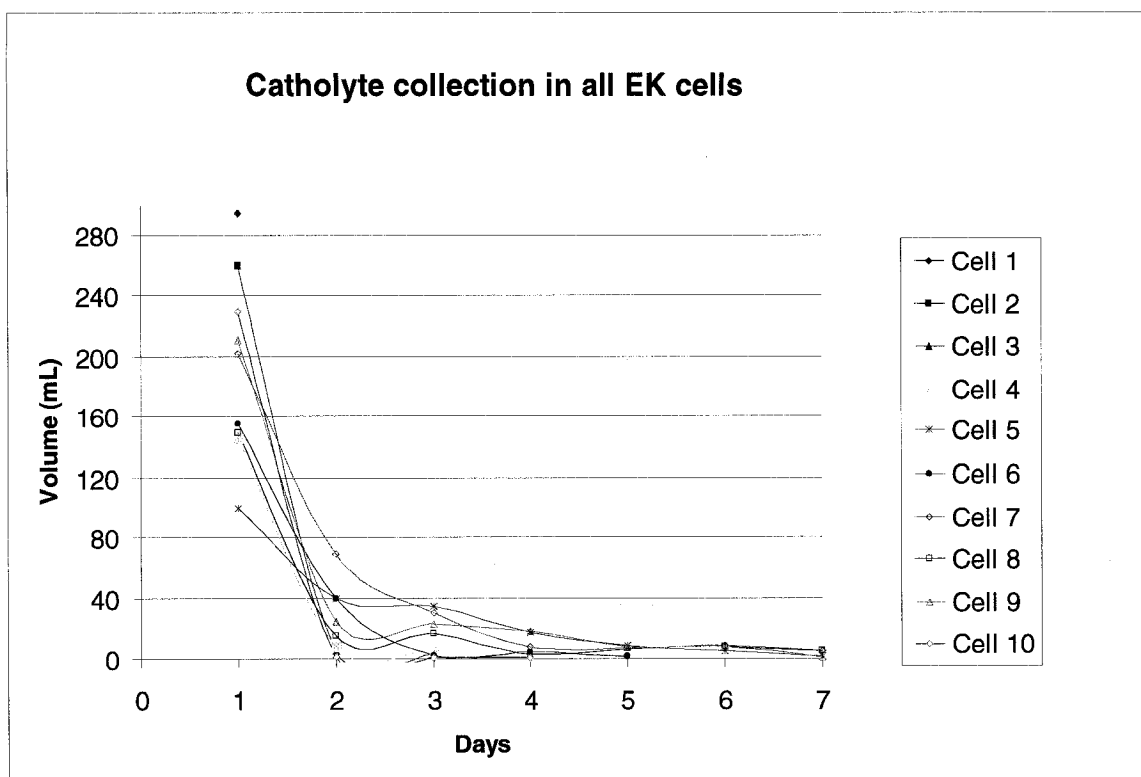


Figure 4-43 Catholyte collection vs. time

The maximum water removal efficiency was reached during the first 48 hours in all cells.

Particularly in some cells (Cells #1 and 2), it reached even during first 24 hours.

4.9 Discussion

This chapter provides the discussion of results from the experimental work.

4.9.1 Drying Process

Dewatering efficiency differed in terms of the types of biosolids, the addition of the conditioner, the application of the blower system, and the voltage gradient.

4.9.1.1 Effect of Sludge Type on Drying

Results illustrate that the electrokinetic dewatering of mixed primary and secondary sludge could achieve highest total solids content (98.5% TS) than primary and anaerobic digested sludge. The sludge in Cells #1 (MCLB1) and #2 (MLB1), Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct) express a high non-uniformity due to mixture of various components, which is the most suitable case for electrokinetic treatment. In addition, combined thickened sludge in Cells #1 and #2, which showed the highest dewatering, contained already a polymer enhancing the effectiveness of the process. Figure 4-43 illustrates the average, the maximum and the control total solids content in all the ten cells. The figure demonstrates that the newly developed electrokinetic methodology is able to achieve 3 to 4 times higher dewatering rate than the currently applied methods.

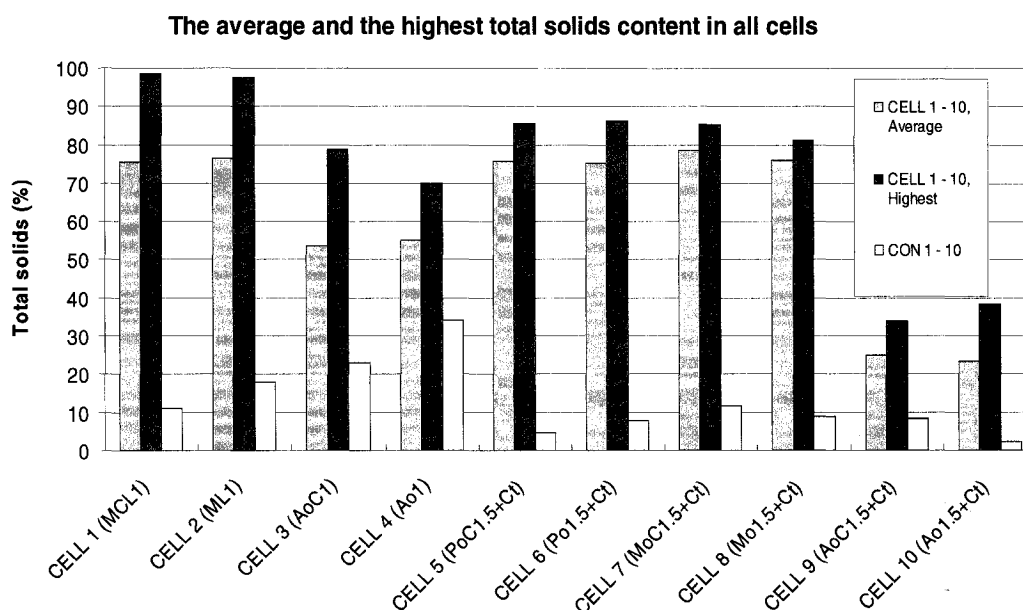


Figure 4-43 The average and the highest total solids content

4.9.1.2 Effect of Voltage Gradient

The higher voltage gradient yielded higher average total solids content among the cells with mixed sludge. The average total solids content was higher in Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct) with 1.5 V/cm than in Cells #1 (MCLB1) and #2 (MLB1) with 1V/cm. Contrary, it is speculated that for anaerobic sludge the lower gradient is also more suitable because it permits on slower formation of flocs due to electro-coagulation and better release of associated water (Elektorowicz et al., 2006).

4.9.1.3 Effect of Blower on Electrokinetic System

The combination of electrokinetic system with blower had higher dewatering efficiency on the biosolids. Therefore, Cells #3 (AoCB1) and #4 (AoB1) had higher total solids content than Cells #9 (AoC1.5+Ct) and #10 (Ao1.5+Ct) although they were the same type of sludge. It was estimated that the blower accelerated evaporation of free water released during the electro-coagulation process. Therefore, a methodology on two-step process: electro-coagulation (due to EK) and accelerated evaporation (due to additional blower) seems to be the most successful technique for biosolids dewatering.

4.9.1.4 Effect of Conditioner

The addition of conditioner could enhance the dewatering efficiency of biosolids due to an improvement in electro-coagulation process. The average total solids content was higher in cells with conditioner than that of their counterparts. It was speculated that a higher concentration of the conditioning liquid could much more enhance the dewatering process. A combination of two conditioners might also give some better results.

4.9.2 Volatile Solids Content

Compared to all cells, most of the initial samples had higher volatile solids content than that of the control cells. The control cells had higher volatile solids content than most of the EK cells. Electrokinetic system can achieve the removal of the volatile solids contents.

The lowest average values of VS were observed in mixed sludge from Laval (Cells #1 and #2), and the highest in anaerobic sludge (Cells #3 and #10).

The highest reduction of VS was found to be 70.8% (Cell #6); however the lowest average decrease was found in anaerobic sludge (5% in Cell #3). The average volatile solids contents were 2% higher in the cells with conditioner than the cells without conditioner. The volatile solids content was close at the anode area and the cathode area. Figure 4-44 illustrates the average and the highest volatile solids removal in ten cells. The average reduction rates showed in descendent order were the following: 43% (Cell #5), 32% (Cell #6), 25% (Cell #7), 17% (Cell #1), 12.1% (Cell #8), 11.8% (Cell #2), 10.8% (Cell #4), 7.8% (Cell #9), 6% (Cell #10), and 5% (Cell #3).

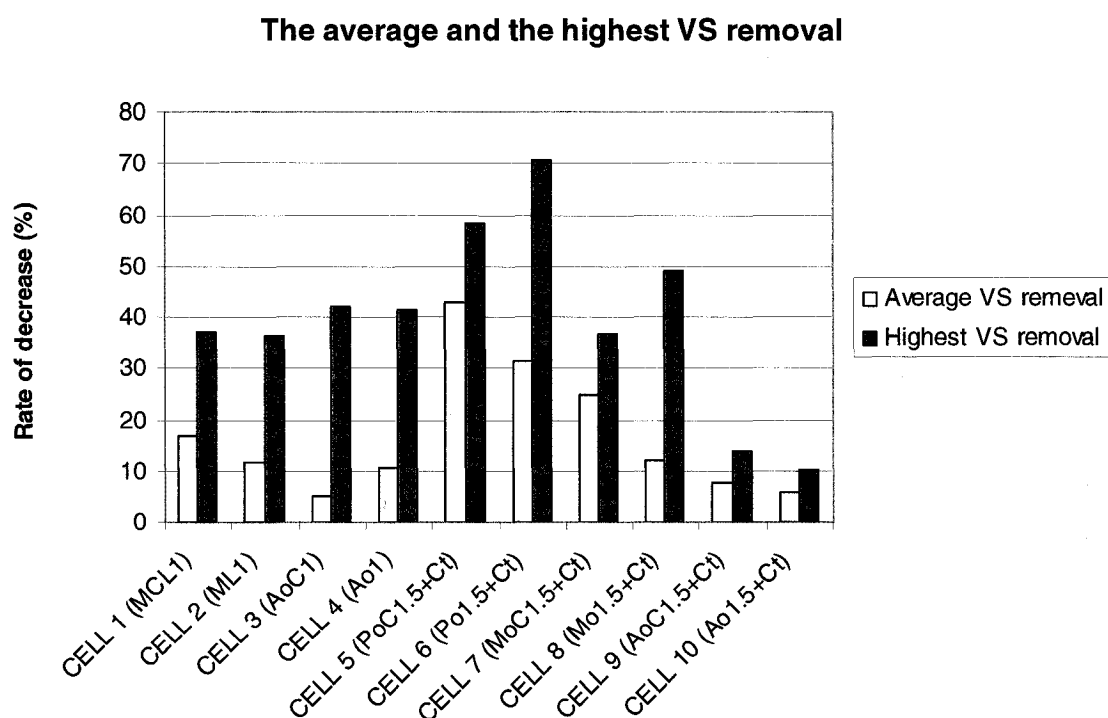


Figure 4-44 The average and the highest VS removal in all cells

In general, the highest VS removal was observed in cells with the conditioner. The distribution of VS in cells with conditioner had also similar trend as TS distribution.

4.9.3 Anions

4.9.3.1 Chloride

The chloride content is higher in control cells than in any of the electrokinetic cells. The initial chloride concentration was much lower than the value of the control cells. The cells with conditioner had higher chloride content than that of the cells without conditioner. It was speculated that conditioner could enhance the dissociation of the electrolytes under the electric field.

The electrokinetic removal had the highest impact on chloride content in Cell #1 and #2. It is speculated that polymer previously added to the original samples facilitated the removal of chloride. Generally, the cells without conditioner had higher chloride removal.

4.9.3.2 Sulfate

The sulfate content in control cells was much higher than that of the EK cells. The initial sample usually had higher sulfate content than the EK cells. Sulfate reduction can be attained by the application of electrokinetic system. The high reduction of sulfate was observed in all EK cells. The highest removal was observed in Cell #8 (99.4%), and Cell #6 (97%); the lowest removal in Cell #9 (72%).

4.9.4 Pathogen Inactivation

The *Salmonella spp.* reduction was achieved by the electrokinetic system. In Cell #1 (MCLB1), 8-log reduction was attained in the near anode area which covered the range of acidic front of the cell. From the acidic front to the cathode, 9-log reduction was

achieved. In Cell #2 (MLB1), 7-log reduction was achieved in the near cathode area, and 9-log reduction was achieved from anode to the near cathode area. In Cell #3 (AoCB1), 9-log reduction was achieved at near anode area. In Cell #4 (AoB1), 11-log reduction was achieved. In Cells #5 (PoC1.5+Ct) and #6 (Po1.5+Ct), 10-log reduction was achieved. In Cells #7 (MoC1.5+Ct) and #8 (Mo1.5+Ct), 9-log reduction was achieved. In Cell #9 (AoC1.5+Ct), 6-log reduction was achieved in the middle cathode area. From the near cathode area to the cathode, the log reduction decreased gradually from 7-log reduction to 6-log reduction. In the back cathode area, the log reduction increased to 7-log reduction. In Cell #10 (Ao1.5+Ct), 6-log reduction was achieved at the cathode area. Figure 4-45 illustrates the log-reduction of *Salmonella* spp. in all the EK cells.

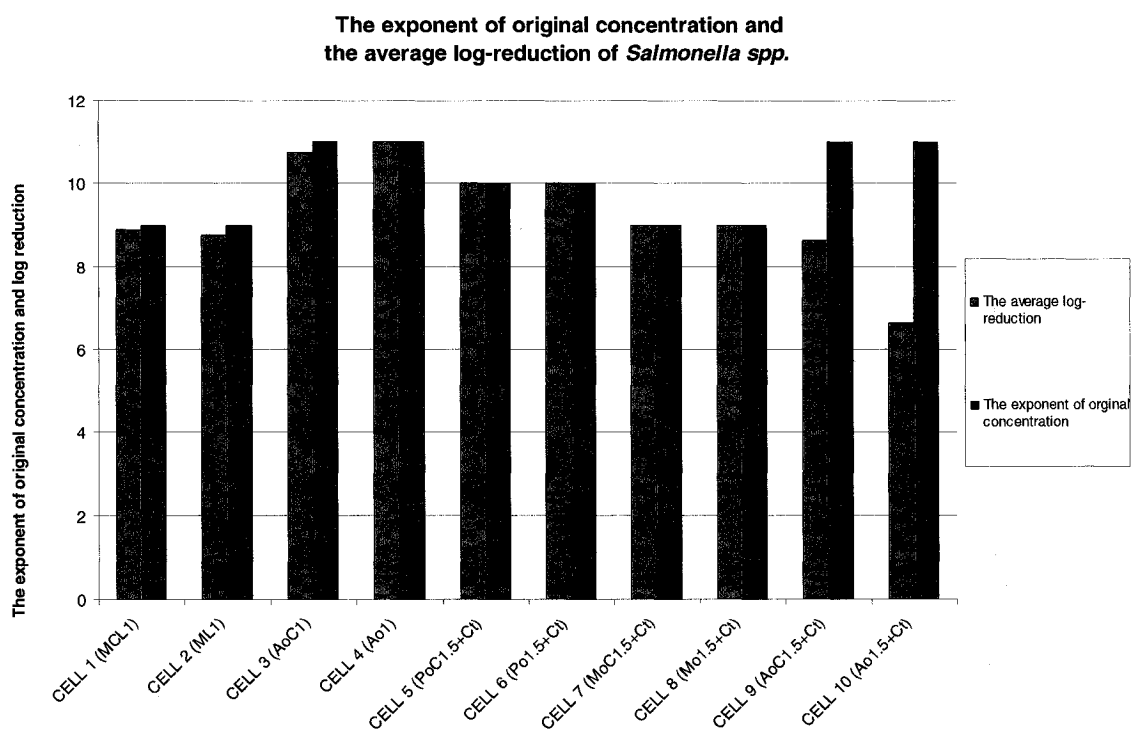


Figure 4-45 The average log reduction of *Salmonella* spp. in all cells

The anode area achieved higher log reduction than that of the cathode area. It is estimated that the acidic front yielded the highest log reduction of *Salmonella spp.*. Anaerobic digestion system achieved the highest *Salmonella spp.* removal among all the cells with electrokinetic systems.

It seems that presence of *Salmonella* in some cells' sections is also related to the cracking of the dried sludge material leading to a non-uniform influence of electrokinetic phenomena (acidic/oxidation front) in all segments.

The key mechanisms responsible for inactivation of microorganisms were speculated as follows:

1. Extended acidic zone indicated oxidation zone that affected the survival of microorganisms.
2. Rapid desiccation in the EK cells enhanced the oxidation process which destroyed the cell walls of microorganisms.
3. Addition of ammonia salts enhanced pH gradient leading to enhanced oxidation and reducing zones.
4. Competitions between *Salmonella spp.* and other bacteria affected the living condition of microorganisms. *Bacillus amiloliquefaciens* (Figure A-14) were identified in Cells #9 and 10, mostly in the back of anode and to some distance from anode until neutral area. *Clostridium* was also added to Cells #5-10; however, no *Clostridium* was detected either in EK cells or in catholyte.

4.9.5 Catholyte

The first day's catholyte collection reached more than 50% of the total collection in most EK cells. The cells with conditioner usually removed more liquid than the cells without conditioner on the first day of the experiment. For pictures of catholyte please refer to Appendix (Figure A-6 to A-12). Figure 4-46 illustrates the volume of catholyte and the *Salmonella spp.* concentration in catholyte.

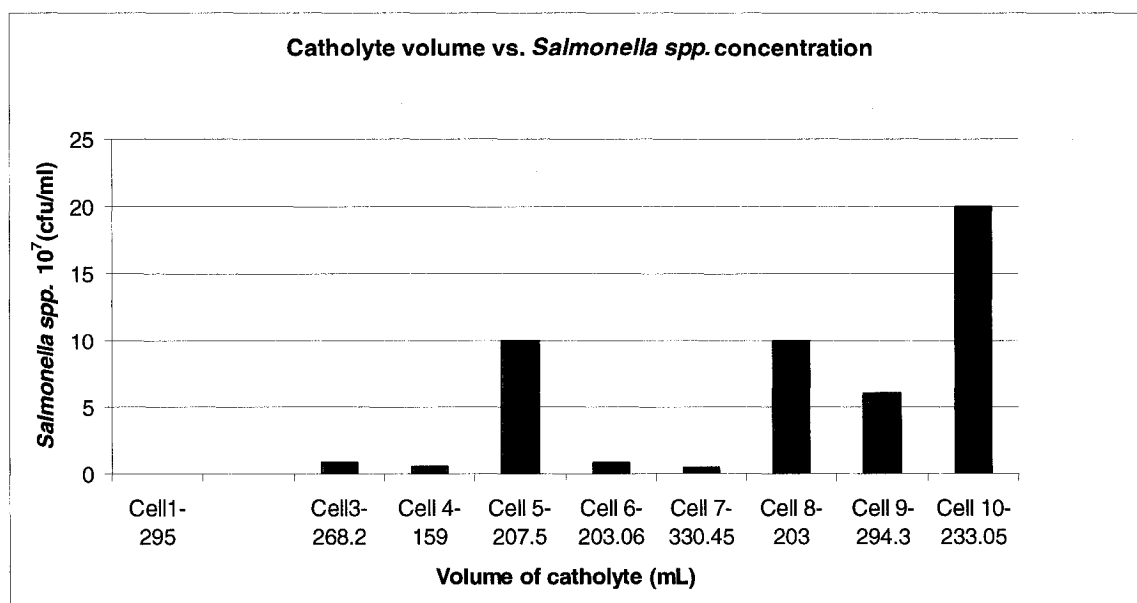


Figure 4-46 The catholyte volume and the *Salmonella spp.* concentration in catholyte

Since no Fecal coliform was detected in catholyte, it was concluded that EK method applied to biosolids provoked its disinfection in respect to standard pathogens. A significant decrease of *Salmonella spp.* was observed in all EK cells. This decrease was due to partial removal with catholyte and inactivation of *Salmonella spp.* within the mass of biosolids.

4.9.6 Residuals and their fate after EK treatment

Catholyte and dried sludge are residuals remaining from the EK process. The catholyte can be redirected to further treatment or can be returned to activated sludge reactor. Sludge is ready for land application as it has an Exceptional Quality level. In this study, ammonia salts were added as a conditioner, which was regarded as nutrients - non-harmful for land neither for biological treatment in WWTP.

4.9.7 Power Consumption

Figure 4-47 illustrates the average resistance variation versus time.

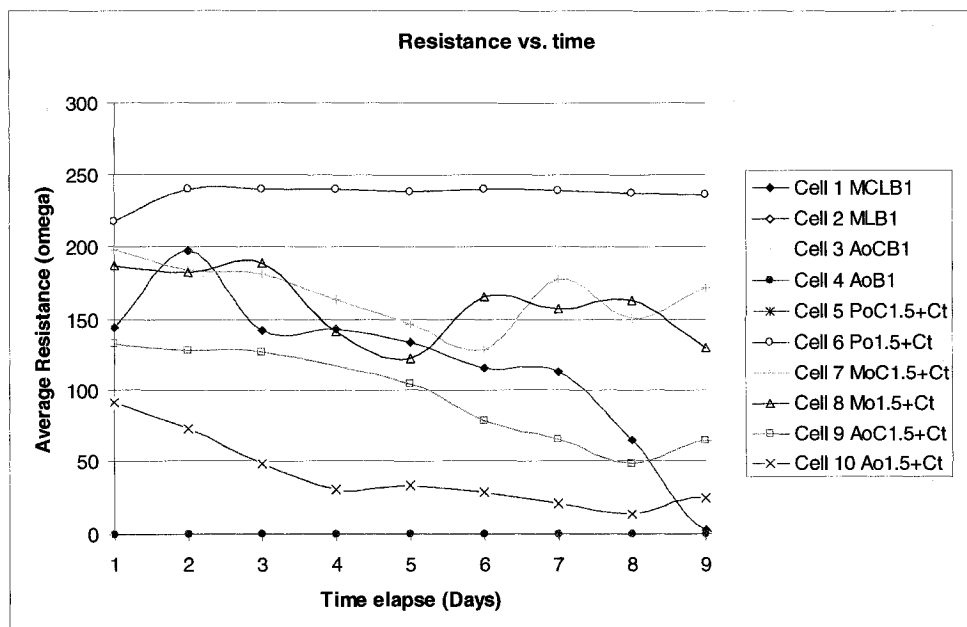


Figure 4-47 Average resistance vs. time

The power and energy consumption of Cells #1 to #10 was summarized in the Table 4-12. The current electric rate is \$0.04/kW·h; the cost of electric power and the unit price for biosolids management were calculated in the table. The cost of one cell operation was quite low. The best results for disinfection only cost 0.029 \$ per cell.

Table 4-12 Power and energy consumption of EK process

Cell Energy Consumption	1 MCLBI	2 MLBI	3 AoCBI	4 AoI	5 PoCl ₅ +Cl	6 PoI ₅ +Cl	7 MoCl ₅ +Cl	8 MoI ₅ +Cl	9 AoCl ₅ +Cl	10 AoI ₅ +Cl
kW·h	0.0432	0.0432	0.0323	0.0344	0.0504	0.0498	0.0576	0.0548	0.0453	0.0288
kW·h/m ³ of biosolids	108	108	80.7	86	126	124.5	144	137	113.2	72
\$/ m ³ of biosolids	4.32	4.32	3.23	3.44	5.04	4.98	5.76	5.48	4.53	2.88
\$/ m ³ of Total Solids	179	179	131	140	92	91	152	145	185	118

The overall economical calculations demonstrated the fact that the developed EK treatment process accomplished dewatering, drying, disinfection and leaching of metals in one single unit operation. Subsequently, the lower capital, lower operational and maintenance costs render the electrokinetic process more economically and environmental sustainable.

CHAPTER 5 CONCLUSION

Conclusions can be drawn in the following aspects:

The dewatering process:

1. The dewatering efficiency of mixed sludge was higher in cells with conditioner than the cells without conditioner, which was demonstrated by the total solids results from cells containing the combined sludge (Cells #1, #2, #7 and #8). The TS content was similar in both cells with primary sludge (Cells #5 and #6). The dewaterability of combined sludge and primary sludge was much higher than anaerobic digested sludge due to the floc structure and conditioner additions.
2. The highest total solids content was produced at cells with the lower voltage gradient. The accumulation of solid particles increased at the anode area due to the electroosmosis and electrophoresis phenomena, which, in turn, increased the resistance at that area. The process was strongly dependent on the electrical potential. It was observed that the lower voltage gradient produced slower electrocoagulation process, and then formed solids with more compacted structure and higher solids content. And subsequently, higher removal of water was obtained.
3. Although, the anaerobic digested sludge have achieved lower total solids content than the primary and mixed sludge, this TS was higher than that after a conventional treatment. An average total solids content was around 20 - 55% higher in cells with primary and mixed sludge than with aerobically digested sludge. In cells with conditioner and blower system, the average total solids content was 22% higher in mixed sludge than in anaerobic digested sludge. In cells without conditioner, but with blower, the average total solids content was

21% in cells with mixed sludge than with anaerobic digested sludge. The similar trend was observed if the highest values of TS in combined and anaerobic sludge were compared.

The inactivation of Fecal coliforms and *Salmonella spp.*:

1. No Fecal coliforms were detected after EK treatment in all EK cells, except that in Cell #3 (anaerobic digested sludge with conditioner and under gradient of 1 V/cm where 3-log reduction was achieved).
2. Primary sludge had a significantly high average 10-log reduction of *Salmonella spp.* It was found that pathogens in the primary sludge were vulnerable to EK inactivation.
3. In the combined sludge, the disinfection results showed that the addition of conditioner coupled with the EK higher voltage gradient increased the inactivation effects.
4. The inactivation of pathogens in anaerobic digested sludge seems to be affected significantly by the voltage gradient. Lower voltage produced better results (Cells #3 and #4).
5. The vulnerability of pathogens had relations to pathogens presence in catholyte. It was found that higher the *Salmonella spp.* concentration in catholyte, the lower the *Salmonella spp.* log reduction (Cells #9 and #10).

It was observed that different types of biosolids showed different responses to the EK system. For primary sludge, under the higher voltage gradient, the addition of conditioner did not have significant influence on the removal of *Salmonella spp.* and dewatering. For

anaerobic digested sludge, the lower voltage gradient was better for the removal of *Salmonella spp.* and achieved higher dewatering efficiency. For combined sludge, the higher voltage gradient facilitated better removal of *Salmonella spp.*, but the lower voltage gradient yielded higher total solids contents in the cell.

The results showed that the electrokinetic method permitted to achieve the upgrading all types of sludge to level A and “Exceptional Quality”. The dewatering achieved the level from 3 to 4 times higher than conventional methods. The pathogen (including *Salmonella*) log reduction was much higher than 3 log which is an acceptable by EPA standard level.

The study changed the concepts of sludge to biosolids conversion from the standpoint of currently used sludge processing trains in the conventional WWTP. The developed EK treatment process accomplished dewatering, drying, disinfection and leaching of metals in one single unit operation. The lower cost, less unit operations, and less maintenance render the electrokinetic process more environmental sustainable.

Recommendations and Future Work

The following further research work is recommended:

1. Investigation of stressors affecting microorganisms subjected to combination of electrokinetic phenomena and various conditioners;
2. Application of other voltage gradients, cell configurations and different types of the electrodes;
3. Investigation of a competition of the bacteria in the cells during the EK disinfection/dewatering;
4. Investigation of the impact of the polymer on the disinfection process.

Contributions

1. Achieved generation of Class A / “Exceptional Quality” biosolids by applying Electrokinetic phenomena;
2. Achieved 3 to 4 times higher dewatering efficiency for biosolids than conventional systems;
3. Developed a method for simultaneous dewatering of biosolids and disinfecting for all types of biosolids;
4. Deactivated *Salmonella spp.* and Fecal coliforms in biosolids and obtained high log reduction by applying electrokinetic phenomena;
5. Evaluated the response of different aerobic and anaerobic digested sludge to the application of the conditioner at a medium concentration.

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APPENDIX

Photographs

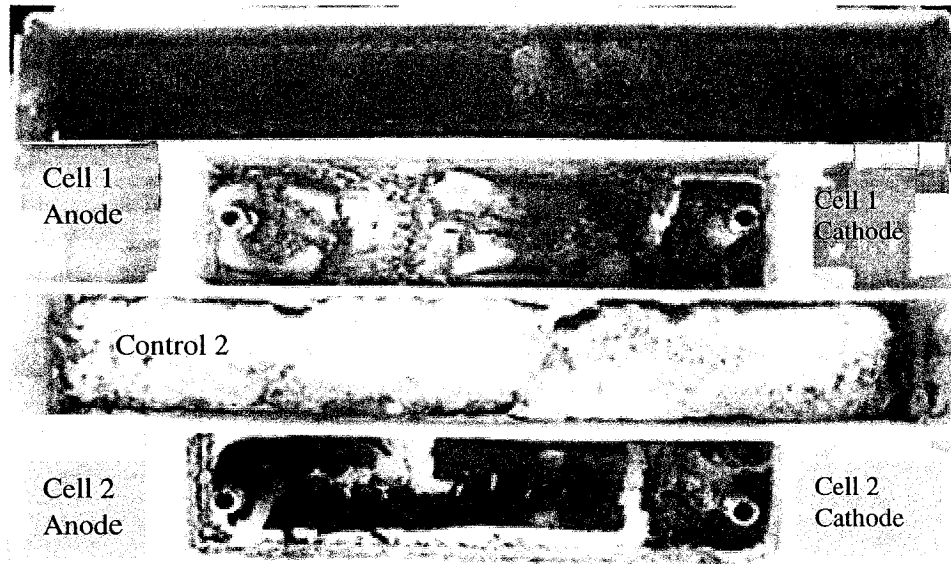


Figure A-1 Cells #1 and 2 after EK treatment

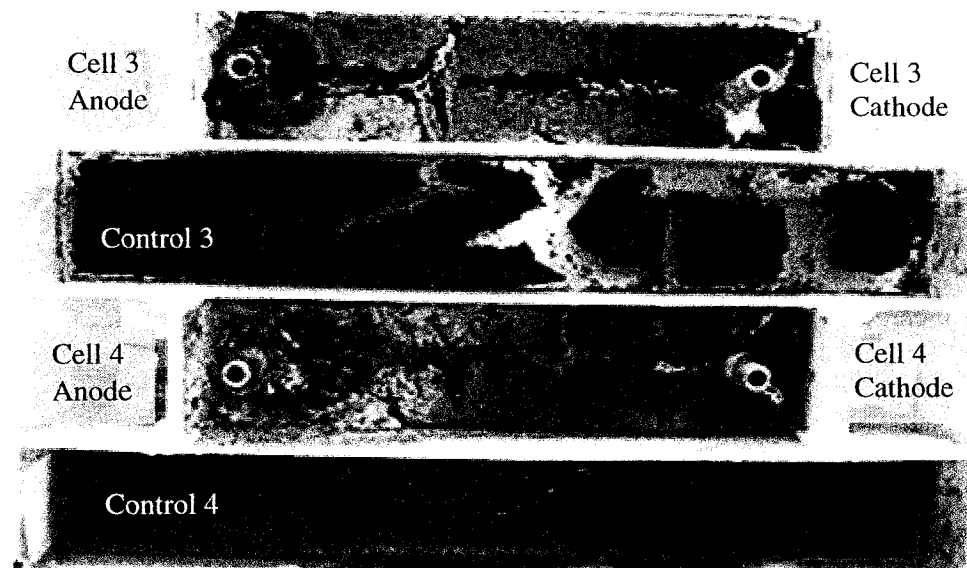


Figure A-2 Cells #3 and 4 after EK treatment

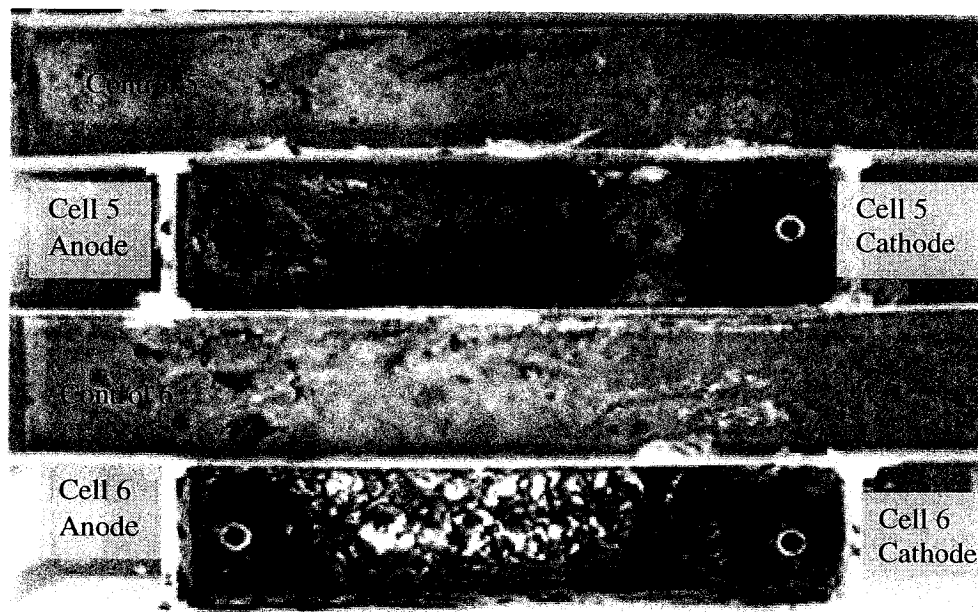


Figure A-3 Cells #5 and 6 after EK treatment

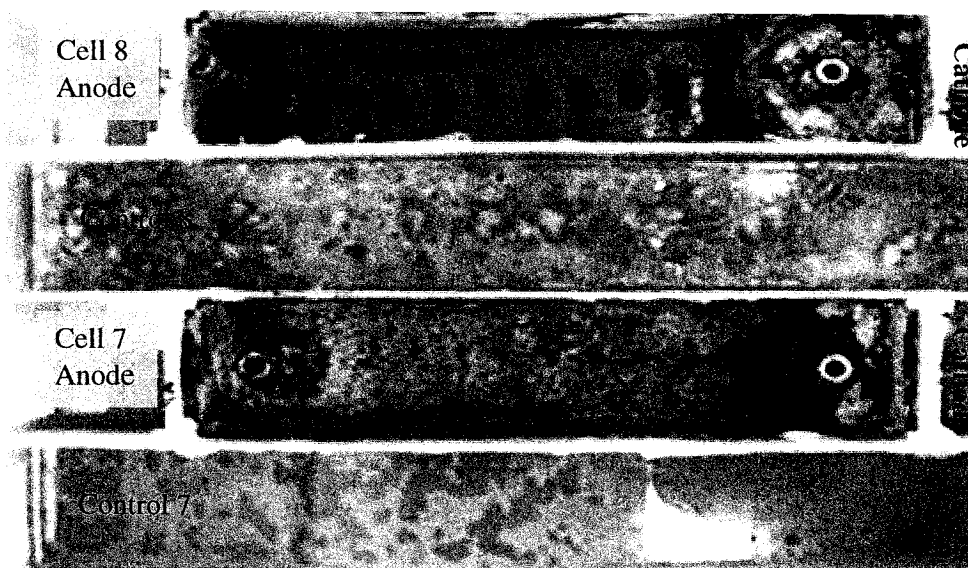


Figure A-4 Cells #7 and 8 after EK treatment

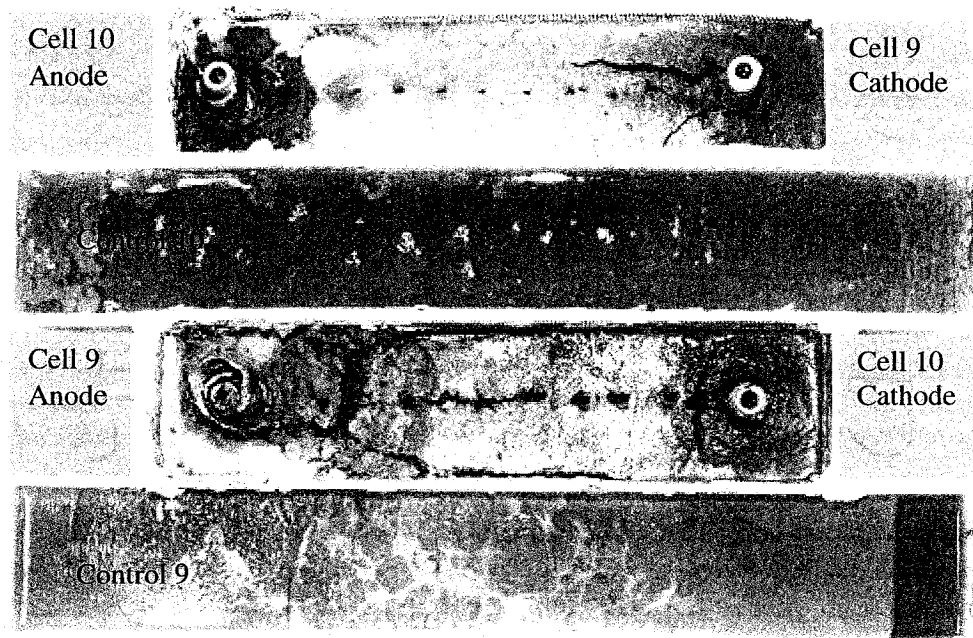


Figure A-5 Cells #9 and 10 after EK treatment

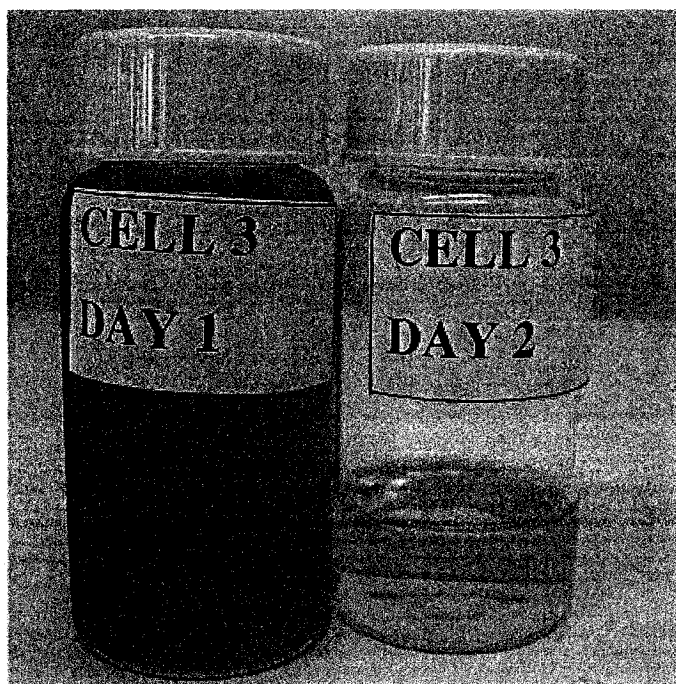


Figure A-6 Catholyte of Cell #3

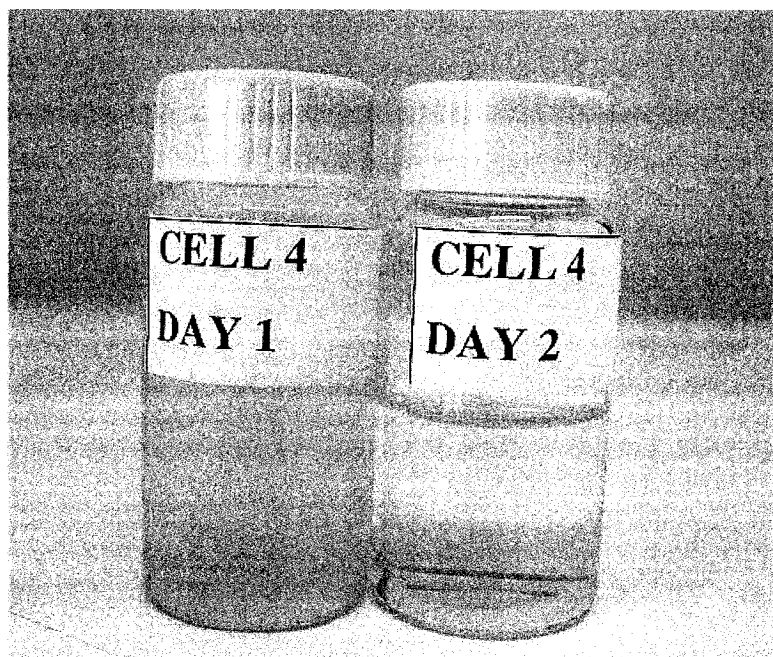


Figure A-7 Catholyte of Cell #4

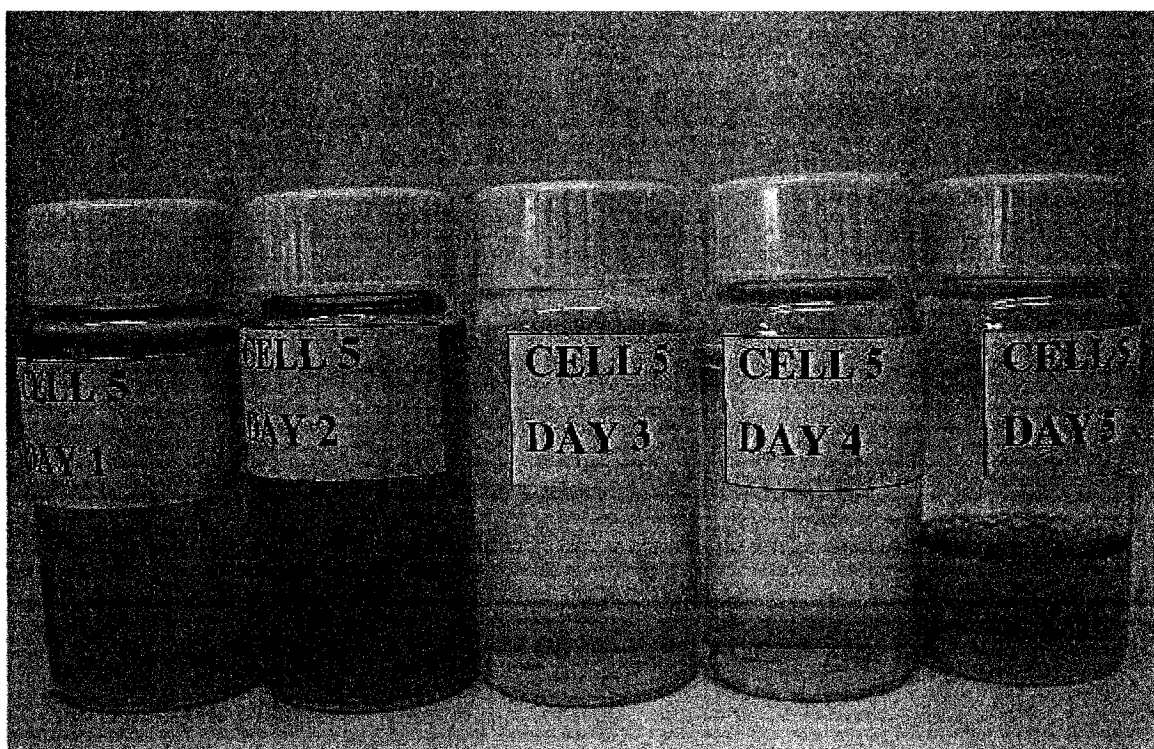


Figure A-8 Catholyte of Cell #5

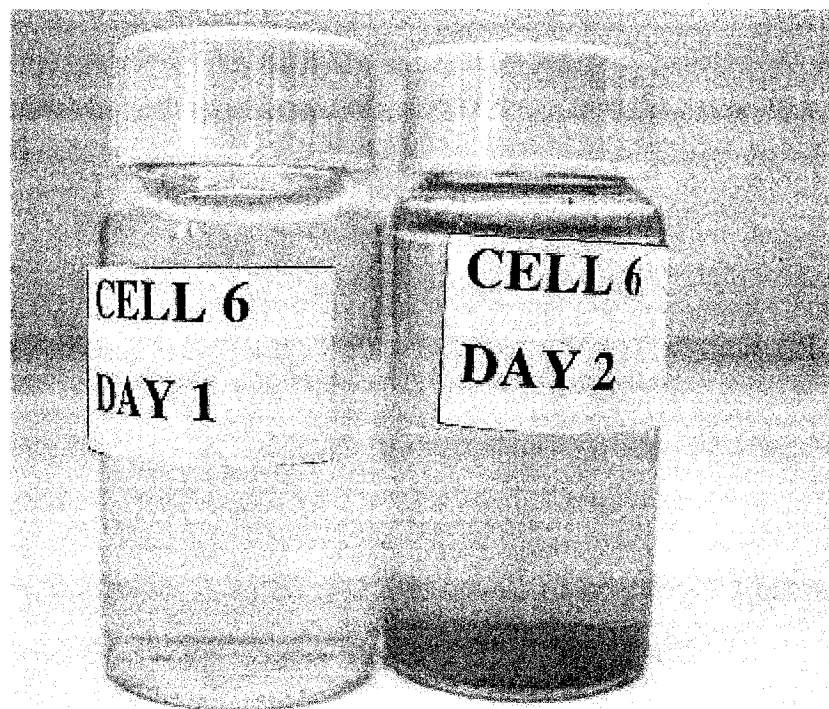


Figure A-9 Catholyte of Cell #6

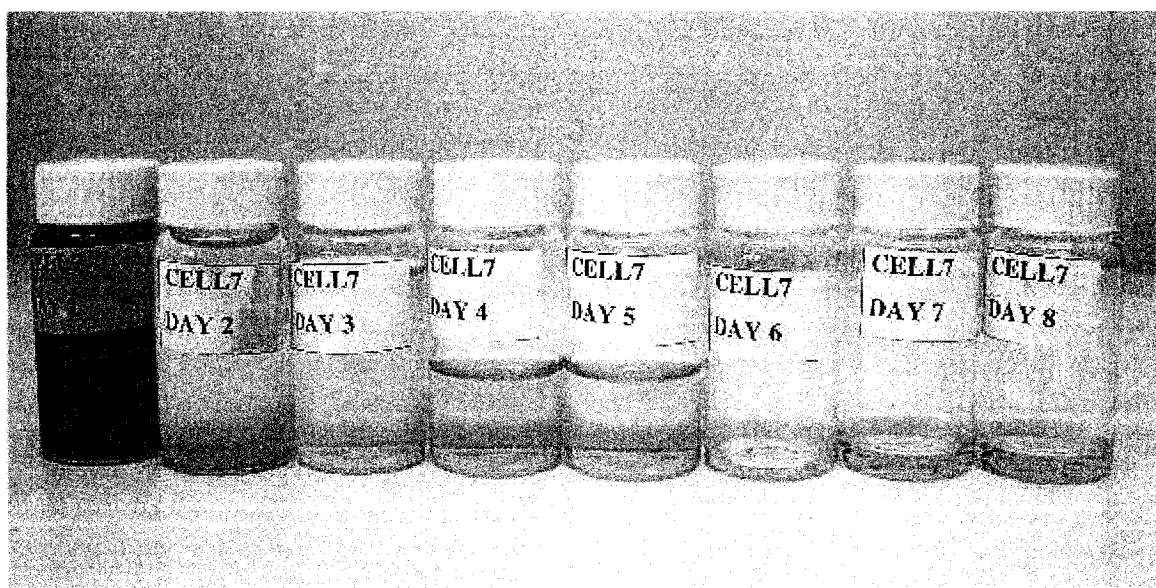


Figure A-10 Catholyte of Cell #7

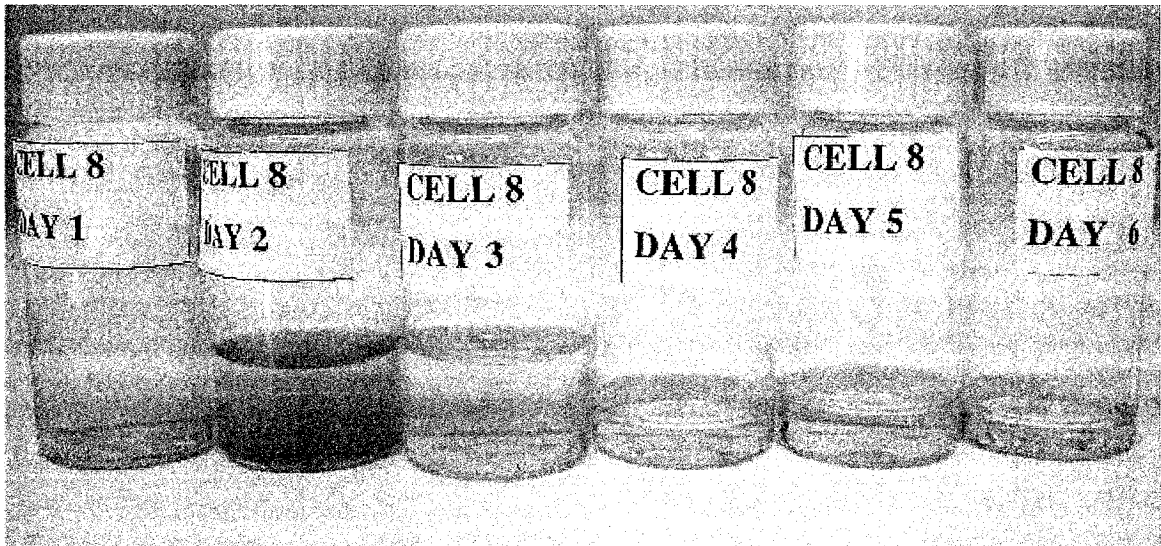


Figure A-11 Catholyte of Cell #8

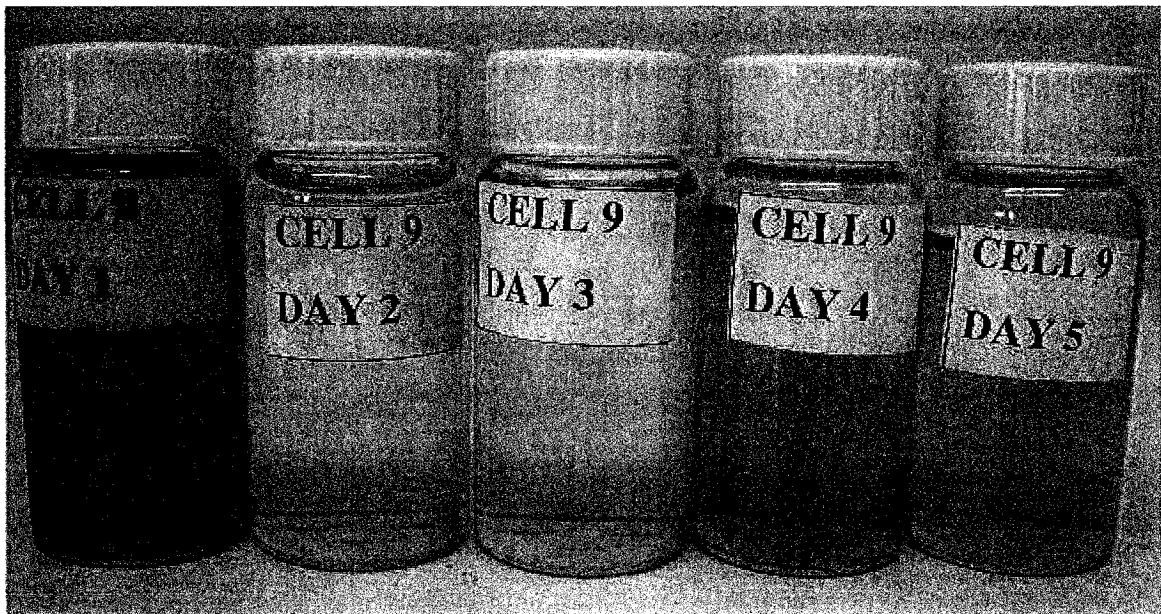


Figure A-12 Catholyte of Cell #9

Note: Materials may be taken for sampling procedures. Figures may not be a full representative of the real laboratory results.



Figure A-13 *Salmonella spp.* colonies on BG agar



Figure A-14 Gray-white *Bacillus amiloliquefaciens* colonies

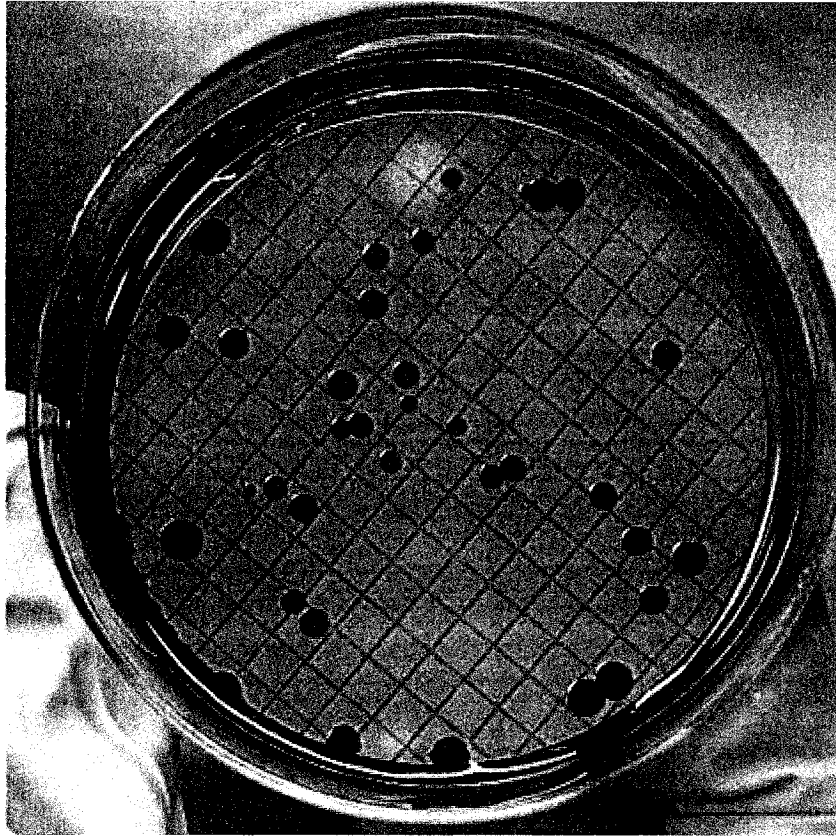


Figure A-15 Fecal coliforms colonies