Application of Electrokinetics to Control Metal Transports in Biosolids in a Cold Climate

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ABSTRACT

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Biosolids, the end product of municipal wastewater treatment contains many of the constituents removed from the influent wastewater. Constituents of wastewater sludge include organic contents, nutrients, pathogens, metals, and toxic organics. Concentration of heavy metals in sewage sludge is one of the major issues of public concern, when sludge is applied on land. Municipalities in cold climate regions face specific problems during winter months due to snow and severe weather conditions when land application of biosolids becomes difficult or impossible. The major goal of this research was to investigate the impact of extremely low winter temperatures as faced on the Canadian prairies on the functionality of electrokinetic processes and to assess technical feasibility of the electrokinetic method for the removal of metals from municipal biosolids in extreme cold winter condition.

Biosolids in rectangular polyethylene cells were subjected to electrokinetic processes at –8 and –15 °C ambient temperatures. Tests were carried out both biosolids alone and biosolids mixed with conditioning liquid. Metal contents analyses of biosolids samples after the application of electrokinetics indicated excellent movement of metal ions towards the cathode. Concentrations of cadmium, copper, lead, nickel and zinc in the cathode areas were found respectively 195%, 97%, 118%, 26% and 1686% higher than the concentrations in the anode areas in cells that showed the best movement of the respective metals. Use of conditioning liquid slowed down the biosolids freezing process.

A 10% concentration increase of the conditioning liquid helped to extend the working period of the electrokinetic processes in freezing biosolids by 15%, thus the conditioning liquid enhanced the performance of the system and helped to obtain better movement of metals.

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TABLE OF CONTENTS

List of Figures

List of Tables

Abbreviations

AAS	Atomic Absorption Spectrometry
BOD_5	Biological Oxygen Demand (5 days)
DC	Direct Current
DNAPL	Dense Non-Aqueous Phase Liquid
EC	Electrocoagulation system
EC-ER	Electrocoagulation-electroreduction system
EDL	Electric Double Layer
EDTA	EthyleneDiamineTetraacetic Acid
EK	Electrokinetics
EPA	Environmental Protection Agency
ER	Electroreduction system
IET	Ion Exchange Textile
NTA	NitriloTriacetic Acid
POTW	Publicly Owned Treatment Works
SD	Standard Deviation
SS	Suspended Solid
TCE	Trichloroethylene
UK	United Kingdom
WCL	With Conditioning Liquid
WOCL	Without Conditioning Liquid
WWTP	Wastewater Treatment Plant

CHAPTER 1 INTRODUCTION

1.1 Statement of the Problem

Human civilization has been facing the challenge of dealing with human wastes historically from the days they started living in communities. In the early ages, when population densities were low, land and water bodies could handle human wastes and even enhanced soil fertility. Later, as the population increased and the consequent waste generation the surrounding lands were incapable of handling the increased waste load; they were dumped into streams and rivers that carried them away but usually created problems downstream.

Biosolids are the end products of municipal wastewater treatment and contain many of the constituents removed from the influent wastewater. The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500, 1972) and subsequent legislations in the United States and similar laws in different countries world-wide around that time placed restrictions on the discharge of pollutants to waterways and encouraged beneficial uses. Furthermore, stringent requirements of effluent quality obliged municipal sewage treatment plants, or Publicly Owned Treatment Works (POTWs), around the world to apply higher degrees of treatments and as a consequence, biosolids produced in the treatment works contain higher quantities of pollutants.

Biosolids (historically known as sewage sludge) are by far the largest in volume of the constituents removed from wastewater by treatment and its processing and disposal is perhaps the most complex problem facing the engineer in the field of wastewater

treatment. The problems of dealing with sludge are complex because (1) it is composed largely of the substances responsible for the offensive character of untreated wastewater; (2) the portion of sludge produced from biological treatment requiring disposal is composed of the organic matter contained in the wastewater in a different form, which can also decompose and become offensive; and (3) only a small part of the sludge is solid matter (Metcalf and Eddy, 1995).

Wastewater treatment operations and processes produce sludge usually in the form of a liquid or semisolid liquid that typically contains from 0.25 to 12 percent solids by weight (Metcalf and Eddy, 1995). Constituents of wastewater sludge include organic content, nutrients, pathogens, metals, and toxic organics. Concentrations of heavy metals in sewage sludge are one of the major issues of public concern when sludge is applied on land and may limit the sludge application rate and the useful life of the application site. Metals in sludge come mainly from industrial, institutional, commercial and residential effluent, and from the water supply pipes themselves. Both the type and degree of treatment in the wastewater treatment plant affect the concentration of metals in biosolids. In primary treatment only the solid portion of trace metals are removed, whereas in secondary treatment the microbial mass accumulates it, at the same time the remaining trace metals can be adsorbed on the cell walls of these masses. In biosolids production, biomass produced from both the processes undergoes digestion or stabilization that results in the reduction of biomass and the production of methane and carbon dioxide. During this process the trace metals accumulate in the biosolids organic matter matrix and oxides of iron, aluminum and manganese either through ion exchange or complexation reactions (The Biosolids Report, 1999).

Recent regulations restrict ocean disposal of wastes and landfilling, as well as there are shortage of available disposal and landfilling sites. Moreover, there are increasing concerns about incineration of wastes worldwide and legislations encourage land application of biosolids. All these, perhaps left land application as one of the best, if not the only option of biosolids management for many municipalities around the world. However, public concerns persist regarding the presence of pollutants and pathogens in biosolids that might find their way to humans through plant uptake, direct contact, and animal ingestion and pollute water resources (Reilly, 2001; Apedaile, 2001; EPA530-R-99-09). One of the major concerns of land application of biosolids is that trace metals can accumulate in soils through repeated applications and become toxic to plants or lead to increased uptake of metals into the food chain. There are organizations of farmers around the world reluctant to accept biosolids on their lands and groups of peoples oppose land application of biosolids also because of the trace metal issue among others. Ten trace metals e.g., arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium and zinc are identified to be of concern because of their toxic effects to plants, animals and humans (The Biosolids Report, 1999).

Removal of metals from biosolids is therefore an essential and contemporary challenge for environmental engineers working in the field of wastewater engineering to return biosolids to land in a more acceptable way and to eliminate any possibility of pollution or risks to human health and well beings.

Municipalities in cold climate regions face specific problems during winter months due to snow and severe weather conditions when land application becomes difficult and outdoor

composting – the preferred alternative to land application – cannot or hardly meets regulatory standards (McCartney and Eftoda, 2005). Management of municipal biosolids in areas that experience extremely low winter temperatures as on the Canadian prairies is, therefore, of particular concern.

1.2 Objectives

Based on the state of the problems, the relevant previous work and data as presented in chapter 1 and chapter 2, the primary objective of this research was the assessment of the functionality of electrokinetic processes and its effect on the movement of metals in biosolids in cold environment.

In addition to this primary objective, the following secondary objectives were taken into consideration to be fulfilled as a matter of course:

- Observation of the impacts of electrokinetics on biosolids characteristics (pH, total solids, organic contents) under such environments and generation of related data.
- Observation of the freezing process of biosolids based on the resistance development in electrokinetic cells with biosolids.
- Defining favourable conditions for metal removal from biosolids in freezing temperatures using a conditioning liquid.

1.3 Thesis Organization

In order to address the problems systematically and to present the whole work in a sequential manner the thesis has been divided into 5 chapters. The subject matter discussed in each chapter is as follows:

Chapter 1: This is the introductory chapter. It states the problem, objectives of the study and an overview of the contents of various parts of the thesis.

Chapter 2: This chapter presents a review of previous relevant work and available literature emphasizing the application of electrokinetic methods to the removal of contaminants from biosolids and soils, behavior of contaminants in biosolids and soils, and the effect of temperature on the phenomena, etc.

Chapter 3: This chapter details the experimental approaches and methodologies followed all through this research work.

Chapter 4: The results obtained in different experiments in the laboratory have been analyzed and discussed in detail in this chapter. This is the chapter that contains and presents the findings of the laboratory experiments, analysis of the contaminant flow trends, efficiencies, etc.

Chapter 5: This is the conclusive chapter that presents a summary of the whole work, contributions of new knowledge made by this research and recommendations for further research.

CHAPTER 2 LITERATURE REVIEW

2.1 Biosolids

2.1.1 Generation, characteristics and quantities

Generation

Biosolids, historically known as sewage sludge, is the sludge produced during the treatment of municipal wastewater in wastewater treatment plants (WWTPs). Domestic, commercial and industrial wastewater are collected and transported to wastewater treatment plants through an extensive network of sewers, where it undergoes preliminary, primary, secondary and in some cases tertiary treatment depending on the influent characteristics and regulatory requirements of effluent quality before its discharge into the environment (EPA530-R-99-009, 1999). All these operations and processes during the treatment of wastewater produce sludge, which is by far the largest in volume among the constituents removed by treatment from wastewater (Metcalf and Eddy, 1995).

Characteristics

The quantity and characteristics of the biosolids generated at a POTW depend on the composition of the wastewater, the type of wastewater treatment used, and the type of subsequent treatment applied to the biosolids. Even within an individual plant, the characteristics of the biosolids produced can change annually, seasonally, or even daily because of variations in the incoming wastewater composition and variations in treatment processes. Higher levels of treatment increase the concentrations of contaminants in the sludge because the constituents removed from the wastewater normally end up in the

sludge. Furthermore, when chemicals are added to remove solids (such as ferric chloride, alum, lime, or polymers), it increases concentrations of these chemicals in the biosolids (EPA530-R-99-009, 1999). Typical constituents present in sludge that affect its suitability for beneficial use and ultimate disposal method include organic content, nutrients, pathogens, metals, and toxic organics (Metcalf and Eddy, 1995). Specifically, Table 2.3 (discussed later in section 2.2.1) presents some data on the typical metal content in wastewater sludge.

Quantities

Generally, higher degrees of wastewater treatment can increase the total volume of biosolids generated (EPA530-R-99-009, 1999) and also depend on the quantity of solids present in the wastewater. The quantity of solids entering the wastewater treatment plant daily may be expected to fluctuate over a wide range (Metcalf and Eddy, 1995). Some typical data on the quantities of sludge produced from various processes and operations are presented in Table 2.1.

Table 2.1: Typical data on the quantities of sludge produced from various wastewater treatment operations and processes

Treatment operation or process	Dry solids, lb/10^3gal	
	Range	Typical
Primary sedimentation	0.9-1.4	1.25
Activated sludge (waste sludge)	0.6-0.8	0.7
Trickling filtration (waste sludge)	0.5-0.8	0.6
Extended aeration (waste sludge)	0.7-1.0	0.8[a]

Treatment operation or process	Dry solids, lb/10^3gal	
	Range	Typical
Aerated lagoon (waste sludge)	0.7-1.0	0.8[a]
Filtration	0.1-0.2	0.15
Algae removal	0.1-0.2	0.15
Chemical addition to primary sedimentation tanks for phosphorus removal		
Low lime (350-500 mg/L)	2.0-3.3	2.5[b]
High lime (800-1,600 mg/L)	5.0-11.0	6.6[b]

Source: Metcalf & Eddy, 1995.

[a] Assuming no primary treatment.

[b] Sludge in addition to that normally removed by primary sedimentation.

2.1.2 Biosolids management practices

Biosolids management practices generally followed by different treatment works or municipalities are:

Beneficial use of biosolids

1) Land application

2) Advanced treatment, such as composting, heat drying or advanced lime stabilization.

Elimination of biosolids

1) Landfilling

2) Incineration

In recent years, beneficial use of biosolids has been receiving considerable attention throughout the world because of the decline of available landfill sites and the interest in using the beneficial nutrients and soil conditioning properties of sludge (Metcalf and Eddy, 1995). Furthermore, the prohibition of ocean dumping and stringent regulatory requirements for landfilling of sludge and increased opposition to incineration of wastes world-wide due to the concerns of air pollution perhaps left this as the only option of biosolids management for many municipalities around the world.

In Canada, about 43% of all biosolids produced are applied to land, 47% are incinerated and 4% are sent to landfill, with the remainder used in land reclamation and other uses. By comparison, the United States and Europe apply approximately 60% and 34%, respectively, of their biosolids to agricultural land (Apedaile, 2001).

2.1.3 Sources of heavy metals in biosolids

Historically, the sources of heavy metals in sludge have been industrial activities such as surface treatment with elements such as Cu, Zn, Ni and Cr. In recent years, industries have to a large degree moved out of the cities and due to stringent regulatory requirements the release of heavy metals and other compounds has decreased due to various pre-treatments of the effluent.

Bergback et al. (2001) confirmed that the industrial sources were minimal in comparison to diffuse sources from various goods. Diffuse sources are, for example, emissions from different goods in the traffic environment (e.g. brake linings, tires), from buildings (roofs), and from households (food).

In case of Cu, the dominant sources are from Cu pipes and taps in residences and businesses, and Cu roofs. For Zn, large contributors are residences (food, pipes and taps), other buildings (galvanized goods), and businesses (car washes). For Cr and Pb, businesses (car washes) are the largest contributors. In the case of Cd, businesses (car washes) are the dominant source, followed by households (food and artist paint). And lastly, in the case of Hg, households (amalgam) are the largest contributor; the emission from businesses (dentists) is very uncertain (Sorme and Lagerkvist, 2002).

2.1.4 Trend of changes of heavy metals concentrations in biosolids

Biosolids commonly have concentrations of heavy metals that might lead to accumulation in soils when applied repeatedly or at high rates (Oliver et al., 2004; Bhogal et al., 2003; King and Hajjar, 1990; MacLean et al., 1987; McGrath, 1987). Such accumulations have the potential to cause unwanted environmental impacts, such as phyto- and microbial toxicity and food chain and ground water contamination (Oliver et al., 2004; Bhogal et al., 2003; Chang et al., 1987; Chaudri et al., 2000; Dahlin and Witter, 1993; Zwarich and Mills, 1982). It is therefore critical to know the physical and chemical properties of biosolids applied to land, particularly their elemental contents—both in terms of total concentrations and the amount that is potentially 'biologically available'. It is also important to determine how these may vary temporally (Oliver et al., 2004).

Oliver et al. (2004) conducted a survey on Australian biosolids to evaluate similarities and differences between biosolids produced and analysed in the early 1980s and those examined in 2001, with particular emphasis on total element concentrations and the

availability of nutrients and potentially toxic elements. Although biosolids are variable by nature, even those from within a single treatment plant (Oliver et al., 2004; Levi-Minzi et al., 1981), they were able to examine some long-term trends. Total concentrations of Cu, Mn, Ni, Na, and Ca in Australian biosolids have changed little over the period examined. Median values of Cd, Mg, Pb, and Zn determined in 2001 were all greatly reduced compared to those of the previous survey (87%, 86%, 77%, and 58% reductions, respectively) (Oliver et al., 2004). The range of values observed for these elements had also considerably contracted since 1983. The likely cause of the decreased Pb concentrations in modern biosolids is the change to lead-free petrol, which has been shown to decrease atmospheric Pb levels around cities and industrialized areas (Oliver et al., 2004; Bravo and Torres, 2000). Reasons for decreases in other elements are less clear but may be related to improved industrial processes and the increasingly stringent regulations governing contents of industrial wastes entering sewers (e.g., ARMCANZ, 1994).

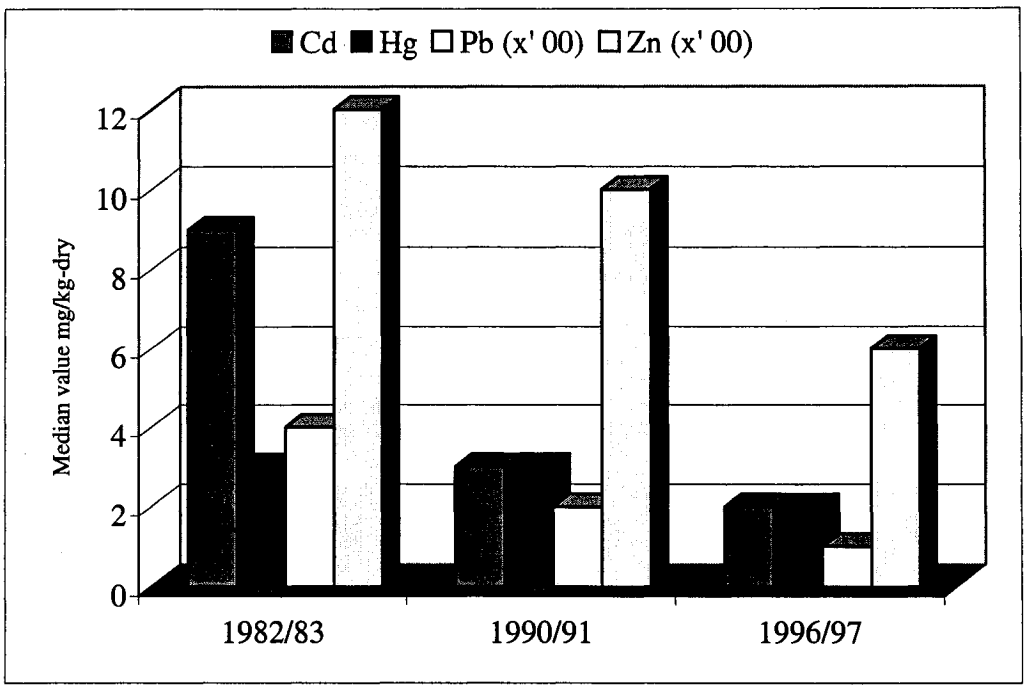

Fig. 2.1 Total concentrations of selected metals in UK biosolids from 1982–1997 (Oliver et al., 2004; Environment Agency, 1999)

They compared their findings of the reductions in total metal concentrations (particularly Pb, Cd, and Zn) of Australian biosolids with the biosolids produced in UK over the last 30 years and found similar reductions in metal concentrations (Fig. 2.1: Oliver et al., 2004; Environment Agency, 1999). In discussion of such concentration decreases in the UK, Smith (1996) also cited changes to manufacturing processes and waste content controls as driving forces (Oliver et al., 2004).

Examination of biosolids from individual treatment plants over time revealed that although some general trends may be identified, a high level of variability is observed between biosolids of different origin, both in terms of total and available element concentrations. This highlights the need to assess biosolids on a case-by-case basis if a

true indication of their potential detrimental environmental impacts and benefits are to be gained (Oliver et al., 2004).

2.1.5 Effect of low temperatures on concentrations and mobility of ionic species in porous mediums

Mazus (1993) studied the effect of freezing on the transfer of moisture and contaminants in illitic silty clay soil and investigated water and ion migration in the frozen soil previously subjected to different numbers of freeze and thaw cycles. In her study, she introduced a soil sample of 110 mm to subfreezing temperature from the top end. The following table presents some initial and boundary condition data as well as the time for freezing the samples.

Table 2.2: Initial and boundary condition data of the samples

Sample No.	Initial Water Content (%)	Time for Freezing (h)	Temperature (°C)		Duration of Test (h)
			Bottom	Top	
1	17.2	13.0	-1.6	-7.2	24
2	16.6	12.0	-2.9	-9.6	47.5
3	17.9	16.0	-1.8	-8.0	99.5
4	17.6	21.5	-1.5	-7.4	191
5	17.9	18.0	-1.9	-7.4	384
6	17.9	10.5	-2.3	-8.3	22.5

Sample No.	Initial Water Content (%)	Time for Freezing (h)	Temperature (°C)		Duration of Test (h)
			Bottom	Top	
7	17.5	10.0	-4.4	-13.1	48
8	17.6	9.0	-3.7	-12.3	96
9	17.3	10.5	-4.1	-13.4	192
10	16.6	11.5	-2.0	-9.5	384
11	17.5	8.5	-4.1	-10.8	24
12	17.6	16.5	-1.8	-7.4	47.5
13	17.6	10.0	-3.8	-11.7	71
14	17.3	10.0	-4.0	-12.6	192
15	17.6	7.5	-5.6	-12.5	383

Source: Mazus, M.T (1993)

Experiments on unsaturated soil show that moisture intake and redistribution are closely related to the temperature gradient, the duration of freezing and the type of liquid (Mazus, 1993). The unfrozen water content, ionic concentration and temperature gradient are the controlling parameters contributing to contaminant transport in frozen soil (Mazus, 1993). The distribution of exchangeable cations changes with the freezing time due to their migration and replaceability. The accumulation of heavy metals in the soil occurs as a result of cation exchange and precipitation mechanisms (Mazus, 1993). The imposition of subfreezing temperatures makes the reactions in the soil system more complex.

Formation of pure ice crystals in the pore space causes the increase of ion content in the pore solution (Cary and Mayland, 1972; Mazus, 1993).

The influence of electrical and temperature gradients on water movement was studied by Hoekstra and Chamberlain (1964) and Oliphant et al. (1983), respectively. Hoekstra and Chamberlain noted the significance of electro-osmosis phenomena for redistribution of moisture in frozen ground. Most of the cations which are expelled from the ice phase during water freezing are accumulated in the unfrozen water film around soil particles.

Mazus (1993) observed that the unfrozen water content was slightly less than 6% at about -10°C, and remained more or less the same below this temperature (Mazus, 1993; p-47, and Fig. 4.1 & 4.2). The distribution of unfrozen water in the frozen soil samples is directly related to the temperature and the unfrozen water content decreases with temperature decrease. The chemistry of the used liquid did not affect the unfrozen water content (Mazus, 1993; p-49 and Fig. 4.3 & 4.4).

In a closed system, such as the frozen soil column, the osmotic water movement will result in the development of pressure differences across the clay. The magnitude of osmotic pressure is directly proportional to the ion concentration in the soil pore solution (Yong and Mohamed, 1992; Mazus, 1993). During freezing, the ion concentration in the unfrozen soil water increases. Moreover, water from interlamellar regions of the soil particles migrates into the pore spaces to join the ice crystals. The loss of water causes a decrease in lattice spacing (Anderson and Hoekstra, 1965; Mazus, 1993). The increase in the ion concentration and the decrease in the spacing between mineral layers contribute to the rise of the osmotic pressure. Since both phenomena are related to the temperature of

the system, the osmotic pressure should rise as the temperature is reduced and must be directly proportional to the time of freezing (Anderson and Hoekstra, 1965; Yong et al., 1979; Mohamed, et al., 1993 and Mazus, 1993; p-50).

During soil freezing, all ions present in the soil pore solution are expelled from the growing ice crystals and forced into the unfrozen water film around the soil particles. Under the influence of different potential gradients, unfrozen water can migrate throughout the soil carrying the ions (Mazus, 1993; p-72).

2.1.6 Conclusions

Biosolids are the end product of wastewater treatment and their characteristics and quantities depend on various factors like the composition of the wastewater, the type of wastewater treatment used, and the type of subsequent treatment applied to the biosolids. Constituents in biosolids also vary over time even in individual treatment plant and lead the necessity to assess biosolids on a case-by-case basis. Heavy metals present in biosolids are one of the major concerns regarding its beneficial use through land application.

In the case of soil freezing, ion concentrations in unfrozen soil pore solution increases with the formation of ice crystals in the pore spaces. These ions can migrate throughout the soil medium with the unfrozen water under the influence of different potential gradients.

2.2 Metals

2.2.1 Occurrences and availability in biosolids

Heavy metals have found industrial, agricultural and military uses for several centuries of time. As a result they are now widely dispersed in a range of different forms, and there are environmental problems resulting from their mining, extraction, and purification. In many cases these metals are present in nature as mixtures rather than as a metal residue in pure form. The combination of a widespread possibility for human exposure, coupled with an extremely high toxicity, leads to certain heavy metals being a particular concern with regard to their toxic effects. Among these metals are cadmium, mercury, lead, copper and chromium in its hexavalent state (Roundhill, 2001).

Wastewater sludges contain traces of metals. Since sludge is used for land farming, metals retained in the soil pose potential toxic risks to plants, animals and humans. The principal metal of concern is cadmium because it can accumulate in plants to levels that are toxic to humans and animals but below levels that are toxic to plants (Metcalf & Eddy, 1995). The constituents concentrations found in various sludges vary widely depending on the characteristics of the treated wastewater; however, some common metals can reach values as presented in Table 2.3.

Table 2.3: Common metal content in wastewater sludge

Metal	Dry sludge, mg/kg	
	Range	Median
Arsenic	1.1-230	10
Cadmium	1-3,410	10
Chromium	10-99,000	500
Cobalt	11.3-2,490	30
Copper	84-17,000	800
Iron	1,000-154,000	17,000
Lead	13-26,000	500
Manganese	32-9,870	260
Mercury	0.6-56	6
Molybdenum	0.1-214	4
Nickel	2-5,300	80
Selenium	1.7-17.2	5
Tin	2.6-329	14
Zinc	101-49,000	1700

Source: Metcalf & Eddy, 1995.

2.2.2 Metal complexations and its effects in biosolids

The metal incorporated in labile complexes is more available and therefore represents a greater risk of toxicity than if it forms stable, non-labile complexes. Baron et al. (1990), had studied the binding capacities and conditional stability constants for Cu and Cd in two different sewage sludges, namely a secondary sludge and an anaerobically digested

sludge, and found that the complexes formed with Cd are significantly more labile than those formed with Cu and therefore, the cadmium present in the sludges are more available than the copper. They also found that the measured binding capacities are much greater than the concentrations of metals in sewage sludges, even in the case of high contamination and concluded that the metals contained in the sludges are primarily in adsorbed or complexed form and that the mobile forms are dissolved complexes. The existence of these complexes must be taken into account when considering methods of decontaminating sludges.

Anaerobic digestion of the sludges increases the proportion of dissolved ligands (Baron et al., 1990). Comparing the complexation capacities of the two types (secondary and anaerobically digested) of sludges, they found that the capacities are substantially the same in the case of raw sludges, while the pore water of digested sludge has a significantly greater capacity than the pore water of secondary sludge. They concluded that digestion of the sludge contributes to increasing the mobility and availability of the metals. There is also a large increase in the complexation capacities and conditional stability constants when the pH of the pore water of secondary or digested sludge is increased.

2.2.3 Forms of metals in biosolids

The knowledge of the chemical forms in which the metals are present in sewage sludge is of particular interest in terms of their availability (Leita and De Nobili, 1991; Petruzzelli et al., 1989). Heavy metals in sewage sludge can be present under different chemical forms according to their initial chemical state in the sewage, the adsorption, precipitation

mechanisms in sludge, and the treatment undergone by the sludge (Petruzzelli et al., 1994). In fact, the chemical forms of heavy metals in sewage sludge will largely determine their fate in the soil environment (Corey et al., 1985). Heavy metals in ionic form, or complexed by organic materials, incorporated in mineral compounds in sewage sludge have a very different nature and strength of bonding and therefore will react differently. However, the amount of these elements in available forms will greatly differ among different types of sludges (Petruzzelli et al., 1994).

Petruzzelli et al. (1994) determined the mobile or mobilizable species of heavy metals in two different kinds of sewage sludge (which had undergone different treatments) through a sequential extraction procedure. Three fractions were distinguished: soluble (extractant water), exchangeable (extractant KNO_3), adsorbed and/or complexed (extractant EDTA). The water-soluble metals represent the most mobile fractions. The so called exchangeable fraction consists of those metals retained by the matrix of the sludge by linkages of coulombic nature or by means of Van der Waals forces. These metals are solubilized by an exchange reaction with excess K^+ ion present in the extractant solution. Finally, the complexing agent EDTA extracts the heavy metals adsorbed or complexed by organic materials, and it was shown to be able to dissolve heavy metal carbonates and partially some sulfides.

The general pattern of extractability showed that with the exception of Pb, a certain amount of metals are in a water-soluble form. Table 2.4 presents the total extractability of different metals in the two different sludges:

Table 2.4: Total extractability (%) of heavy metals in two sludges

Sample	Zn	Cu	Cd	Ni	Pb	Cr	Remarks
1	50.8	38.1	37.4	47.7	24.8	6.6	Sludge A
2	66.5	30.0	53.4	63.5	28.2	7.0	Conditioned with
3	71.7	35.1	95.0	41.7	26.3	6.4	$AlCl_3$
4	1.67	58.9	12.4	31.8	4.39	6.5	Sludge B
5	0.92	45.9	10.4	29.3	4.12	6.5	Conditioned with
6	0.11	39.6	11.2	22.1	3.46	7.9	CaO and $FeCl_3$

Source: Petruzzelli et al., 1994

The data show that the total amount of extractable metals differ with the type of sludge and in this case it is lower in sludge B which is conditioned by CaO and $FeCl_3$, with the exception of Cu compared to sludge A conditioned by $AlCl_3$.

2.2.4 Factors influencing mobility of metals in biosolids

Mobility is a term used to estimate the movement and risk of contamination of a contaminant, in this case heavy metals. We often are more interested about the total concentration with respect to the toxicity of heavy metals; however, the fraction of the total concentration that is bioavailable or has the potential to contaminate the food chain or in other words, the fraction with higher potential of mobility, is of higher importance. The concept of mobility of heavy metals has long been studied by many researchers (Gerritse et al., 1982; Domergue and Vedy, 1992; McBride et al., 1997) and has been found to be influenced by several parameters, such as the reduction potential, pH, quantity of organic matters, competition between the ions, etc (Losier, 2001). Moreover,

speciation of heavy metals is important because the ions could be present in different states, such as soluble in water, exchangeable, precipitated, co-precipitated, adsorbed and complexed with organic matter (Warman et al., 1995; Losier, 2001). Thus, there are several factors that influence the mobility of heavy metals.

Organic matter

Quantity of organic matter present in the medium can have a significant influence on the mobility of heavy metals. In our case, it is an important factor because biosolids are rich in organic matter. When organic matter is under the form of a colloidal material, it can adsorb even more cations (Scott, 1968; Losier, 2001). Moreover, humic substances, humic and fulvic acids can form complexes and precipitate; thus they play an important role in the fixation of heavy metals (Serpaud et al., 1994). In addition, humic substances can strongly integrate to several heavy metals.

These materials are capable of exchanging ions or can be attached to metals depending on the appropriate conditions. The mechanism of exchange of ions depends on the charge of the ions and the amount of ions hydrated (Flaig et al., 1975; Losier, 2001). Moreover, the concentration of hydrogen ions present in the solution (i.e. pH) also influences the capacity of exchange of ions (Flaig et al., 1975; Losier, 2001). Though there are several other possibilities of adsorption of heavy metals by organic matter, in general there is a lack of information regarding the mechanism of movement and the complexation of heavy metals by organic matter (Losier, 2001; Al-Wabel, 2001).

pH

Effect of pH on the mobility of heavy metal is very important, because the majority of heavy metals precipitate at a pH value higher than 7 (Basta and Tabatabai, 1992). Moreover, increase of pH favours adsorption of metals on the reducible fractions through the exchange of metallic cations with hydrogen ions on certain sites of the surface (Serpaud et al., 1994; Losier, 2001) and thus, reduce the mobility of heavy metals.

pH also affects exchange of cations (Gould and Genetelli,1978; Basta and Tabatabai, 1992). Competition between the hydrogen and metal ions for the same site increases as the pH decreases; more hydrogen ions are adsorbed with the organic matters compared to the metallic ions and as a consequence, the metallic ions become more mobile (Losier, 2001). According to the isotherm of Freundlich, cadmium, nickel and zinc compete with one and copper with two hydrogen ions (Losier, 2001). A reduction of pH from 6 to a value of 5 causes a reduction of adsorption of metals by a factor of 3 to 5 (Losier, 2001). Table 2.5 presents a guideline on the influence of pH on the relative mobility of some metal cations.

Table: 2.5: Influence of pH on the mobility of metal cations

pH Range	Very Mobile	Moderately Mobile	Slowly Mobile
4.2 – 6.6	Cd, Hg, Ni, Zn	As, Be, Cr	Cu, Pb, Se
6.7 – 8.8	As, Cr	Be, Cd, Hg, Zn	Cu, Pb, Ni

Source: (Esmaeily, 2002; Merian, 1991)

Speciation of heavy metals

In environmental studies, information about the total concentration of heavy metals is not always sufficient to understand the risk of contamination and the effect of possible toxicity (Petruzzelli et al., 1992; Losier, 2001). Determining the speciation of metals, it is possible to have an idea about the toxicity and mobility of a metal (Bellanca et al., 1996; Laxen, 1985; Losier, 2001). The principal parameter that influences speciation of an element is its origin (Petruzzelli et al., 1992; Losier, 2001). The different forms of the metal ions, such as soluble, precipitated, co-precipitated, complexed, adsorbed, etc. are very important in terms of mobility of the metal (Losier, 2001).

Effect of salinity

Salinity of a solution can affect the mobility of heavy metals in two different ways. Firstly, it is possible that the anion attached to heavy metals changes according to speciation, like for example, NaCl in a solution with cadmium ion, it is possible that cadmium will have forms like, Cd^{2+}, $CdCl^{+}$, $CdCl_2$, $CdCl_3^{-}$ and $CdCl_4^{2-}$ (Losier, 2001). Moreover, the cation of salt (e.g. Na^{+}) might be in competition with the cation of metals for the same site of complexation. As a result, there will be less available sites and thus salts will have a great influence on the mobility of heavy metals. Of course, everything will depend on whether the metal ions have more affinity for anions of salt than the site of complexation or the site have more affinity for the cation of salt than that of metals (Losier, 2001).

Effect of a ligand

Ligands can bind to metals to form complexes, and as a result the mobility of heavy metals might be affected since the speciation of metals will be modified. Thus, adsorptions will possibly also be affected since a fraction of metals will no longer be in the same form (Losier, 2001).

The more the metal ions are complexed, we can expect that the more it will be mobile. As an example, in a solution of pH of around 4.5 of about 50 μM of a metal ion and about 50 μM of NTA, percentages of heavy metals complexed with NTA have been calculated as presented below in Table 2.6 (Losier, 2001).

Table 2.6: Percentage of heavy metals complexed with NTA

Metal	Concentration of metal (μM)	pH	Percentage complexed (%)
Cd	49.6	4.53	59.6
Cu	48.9	4.53	98.6
Pb	41.8	4.50	97.4
Zn	44.7	4.54	76.2

Source: Losier, 2001.

According to the values obtained, it is obvious that mobility of copper will be affected the most, followed by lead, zinc and cadmium.

2.2.5 Conclusions

Heavy metals are now widely dispersed in a range of different forms due to their different applications over centuries. Human exposure to certain heavy metals, e.g. cadmium,

mercury, lead, copper and chromium, are of particular concern with regard to their toxic effects. Trace metals from wastewater sludges that are applied to the soil pose potential toxic risks to plants, animals and humans. The fraction of the total concentrations of heavy metals that has the potential of contaminating the food chain or in other words, the bioavailable fraction or the fraction with higher potential of mobility, is of higher importance. Mobility of heavy metals depend on several parameters, such as the reduction potential, pH, quantity of organic matters, competition between the ions, and speciation of metal ions.

2.3 Electrokinetic Method

2.3.1 Introduction

The electrokinetic method is an emerging soil remediation technology that has attracted increased interest among scientists and governmental officials in the last decade (Virkutyte et al., 2001; Hatem, 1999). Electrokinetic phenomenon was observed, at first, by Reuss at the beginning of the 19th Century when he applied direct current to a clay-water mixture (Virkutyte et al., 2001; Hatem, 1999; Acar and Alshawabkeh, 1993; Swartzbaugh et al., 1990).

The research group at Concordia University has been performing investigations for several years on phase separation in oily sludge (Habibi, 2004) and contaminant removal from different types of soils and pioneering investigations for contaminant removal from biosolids through the application of electrokinetic technology. Details of the work done so far have been presented in sub-section 2.3.3.

The electrokinetic process is capable of separating and removing water, heavy metals, radionuclides and organic contaminants from low permeability soil, mud, sludge and marine dredging (Habibi, 2004; Esmaeily, 2002; Virkutyte et al., 2001). This is an in-situ technology primarily used for soil consolidation and recently, some researchers have been using it for contaminants removal (Choudhury, 1998). It uses electrochemical and electrokinetic processes to desorb, and then remove, metals and polar organics. This in situ soil processing technology is primarily a separation and removal technique for extracting contaminants from soils (Hakimipour, 2001; Virkutyte et al., 2001). Contaminants affected by electrokinetic processes include (Habibi, 2004; Cauwenberghe, 1997):

- Heavy metals (lead, mercury, cadmium, nickel, zinc, copper, chromium) (Lageman, 1989; Pamukcu and Wittle, 1992; Choudhury, 1998; Shiba et al., 2000).
- Radioactive species (Cs_{137}, Sr_{90}, Co_{60}, Ur) (Buehler et al., 1994).
- Toxic anions (nitrates, sulfate) (Chew and Zhang, 1998).
- Dense non-aqueous phase liquids (DNAPLs) (Kokal et al., 1995).
- Cyanides (Podol'skaya et al., 2001).
- Petroleum hydrocarbons (diesel fuel, gasoline, kerosene and lubricating oils) (Bhattacharya et al., 1996; Elektorowicz et al., 2000).
- Explosives (Hilmi et al., 1999)
- Mixed organic/ ionic contaminants (Hilmi et al., 1999; Hakimipour, 2001).
- Halogenated hydrocarbons (TCE) (Wall et al., 2002).

- Polynuclear aromatic hydrocarbons (Maini et al., 2000; Hatem and Elektorowicz, 1999).

2.3.2 Process fundamentals and principles of electrokinetic phenomena

Electrokinetics is a complex phenomenon induced by an applied electric field (Hatem, 1999; Swartzbaugh et al., 1990) and refers to the relative motions of charged species (Habibi, 2004). A schematic representation of the electrokinetic process has been presented in Fig. 2.4. Three principle transport phenomena, e.g. electromigration, electroosmosis and electrophoresis, generally take place when an electric field is applied to a system having charged particles (Hakimipour, 2001; Hatem, 1999; Hicks and Tondorf, 1994; Probstein and Hicks, 1993; Banerjee et al., 1988). Each of the above mentioned process will generate a flux. The movement of contaminant could be as a result of charged, dispersed species or of the continuous phase (Habibi, 2004). The combination of various processes that occur when electric current is applied across such a medium is referred to as electrokinetics, and those various processes can be grouped and presented as shown in Fig. 2.2.

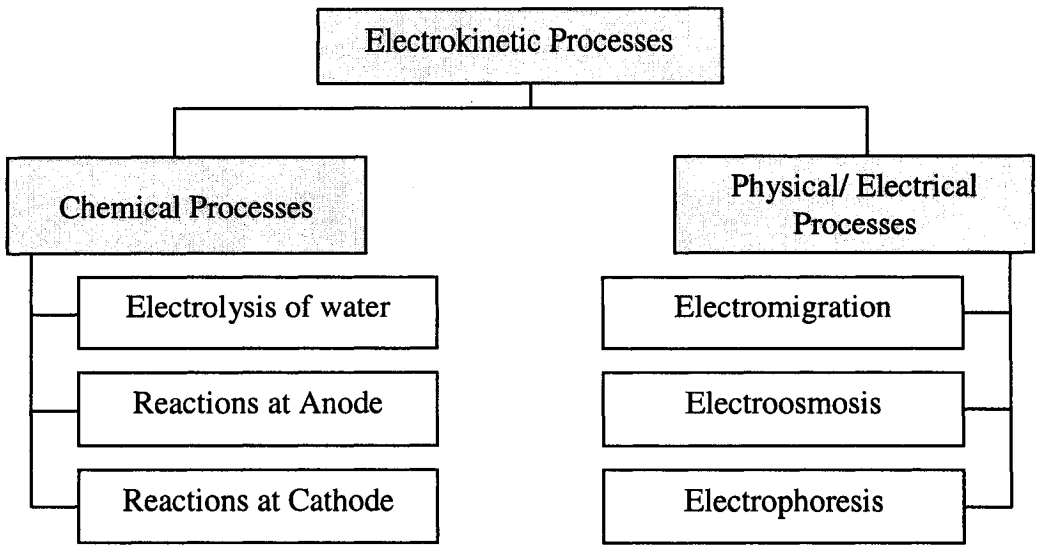

Fig. 2.2 Processes involved in Electrokinetics (Choudhury, 1998)

Electromigration and electrolysis of water

Electrolysis of water is the dissociation of water molecules into hydrogen (H^+) and hydroxyl (OH^-) ions through the passage of an electric current. When direct current is applied through the electrodes across a medium as mentioned above, electrolysis of water takes place at the electrodes. Hydrogen (H^+) ions are produced at the anode, which lowers the pH and creates an acidic condition near the anode area and hydroxide (OH^-) ions are produced at the cathode causing a higher pH and a basic condition near the cathode area (Esmaeily, 2002; Virkutyte et al., 2001; Hatem, 1999). This electrolysis (oxidation-reduction process) of water follows the following reactions:

Oxidation at Anode: $2\,H_2O \longrightarrow O_{2\,(gas)} + 4H^+ + 4e^-$ (Eq. 1)

Reduction at Cathode: $2\,H_2O + 2\,e^- \longrightarrow H_{2\,(gas)} + 2\,OH^-$ (Eq. 2)

Thus, electrolysis of water creates an acid front at the anode and an alkaline front at the cathode, respectively (Virkutyte et al., 2001).

Electromigration is the transport of ions and polar molecules present in the pore fluid as well as the migration of H^+ (produced at the anode) and OH^- (produced at the cathode) in the direction of opposite electrode under an electric field (Esmaeily, 2002; Virkutyte et al., 2001; Hatem, 1999; Pamukcu, 1992). It is the movement of ionic contaminants and pore water without convective movement and independent of the permeability of the medium. Electromigration is the key mechanism in removing inorganic contaminants, especially metal ions, in the electrokinetic remediation of soil and sludges (Hakimipour, 2001; Kim, 1998; Hicks and Tondorf, 1994; Acar and Alshawabkeh, 1993).

Propagation caused by electromigration of the acid and base fronts created by the electrolysis of water at the electrodes promote the dissolution and transport of heavy metal ions near the anode and the precipitation of metal ions near the cathode. This precipitation forms a barrier in the cathode region and hinders the transport of metal ions from anode to cathode and must be overcome in order to achieve high metal removal efficiency (Esmaeily, 2002; Choudhury, 1998).

Electroosmosis

Electroosmosis is the movement of the pore fluid relative to the stationary porous medium under the influence of an imposed electric gradient (Habibi, 2004; Virkutyte et al., 2001; Esmaeily, 2002). When there is direct current applied across the porous media filled with liquid, the liquid moves relative to the stationary charged solid surface (Virkutyte et al., 2001). When the surface is negatively charged (e.g. clay wetted with water), this charge is balanced by the adjoining layer of liquid induced with a positive space charge and the liquid flows to the cathode. Since there are more cations than anions

in the electric double layer (EDL), the flow of water is toward the cathode (Habibi, 2004; Choudhury, 1998).

Acar et al. (1994, 1996) have found in numerous experiments that the electroosmosis process works well in fine-grained wet soils and observed that it can even be used to remove non-ionic soluble pollutants. The dissolved neutral molecules simply go with the flow by advection. Electroosmosis with a convective movement of pore water can enhance the transport of ionic molecules (electromigration). Electroosmosis is the key mechanism in removing non-polar organic contaminants from the low-permeable soils in electrokinetic remediation processes (Virkutyte et al., 2001; Pamukcu and Wittle, 1992).

In general, the direction and quantity of contaminant movement is influenced by the contaminant concentration, soil type and structure, and the mobility of contaminant ions, as well as the interfacial chemistry and the conductivity of the soil pore water (Virkutyte et al., 2001). The electroosmotic flow rate depends on the magnitude of the applied electrical gradient, the flow resistance of soil, and the fractional drag exerted by the migrating ions on the water molecule (Hatem, 1999; Gray and Mitchell, 1967).

Electroosmotic flow can be estimated using following approach (Esmaeily, 2002; Hatem, 1999; Eykholt and Daniel, 1994; Schaad et al., 1947; Cassagrande, 1952):

$$q_e = K_e \cdot i_e \cdot A \qquad \text{(Eq. 3)}$$

where,

	q_e	=	Electroosmotic flow rate [cm^3/s]
	K_e	=	Coefficient of electroosmotic permeability [$cm^2/V.s$]
	i_e	=	Potential gradient [V/cm]
	A	=	Cross-sectional area [cm^2]

Electrophoresis

Electrophoresis is the transport of charged particles or colloids under the influence of an applied direct current electric field relative to a stationary liquid phase (Esmaeily, 2002; Virkutyte et al., 2001; Hatem, 1999; Mitchell, 1993; Probstein, 1989). All electrically charged particles, such as colloids, clay particles in pore solution, organic particles and droplets present in the porous medium are subjected to this kind of transport (Habibi, 2004; Esmaeily, 2002).

Electrophoresis is of less importance in a compact system of porous plug where the solid phase is restrained from movement, whereas it is an important mechanism in electrokinetic soil remediation when surfactant is added into the fluid to form micelles (charged particles) (Habibi, 2004; Hatem, 1999; Pamukcu and Wittle, 1992). This phenomenon also plays an important role in different types of sludges.

Thus, the main goal of electrokinetic processes is to effect the migration of contaminants in an imposed electric field via electroosmosis, electromigration and electrophoresis. A schematic representation of this process has been shown in Fig. 2.4.

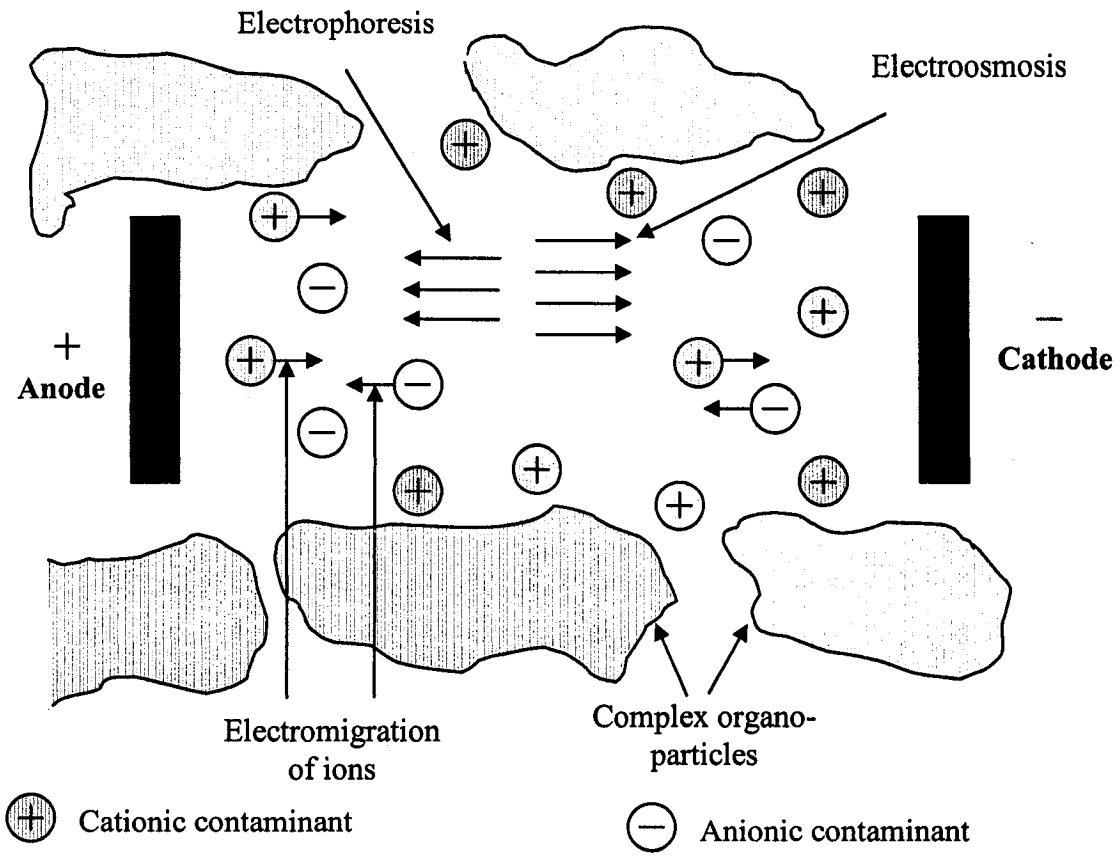

Fig. 2.4 Schematic representation of electrokinetic process

2.3.3 Past research efforts on the application of electrokinetic processes for the removal of heavy metals

Electrokinetics is a relatively new and developing technology for contaminant removal from porous mediums that is gaining increasing interests among scientists and governmental officials. Research work specifically related to metal removal from biosolids using electrokinetic processes are limited, though geotechnical engineers have been using the technology for many years to consolidate fine-grained soils (Gray and Mitchell, 1967; Esrig, 1968; Gray, 1970; Wan and Mitchell, 1976; Mitchell, 1993). Some

research has already been conducted for the removal of various contaminants from different types of soils (Legeman, 1989).

Esmaeily (2002) had studied dewatering, metal removal, pathogen elimination and organic matter reduction in biosolids using electrokinetic phenomena. In their study, they used biosolids in 6 rigid polyethylene cells with applied voltage gradient ranging from 0.5 to 1.5 V/cm, added di-ammonium-phosphate (fertilizer) in two cells and conducted the study for 10 days. At the end of the experiment, they obtained an average of 84% removal of zinc, 100% removal of Cd and Pb, 91% for Fe and a higher removal of Ni and Cu, a 95% increment of solid content and complete removal of fecal coliform. They observed higher removal of contaminants in cells with conditioning liquid (ammonia/ phosphorus combination) and higher voltages and concluded the technology as simple, cost effective and reliable.

Meunier et al. (2004), in their study of removal of metals in leachate from sewage sludge using electrochemical technology, found an electrolytic cell arrangement using an iron-monopolar electrodes (EC-ER cell) system to be effective and more economical than the traditional metal precipitation using either $Ca(OH)_2$ and/or NaOH. They tested three different electrode materials, namely mild steel or aluminium bipolar electrode (EC cell), graphite/ stainless steel monopolar electrodes (ER cell) and iron-monopolar electrodes in electrolytic cell made of acrylic material, to explore an electrochemical technique for heavy metals (Cu and Zn) removal from sludge leachate. They obtained the best performances of metal removal in EC and EC-ER cells using mild steel electrodes operated respectively at current intensities of 0.8 and 2.0A through 30 and 60 minutes of

treatment, which yielded Cu and Zn removal varying respectively from 92.4 to 98.9% and from 69.8 to 76.6%.

Several studies have been conducted on the application of electrokinetics in different types of soils, and efficient transportation and removal of inorganic species have been reported (Runnels and Larson, 1986; Hamed, 1990; Pamukcu et al., 1991; Banerjee et al., 1988; Hamed et al., 1991; Eykholt, 1992; Runnels and Wahli, 1993; Wittle and Pamukcu, 1993; Probstein, 1994; Rodstand et al., 1995; Choudhury, 1997; Elektorowicz et al., 1996). Li et al. (1998) studied two alternative methods to deal with the high pH and metal precipitation problems near the cathode region. One involved a length of tube filled with solution between soil and the cathode so that precipitation occurs in the solution and not in the soil. Another involved the placement of a cation selective membrane in front of the cathode to stop the migration of the base front towards the anode and achieved 90% of copper removal from sand using this technique. Since metals can be present in different forms and only the dissolved forms are available for electrokinetic transportation, sometimes enhancement techniques have been utilized to solubilize extractable metals to achieve better removal. Choudhury (1998) studied electrokinetic phenomena to remove nickel and lead from natural clay soil and used EDTA for enhanced solubilization of metals and ion exchange textiles (IET) to limit migration of high pH zones and localize metal ions and obtained an average of 85% of nickel ions localized within $1/4^{th}$ of the cell and 75% of the lead ions localized within $1/3^{rd}$ of the cell.

2.3.4 Effect of temperature on the removal of metals from biosolids during electrokinetic treatment

In general, there is a serious lack of literature specifically on the effect of temperature on the removal of metals from biosolids during electrokinetic treatment. Past research has been mainly concentrated on the application of electrokinetics to remove pollutants from biosolids.

Let us consider then the theoretical aspects of the influence of temperature on the transport and velocity of the pollutant species during the electrokinetic treatment. Since electroosmosis and electromigration are the two major processes involved during electrokinetic removal of metals from biosolids, the temperature effect on these two mechanisms are discussed here.

Temperature effect on electromigration

In free solution, migration velocity of ionic species (V_{em}^{i}) is expressed by:

$$V_{em}^{i} = u_i E \qquad \text{(Eq. 4)}$$

where, u_i is electrical mobility and E is applied electric field.

In porous medium,

the effective mobility, $u_i^* = u_i / \tau$ (Eq. 5)

where, τ is the tortuosity factor

thus, $V_{em}^{i} = u_i^* i_e$ (Eq. 6)

where, i_e is electrical potential gradient.

Now, electrical mobility, $u_i = \frac{z_i e_0}{6\pi\eta r_i}$ (Eq. 7)

where, z_i is charge of the species; e_0 is elementary charge; η is viscosity; r_i is Stoke radius.

Since viscosity is temperature dependent, change of temperature will primarily affect through the change of viscosity. Temperature induced changes of viscosity are frequently approximated as 2% per °C (Khun, et al., 1993).

Then, $u_i^*(T) = u_i^*(T_0)[1+0.02(T-T_0)]$ (Eq. 8)

where, T, T_0 are temperatures

Hence, electromigration velocity also increases by 2% per °C since temperature has no influence on the value of the imposed electric field.

Then, $V_{em}^i(T) = V_{em}^i(T_0)[1+0.02(T-T_0)]$ (Eq. 9)

Temperature effect on electroosmosis

The influence of temperature on electroosmotic flow is not so well known. Though some authors report that this flow increases with temperature, due to the influence of many simultaneous parameters on the phenomena this variation is hard to quantify (Baraud et al., 1998).

According to Helmholtz-Smoluchwski theory, the electroosmotic permeability coefficient:

$$k_e = \frac{\varepsilon \xi \theta}{4\pi\eta} \qquad \text{(Eq. 10)}$$

where, ε is dielectric constant of the solution which decreases as temperature increases; η is also temperature dependent and generally decreases as temperature rises, but the relationship can be affected by the nature and composition of the solution.

$$\xi = \frac{\lambda_D \sigma}{\varepsilon} \qquad \text{(Eq. 11)}$$

where, σ is surface charge; λ_D is double layer thickness which varies with T according to:

$$\lambda_D = \sqrt{\frac{\varepsilon RT}{2C_e z^2 F^2}} \qquad \text{(Eq. 12)}$$

where, F is Faraday's constant; C_e is electrolyte concentration.

Since the relationship between temperature and each of these parameters are not well defined, the effect of temperature on electroosmosis cannot be precisely theoretically predicted (Baraud et al., 1998).

But, through experimental observations, it appears that ionic electromigration velocity and electroosmotic flow should increase with the increase of temperature (Baraud et al., 1998; Khun et al., 1993; Bonnemay et al., 1974).

Baraud et al. (1998) studied the effect of temperature on ionic transport during soil electrokinetic treatment at constant pH. They carried out laboratory experiments at 20 and 40°C using kaolinite as a soil model and one anion and one cation as model

pollutants and observed enhancement of cationic transport as well as anionic movement with the increase of temperature.

2.3.5 Conclusions

Electrokinetics is a relatively new and developing technology used mainly in soil remediation that is receiving increasing interests among scientists and government officials during the last decades. This in-situ technology uses low voltage direct current (DC) and is capable of separating and removing water, heavy metals, radionuclides and organic contaminants from low permeability soil, mud, sludge and marine dredging. Electromigration, electroosmosis and electrophoresis are the main processes involved for the migration of contaminants in such a medium in an imposed electric field. Geotechnical engineers have been using the technology for many years and there have been numbers of researches conducted for the removal of various contaminants from different types of soils. But, there is a lack of information specifically on the removal of contaminants from biosolids using electrokinetics. Moreover, past researches mainly focused on regular field conditions and there is a serious scarcity of literature on the effect of low temperatures on electrokinetic remediation.

CHAPTER 3 APPROACHES AND METHODOLOGIES

3.1 Planning and Organization of the Work and Necessary Facilities

In order to achieve the objectives of the study as outlined in chapter 1, a detailed approach for performing the laboratory experiments and obtaining required data had been set out through extensive discussions with the supervisor and a thorough review of the existing literature. An assessment of the application of electrokinetics to the biosolids stored in lagoons in cold regions, as described in section 1.1, was the focus of this study. It was presumed that the bottom layers of the lagoons might remain unfrozen while the top layers freezes due to the low ambient temperatures. Moreover, previous work on soil in subfreezing temperatures (Mazus, 1993) suggests that ions present in soil pore solution are expelled out from the growing ice crystal and their concentrations increases in the unfrozen pore solution. These increased concentrations of metallic cations in the unfrozen biosolids solution might be subjected to electrokinetic processes. To simulate the field conditions for tests in laboratory, it was decided to construct a cell insulated in all four sides and bottom but open on the top, which would be placed in a freezer at representative low temperatures. Details of the cell construction have been presented in section 3.2.1. The approaches developed and followed throughout the study to carry out laboratory work have been presented in a schematic diagram in Fig. 3.1. The whole laboratory work can be divided into three parts, such as,

- Preparatory work
- Application of electrokinetics (EK), and
- Measurements and analysis

The laboratory experiments have been performed at two different temperatures. Selection of representative temperatures for winter conditions were based on the Canadian climate normal data for years from 1971 to 2000 in the Winnipeg region. The daily maximum temperatures and the average maximum number of days with that temperature for the months December, January and February were taken into consideration during selection of the representative temperatures. It was decided to perform tests at –15°C to represent conditions during the month of January when the maximum number of days experience temperatures between –10°C and –20°C. Similarly, –8°C was selected as the representative temperature for the months of December and February when the maximum number of days lies between temperatures –2°C and –10°C. Moreover, considering the freezing effect of biosolids at these low temperatures and the consequent rise of resistance, it was decided to perform some tests using conditioning liquid used during previous work (Esmaeily, 2002) with biosolids that helped to keep the resistance low.

Now, considering all these situations, laboratory tests were divided into the following two stages with a series of two tests in Stage I and four tests in Stage II:

- Stage I: a series of two tests with and without conditioning liquid at –8°C temperature.
- Stage II: a series of four tests, three with different concentrations of conditioning liquid and voltage gradient and one without the addition of conditioning liquid at –15°C temperature.

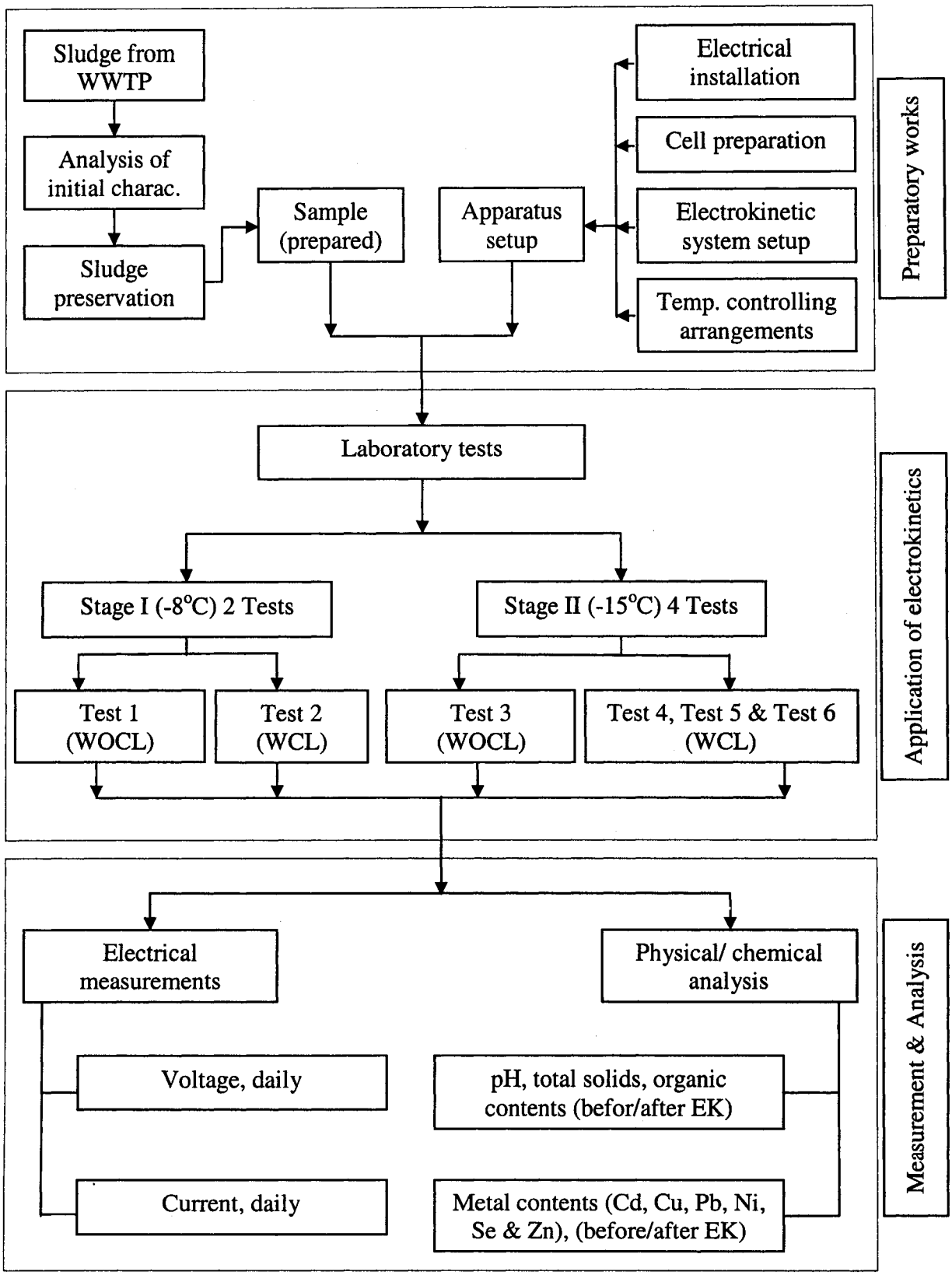

Fig. 3.1 Schematic of the approaches followed throughout the study

3.2 Set Up of Experiment Installation

3.2.1 Cell construction

All the experiments were carried out in rectangular cells made of rigid polyethylene having dimensions of l = 25 cm, w = 14.5 cm and h = 10.5 cm. The electrodes were made of stainless steel (304) sheet with identical dimensions of w = 12 cm, h = 10 cm and thickness, t = 0.2 cm. The distance between the two electrodes was 19.5 cm. A sketch of the electrokinetic cell has been presented in Fig. 3.2.

A total of 8 silver probe electrodes were installed in two vertical lines (4 probe-electrodes in one line), 6.5 cm apart from each stainless steel electrode, on one side of each cell. The distance between two adjacent probe-electrodes in each line was 1.5 cm and each probe-electrode was inserted 2.75 cm inside the cell. The probe-electrodes were useful to study the continuous changes in biosolids physical properties during the electrokinetic phase separation and freezing processes. The electrical parameters were measured along those two vertical lines between anode and cathode. The voltage distribution between the electrodes was monitored by direct measurements of the electrical potential difference between the electrodes and each probe-electrode.

In order to simulate the outside winter conditions when the biosolids are stored in ditches or lagoons in open air, the top of each cell was kept open as much as possible keeping other arrangements (like hanging of electrodes, connection of electrical wires) stable. Each of the cells was then wrapped with insulation foam of at least 1 inch thick around all four sides and the bottom and placed inside a bigger polyethylene container. These

arrangements helped to create an environment that resembles the actual field conditions when the cells were kept in the freezer during the experiments.

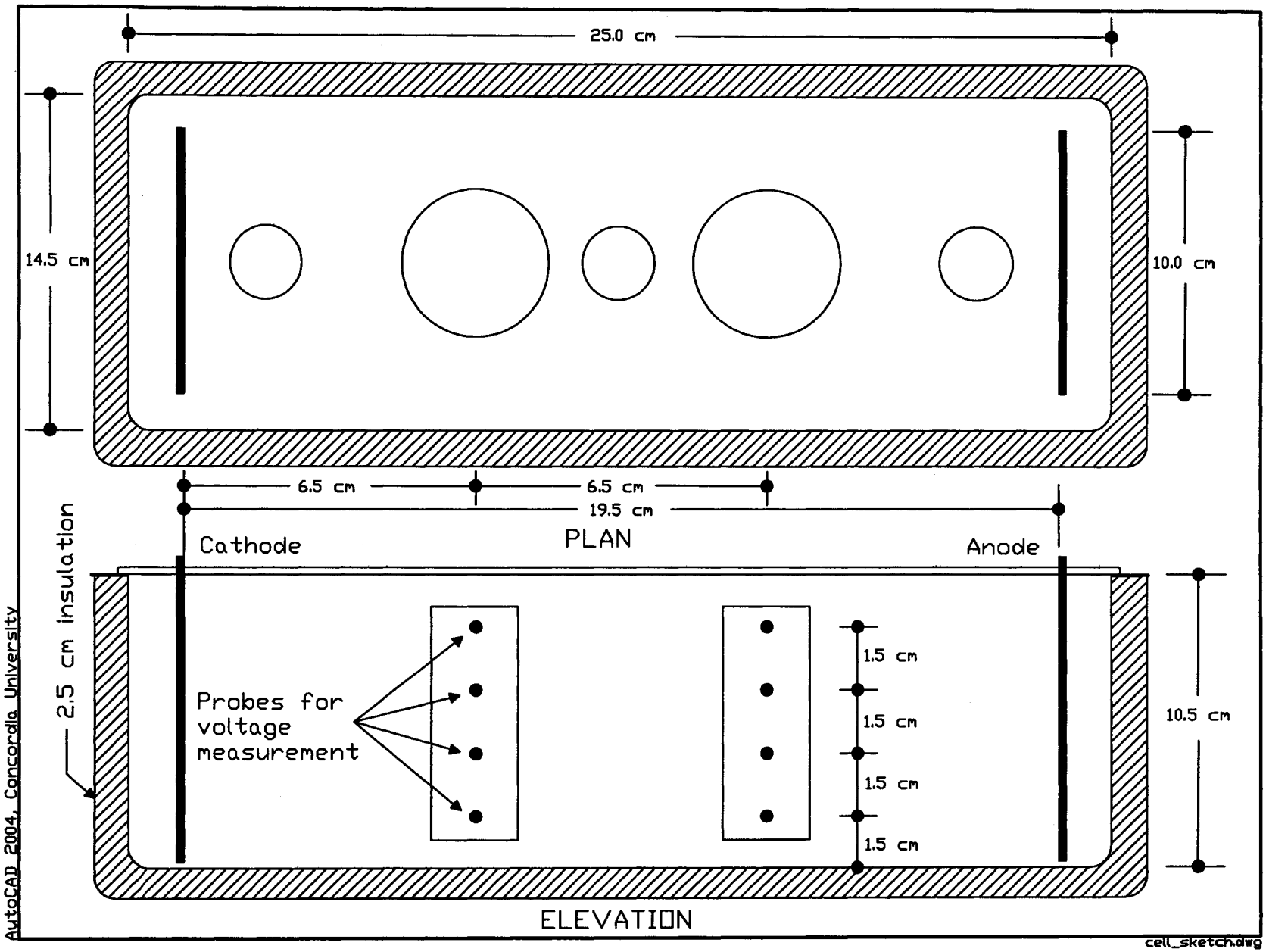

Fig. 4.2 Sketch of the electrokinetic cell

3.2.2 Electrical equipment installation

Each cell was connected to a DC power supply unit to create the electrical field and to induce the electrokinetic mechanism to work. For this study, the TES 6230 brand DC power supply unit with digital display screens was used. The power supply unit was connected to the stainless steel electrodes installed inside the cell via an electrical board to facilitate measurement of electrical currents passing through the circuit at any point in time. In order to monitor the voltage distribution between the electrodes constantly, extension wires were attached to each silver probe-electrode and extended outside the freezer to facilitate measurements. The probes on the cathode side were marked as C1, C2, C3 and C4 respectively from top towards bottom and those on the anode side were marked as A1, A2, A3 and A4. They were respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell. To measure the current and voltage parameters, a commercially available MasterCraft brand digital multimeter was used.

3.3 Sampling of Biosolids

3.3.1 Sampling from Wastewater Treatment Plant

Biosolids used in this research were sampled from "Usine d'épuration" Auteuil (Auteuil Wastewater Treatment Plant) in Laval, Quebec. The plant treats about 45,000 m^3 of wastewater per day with an objective of 85% or more reduction of BOD_5, SS, P, faecal coliform, etc. using both primary and secondary treatment units. The primary treatment unit removes floating and settleable solids, whereas most of the organic matters are removed in the secondary treatment unit. Both biological and chemical processes are applied in the secondary treatment of wastewater to remove pollutants. Biosolids

produced from these treatments of wastewater are transferred to the incineration unit after addition of polymers and subsequent dewatering. For the purpose of this research, biosolids were sampled from the location after the addition of polymers but before dewatering, as shown in Fig. 3.3. Two 20 litres plastic containers of biosolids were collected and stored at $4^{o}C$ temperature in a refrigerator.

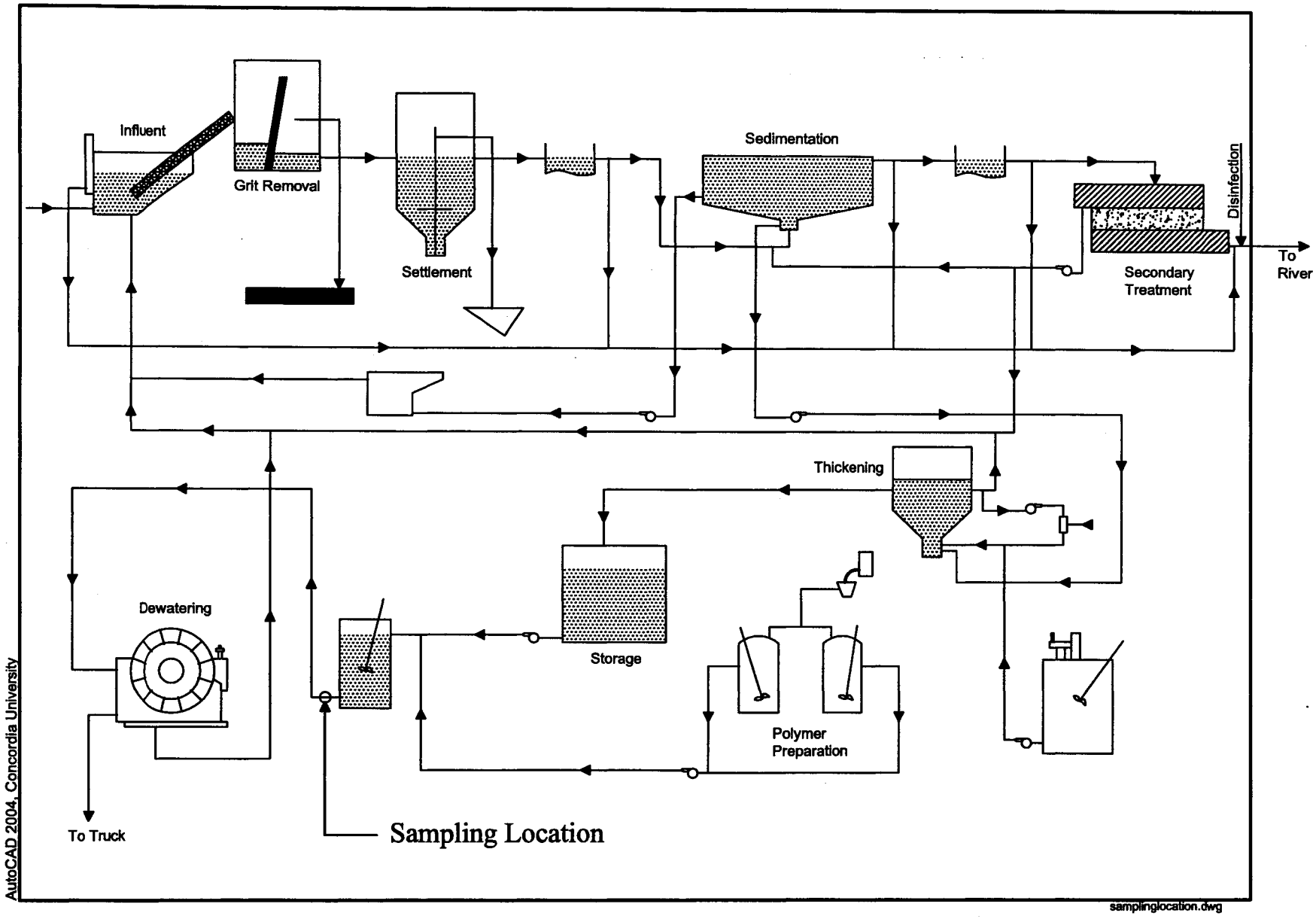

Fig. 4.3 Sampling location with wastewater treatment process flow-chart

3.3.2 Characterization of sampled biosolids before the application of electrokinetics

The biosolids sampled from the wastewater treatment plant were analyzed first to determine the initial characteristics before the application of electrokinetics so that the impact of electrokinetics processes on the distribution of pH, total solids and organic contents and the movement of metal ions could be evaluated properly. The preserved sample was first stirred thoroughly in the container to make a homogenous mixture, and then a portion of it was poured into a beaker and kept undisturbed for one hour to allow the sludge to settle at the bottom of the beaker. The settled sludge from the beaker was then collected and analyzed. The values obtained for the various parameters tested on the initial biosolids samples are presented in Table 3.1.

Table 3.1: Characteristics of the biosolids sampled from the wastewater treatment plant

Parameters	Unit	Value obtained
Total solids	%	4 – 5
Organic content	%	39 – 55
pH		6.4 – 6.7
Metal contents		
➢ Cadmium	mg/kg dry solid	0.17 – 0.53
➢ Copper	mg/kg dry solid	79 – 102
➢ Lead	mg/kg dry solid	3.82 – 9.69
➢ Nickel	mg/kg dry solid	12 – 22
➢ Zinc	mg/kg dry solid	141 – 166

3.4 Laboratory Experiments

3.4.1 Apparatus, reagents and equipments

In this section a list of the apparatus, equipment and/or chemicals has been presented concisely along with the numbers and quantities used during various tests and analysis throughout the study.

Apparatus and equipments

a) For physical and chemical analysis

1) Evaporating dish (ceramic crucibles)
2) Muffle furnace for operation at 550°C
3) Desiccator
4) Drying oven, for operation at 103 to 105°C
5) Analytical balance, capable of weighing to 0.1 mg.
6) Stirrer
7) Wide-bore pipets (1 mL, 10 mL and 20 mL)
8) Graduated cylinders
9) Graduated beakers (1L, 0.5L, etc.)
10) 50 mL plastic centrifuge tubes with caps
11) Mechanical shaker (AROS 160)
12) Filter papers
13) Filter funnel
14) Thermometer
15) Plastic sampling bags
16) pH meter (Fisher Scientific, AR 25)

17) Atomic Absorption Spectrometer (Perkin Elmer, Analyst 100)

b) For electrical measurements

1) 16 Stainless steel (304) plate electrodes (12 cm X 10 cm X 0.2 cm)

2) 8 Silver probe electrodes

3) Electrical wires

4) DC power supply (TES, 6230)

5) Electrical control board

6) Digital multimeter (Mastercraft)

Chemicals and reagents

1) HCl (4M)

2) HCl (1M)

3) Conditioning liquid (ammonia/ phosphorus combination)

4) AA standard solutions for Cadmium, Copper, Lead, Nickel, Selenium and Zinc.

3.4.2 Preparation of the test cells

All the laboratory tests carried out during the whole study have been divided into two stages. Stage I tests were carried out at -8°C and Stage II at -15°C ambient temperatures. In Stage I, a series of two tests, one using conditioning liquid and another without conditioning liquid was performed. In Stage II, a series of four tests, one without the addition of conditioning liquid and three using different concentrations of conditioning liquid and voltage gradient to determine optimal condition were performed. The cell for each experiment was prepared in the same manner, the only difference being the addition

of the specific concentration of conditioning liquid with biosolids in the particular cells where conditioning liquids were used. The preserved sample collected from the WWTP was stirred thoroughly in the container to make a homogenous mixture and was poured into three 1000 mL beakers. The beakers with the well-mixed biosolids samples were kept undisturbed for 1 hour to allow the sludge to settle at the bottom. The settled sludge from the bottom of the beakers was then poured into the cells already prepared as described in section 3.2.1 and also used for the determination of initial contents of total solids, organic matters and metals. A total of 2350 mL settled sludge was used in each cell. For the cells with conditioning liquid, the required amount of conditioner for a total volume of 2350 mL was dissolved in 150 mL of distilled water and then added to 2200 mL of settled sludge and mixed thoroughly. Thus, to obtain the highest (H), medium (M) and the lowest (L) concentrations of conditioning liquid respectively 94.2 g, 31.4 g and 18.8 g of conditioner were used in the respective cells.

After filling the cells with biosolids the stainless steel electrodes were inserted into the biosolids in the cells. The DC power supply unit was connected to the electrodes and the whole arrangement was placed in the desired low ambient temperature. Each experiment started with setting the power supply unit on with the application of the desired voltage gradient. Details of the cell conditions have been presented in Table 3.2.

Table 3.2: Test identification and properties

Test No.	Test ID	Voltage gradient (V/cm)	Concentration of conditioning liquid (g/L)	Ambient Temperature during the test (°C)	Test duration (Days)
Stage I:					
1	*T1(-8,0)	1.0	None	- 8	3
2	*T2(-8,H)	1.0	40	-8	9
Stage II:					
3	*T3(-15,0)	1.0	None	-15	2
4	*T4(-15,L)	1.0	8	-15	3
5	*T5(-15,M)	1.0	13.4	-15	6
6	*T6(-15,L)	1.5	8	-15	5

*Note: T1(-8,0) stands for "Test No.1(ambient temperature, concentration of conditioning liquid)"; H, M and L indicate highest, medium and lowest concentrations of conditioning liquid.

3.4.3 Observations and measurements during the experiments

All measured and calculated electrical and metal content data have been incorporated in **Appendix I**. Discussions and analyses of the results obtained from different experiments have been presented in **Chapter 4**. As already mentioned in various sections above, one of the major objectives of this study was to assess the functionality of the electrokinetic mechanism on the movement of heavy metals in biosolids in cold weather conditions. To achieve this objective the cells were placed at desired low temperatures while

electrokinetics was applied. Current passing through the circuit and voltage between cathode and each probe-electrode were measured every hour to monitor the changes occurring in the cell. Since no previous study or data were available on this kind of experiments, it was important to monitor the cells closely to be certain about the functionality of the whole system.

The maximum current flowing across the system for all the cells was found near the beginning of the test and it gradually decreased with the passage of time and eventually ceased completely. For the cells without conditioning liquid [T1(-8,0) and T3(-15,0)], the flow of current decreased smoothly from the beginning of the test and no fluctuation of current was observed throughout the tests. The maximum measured current was 4.3 mA and 0.4 mA during tests T1(-8,0) and T3(-15,0) respectively. At the end the cells were found completely frozen and significant scouring was observed on the anode electrodes. As already mentioned above, cells with conditioning liquid also showed the same trend of decreasing current over time; however, fluctuations of flow was observed in all the tests. The maximum current of 9.7 mA was observed during test T2(-8,H) and that for tests T4(-15,L), T5(-15,M) and T6(-15,L) were 1.3 mA, 2.8 mA and 4.9 mA respectively, all observed during the 1st day of the experiment. Though biosolids in the cells were frozen and flow of current stopped completely when the cells were disconnected, it was observed during sampling that the bottom layers of biosolids were comparatively softer (insufficient freezing) than the top layers. No such scouring, as observed in cells without conditioning liquid, was found on either electrode.

3.4.4 Sampling procedure of biosolids at the end of the experiments

Each experiment ended when there was no current flowing through the system. The biosolids inside the cell were found completely frozen. The cells were then kept outside at room temperature for a couple of hours to allow the frozen biosolids to thaw partially to facilitate sampling. Biosolids inside a cell were divided into six parts and were sampled accordingly. The sample from the area behind the cathode electrode was designated as BC (backside of cathode) and that from behind the anode electrode was designated as BA (backside of anode); the lengths of these areas were 3 cm each from the respective electrodes. The 19.5 cm distance between the electrodes was divided into four parts as follows: first 4.75 cm from cathode was designated as C and the next 5.0 cm as MC (middle area on cathode side) and similarly, first 4.75 cm from anode was designated as A and the next 5.0 cm as MA (middle area on anode side). Width of each section was 14 cm. The overall sampling scheme has been presented in Fig. 3.4.

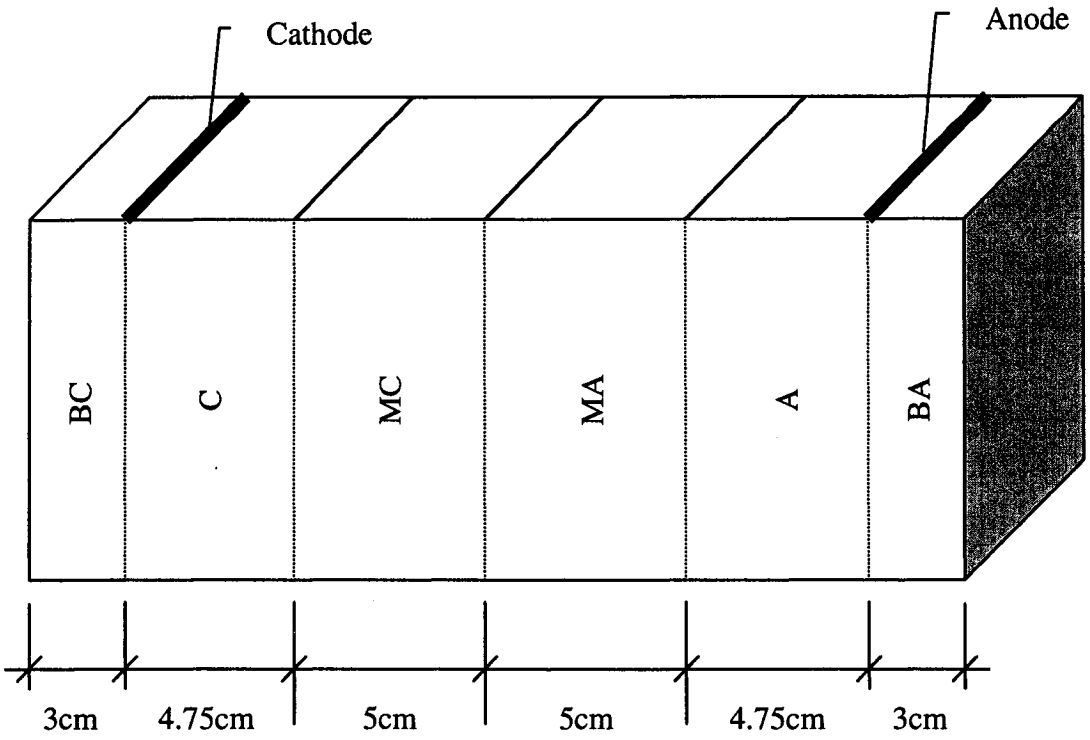

Fig. 3.4 Biosolids sampling scheme

Samples collected according to the above-mentioned procedure were packed and labelled individually in plastic sampling bags. All the samples from one cell were again kept in one plastic sampling bag with proper labels and stored in a refrigerator at 4°C temperature for further analysis.

3.4.5 Measurements and analysis after the experiments

The samples taken after the experiments were subjected to the following tests and analyses in order to ascertain the changes in biosolids qualities that might be affected by the application of electrokinetics:

- Total solid contents
- Organic contents
- pH measurements

- Metal content analysis for Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni), Selenium (Se) and Zinc (Zn).
- Analysis for resistance development in the cells.

Procedures followed to carry out the various tests and analyses have been presented in the following sections.

3.4.5.1 Total solids contents

Tests to determine the percentage of total solids in the biosolids samples were performed following the procedure described in Clesceri et al. (1998) (Method 2540 G). A ceramic crucible was cleaned thoroughly and placed in an oven at 105°C for 1 h to dry, then cooled in a desiccator, weighed and stored in a desiccator until ready for use. When biosolids samples were ready, a sufficient quantity of it was poured into the prepared crucible and weighed. The crucible with wet samples was then placed in an oven at 105°C for 24 hours to dry. It was then taken out of the oven, cooled to balance temperature in a desiccator and weighed.

The percentage of Total Solids was then calculated as follows:

$$\% \text{ total solids} = \frac{(A-B)}{(C-B)} \times 100 \qquad \text{(Eq. 13)}$$

where, A = weight of dried sample + dish, mg.

B = weight of dish, mg

C = weight of wet sample + dish, mg.

3.4.5.2 Organic contents

To determine the percentages of organic content or volatile solids, the samples obtained after the solid contents tests were placed in a muffle furnace at 550°C for 2 hours, then cooled in a desiccator to balance temperature and weighed.

The percentage of organic content was then calculated as follows:

$$\% \text{ organic content} = \frac{(A-D)}{(A-B)} \times 100 \qquad \text{(Eq. 14)}$$

where, A = weight of dried sample + dish, mg.

B = weight of dish, mg

D = weight of residue + dish after ignition, mg.

3.4.5.3 pH measurements

To measure the pH of each sample, an amount of 5 g of biosolids was poured in 20 mL of distilled water in a 50 mL plastic centrifuge tube and the mixture was shaken for 24 hours by a mechanical shaker at a speed of 120 rpm. The centrifuge tube was placed laying down on the shaker. The pH of the mixture was then measured using a digital pH meter (Fisher, AR 25).

3.4.5.4 Metal content analysis

Analysis to determine the metal contents in the biosolids was performed according to the following procedure:

Digestion of samples for metals

The biosolids samples were digested following a less rigorous cold digestion method to reduce interference by organic matter and to convert metals associated with particulates to a form (usually the free metal) determinable by atomic absorption spectrometry. For the purpose of this research, HCl (4M) was used to digest samples for metal content analysis. The dried samples obtained after the total solids content tests were placed in a furnace at 550°C for 2 hours to remove organic matter. Cooled in a desiccator to normal temperature and then crushed to powder in a ceramic crucible. A portion of the powder was poured in a 50 mL plastic centrifuge tube and HCl (4M) was added into the tube at a ratio of 10 mL of HCl (4M) to 1 g of sample powder. The mixture was then shaken by a mechanical shaker (AROS 160) for 24 hours at a speed of 190 rpm. The centrifuge tubes were placed laying down on the shaker.

Analysis for metals

The mixture was then filtered using Whatman grade 40 filter paper and the filtrate was analyzed for metal contents using an Atomic Absorption Spectrometer (Perkin Elmer, Analyst 100). Each sample was analysed for Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni), Selenium (Se) and Zinc (Zn).

Concentration of metals was then calculated as follows:

$$\text{metal concentration, mg/L} = A \times \frac{B}{C} \qquad \text{(Eq. 15)}$$

where, A = concentration of metal in digested solution, mg/L.

B = final volume of digested solution, mL, and

C = sample size, mL.

Results can also be reported on wet- or dry-weight basis as follows:

$$\text{metal concentration, mg/kg (wet-weight basis)} = \frac{A \times B}{g\ sample\ (wet)} \qquad \text{(Eq. 16)}$$

$$\text{metal concentration, mg/kg (dry-weight basis)} = \frac{A \times B}{g\ sample\ (wet)} \times \frac{100}{D} \qquad \text{(Eq. 17)}$$

where, A = concentration of metal in digested solution, mg/L.

B = final volume of digested solution, mL, and

D = total solids, %.

3.4.5.5 Analysis for resistance development in cells

As already mentioned in section 3.4.3, current passing through the circuit and voltage differences between cathode and each probe-electrode were measured directly using a digital multimeter. Changes of resistances due to the freezing of biosolids have been calculated using Ohm's Law, as follows:

Ohm's Law: $V = R \times I$ (Eq. 18)

where, R = Resistance (Ohm)

V = Voltage difference (V), and

I = Electrical current (A)

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

At the end of each experiment, biosolids inside the cell was sampled following the procedure in section 3.4.4. The samples were then analyzed for various parameters as described in section 3.4.5. This chapter presents all the measured data during the experiments and the results obtained from various tests and analysis on the samples. It also presents thorough discussions on the measured data and results and the influence of different cell conditions and environments on the results. The chapter has been divided into various sub-sections to facilitate clear and concise presentation of various data and results.

4.2 pH Distribution

The pH of each sample was measured following the procedure presented in section 3.4.5.3 and the values obtained for various samples in different tests have been presented in Table 4.1. The highest value of 9.3 was obtained in the backside of cathode (BC) region during the test T5(-15,M) that lasted for 6 days using conditioning liquids and the lowest value of 3.3 was obtained in the anode (A) region of test T2(-8,H) that also used conditioning liquid but ran for 9 days.

Table 4.1: pH of samples before and after the application of electrokinetics

Sample code	pH						Remarks
Initial	6.6	6.4	6.5	6.7	6.7	6.7	Before EK
BA	6.6	5.1	6.5	6.5	6.2	6.6	After EK
A	6.2	3.3	5.7	3.9	3.7	4.4	
MA	6.4	3.4	6.3	6.6	4.2	5.5	
MC	6.8	4.1	6.8	7.5	6.6	7.8	
C	7.2	5.9	7.3	8.8	9.1	8.8	
BC	6.9	8.4	6.9	8.9	9.3	8.6	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	**T5(-15,M)**	**T6(-15,L)**	

Detailed comparative analyses on the distribution of pH in different cells based on the different physical-chemical conditions have been presented in the following sections.

4.2.1 pH in cells without conditioning liquid

Fig. 4.1 presents pH distribution inside the cells tested without addition of the conditioning liquid [T1(-8,0) and T3(-15,0)]. The highest and lowest pH values for T1(-8,0) were 7.2 and 6.2 and those for T3(-15,0) were 7.3 and 5.7 in the cathode (C) and anode (A) areas respectively. It can be clearly observed from the figures that the formation of H^+ due to the dissociation of water near the anode (A) areas created an acid front that obviously moved up to middle cathode (MC) areas; the formation of OH^- ions near the cathode (C) areas raised the pH in the middle cathode and cathode areas but it still remained in the acidic range in the middle cathode areas, and the base front could only proceed throughout the cathode area. It is true for both the cases although test T1(-8,0) ran for 1 day longer than the running period of 2 days for test T3(-15,0). It can also be observed that higher pH values reached relatively rapidly but could not create a strong base front towards the anode areas perhaps due to the freezing effect and the consequent

loss of free water for dissociation. This aspect might have a positive impact on the migration of metal ions towards cathode areas with the movement of acid front.

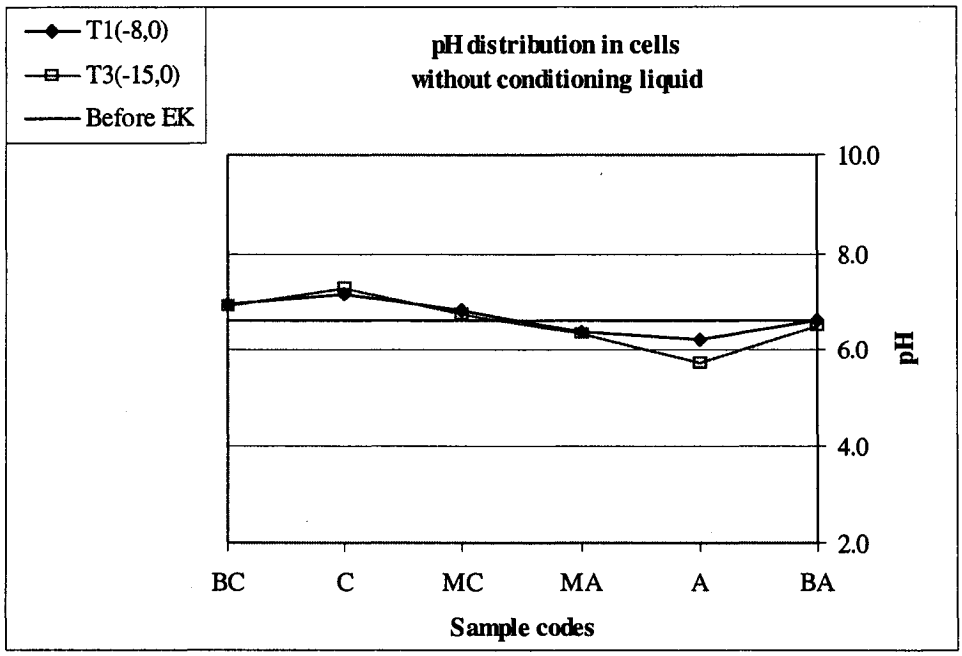

Fig. 4.1 pH values in cells without conditioning liquid

The broader range between the highest and lowest pH values in test T3(-15,0) that ran for 1 day shorter than test T1(-8,0) might be related to the higher moisture content in the initial biosolids of test T3(-15,0) which enhanced rapid production of H^+ and OH^- ions.

4.2.2 pH in cells with conditioning liquid

Four cells have been tested with the addition of different concentrations of conditioning liquid and combination of voltage gradients and temperatures in order to predict the optimal conditions of removal and test duration. Details of the cell properties have been presented in Table 3.2. pH distributions inside the four cells such as T2(-8,H), T4(-15,L), T5(-15,M) & T6(-15,L) have been presented in Fig. 4.2.

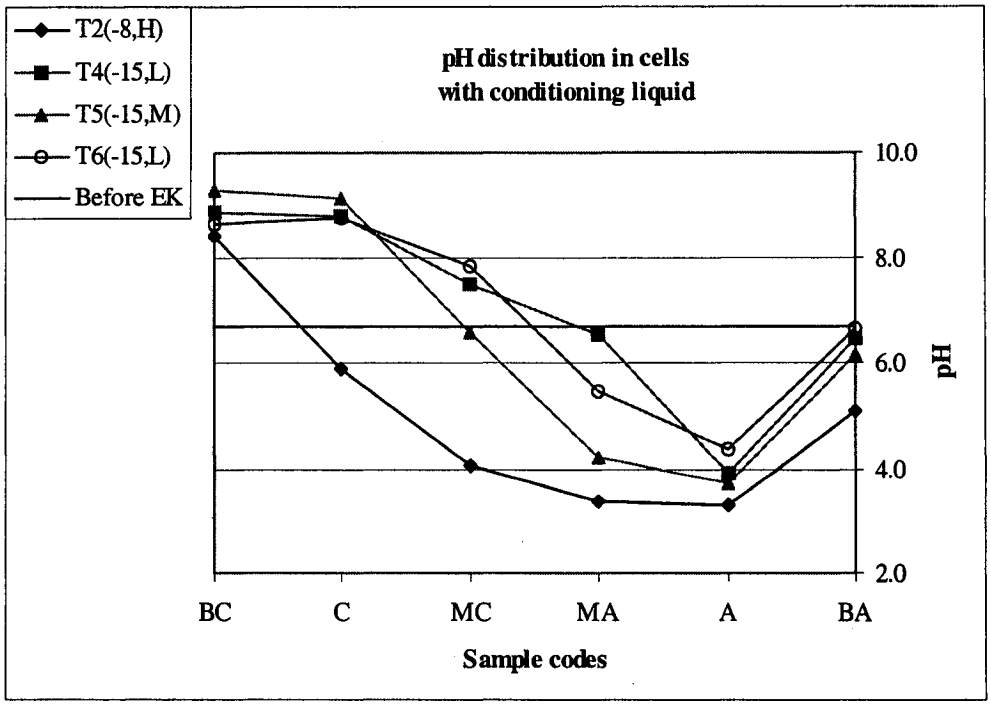

Fig. 4.2 pH values in cells with conditioning liquid

The highest and lowest pH values of 9.3 and 3.3 were observed in the back cathode (BC) region of test T5(-15,M) and anode (A) region of test T2(-8,H) respectively. The similar trend of reaching the higher pH values in relatively shorter period of time as observed in the previous section of without conditioning liquid is also followed here but it can be clearly observed form the figures that as the tests ran for longer periods the pH around anode areas was lowered substantially and the movement of the consequent acid front towards the cathode region was more prominent than the movement of the base front towards the anode region. Moreover, it is also clear from the pH values obtained during different tests (refer to Table 4.1) that there are limitations for the upper range of pH and values exceeding 9.0 are rare. This might also be due to the freezing effect as mentioned before and the excessive ice formation near the cathode areas as observed during the

experiments. And as observed in the previous case the overall impact of all these situations along with the prolonged duration of tests with the addition of conditioning liquid might have an even greater influence on the movement of metal ions towards the cathode region with the acid front.

Now, from Fig. 4.2, it is clear that for test T2(-8,H), which ran for 9 days using the maximum concentration (40 g/L) of conditioning liquid, the acid front moved up to the end of the cathode (C) region. Test T4(-15,L) used the lowest concentration (8 g/L) of conditioning liquid and ran for 3 days, yet the acid front could proceed only up to the middle anode (MA) region. During test T6(-15,L) using the same concentration (8 g/L) of conditioning liquid but a higher voltage gradient (1.5 V/cm), the acid front proceeded a bit further but remained within the same (MA) region. In the case of test T5(-15,M) that used an average concentration (13.4 g/L) of conditioning liquid, the acid front moved up to middle cathode (MC) region.

4.3 Solid Content Distribution

The total solids content of each sample was measured following the procedure presented in section 3.4.5.1. Percentages of total solids obtained for various samples in different tests have been presented in Table 4.2.

The maximum percentage of total solids (10.9%) was obtained in the middle cathode (MC) regions of test T1(-8,0) and the minimum of 4.0% in the back cathode (BC) areas of test T6(-15,L). The amount of total solids in all samples increased and found to be

higher than the initial values with the only exceptions in the boundary locations of test T5(-15,M) and T6(-15,L) that might be ignored.

Table 4.2: Percentages of total solids in samples before and after the application of electrokinetics

Sample code	Total solids (%)						Remarks
Initial	5.3	5.2	4.0	4.6	5.1	5.1	Before EK
BA	9.4	7.2	4.4	4.7	5.2	4.3	After EK
A	10.3	8.3	6.3	4.8	4.4	5.0	
MA	9.0	8.4	6.4	5.9	6.2	6.1	
MC	10.9	8.6	7.2	5.5	8.0	6.9	
C	9.6	11.5	7.4	6.0	6.0	5.4	
BC	10.2	9.1	7.4	5.1	4.7	4.0	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	**T5(-15,M)**	**T6(-15,L)**	

Detailed comparative analyses on the amount of total solids in different cells based on the different physical-chemical conditions have been presented in the following sections.

4.3.1 Total solids in cells without conditioning liquid

The percentages of total solids in various locations inside the cells tested without addition of conditioning liquid have been presented in Fig. 4.3. It is clear from the figure that the amount of total solids increased by 1.5 to 2 times of the initial values during both the tests and there is a general trend of increasing solid content toward the cathode areas.

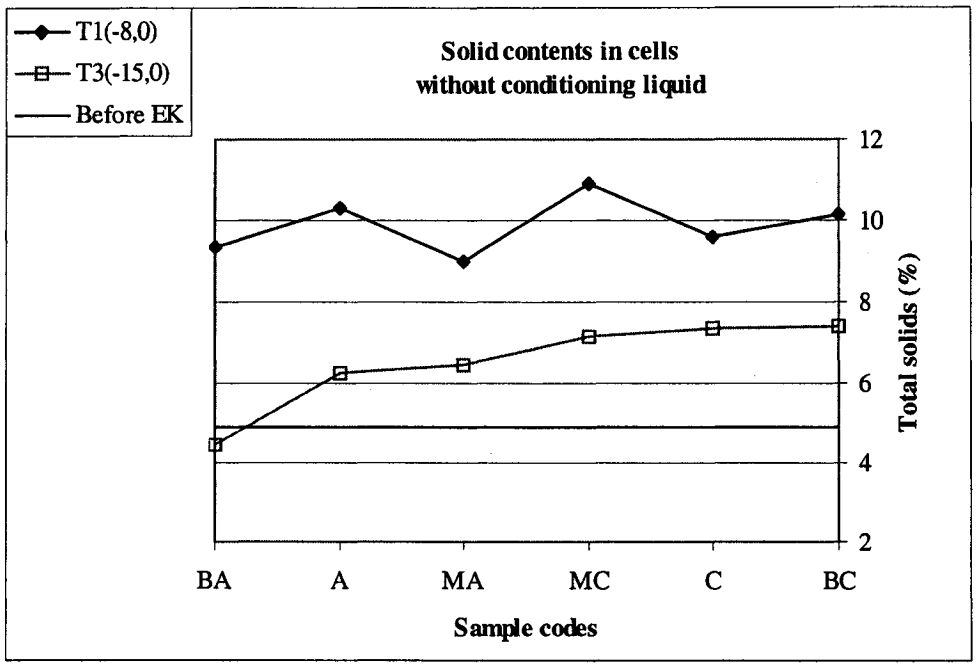

Fig. 4.3 Total solids in cells without conditioning liquid

For test T1(-8,0), the maximum amount of total solids was found as 10.9% in the middle cathode (MC) area and the minimum amount as 9.0% in the middle anode (MA) area with an average total solid content of 9.9% for the whole cell area after the application of electrokinetics which was 1.9 times higher than the percentage of total solids in the initial biosolids. The maximum and minimum amount of total solids for test T3(-15,0) was found to be 7.4% and 4.4% respectively in the cathode (C) and back anode (BA) areas with an average total solid content of 6.5% for the whole cell area after the application of electrokinetics which was 1.6 times higher than the total solids contents in the initial biosolids.

4.3.2 Total solids in cells with conditioning liquid

Fig. 4.4 presents total solids distribution inside the cells using conditioning liquid. Total solids contents increased in all cells and it was gradually higher towards the cathode areas as observed in the previous section of without conditioning liquid but in this case percentage of total solids increased at a much slower rate.

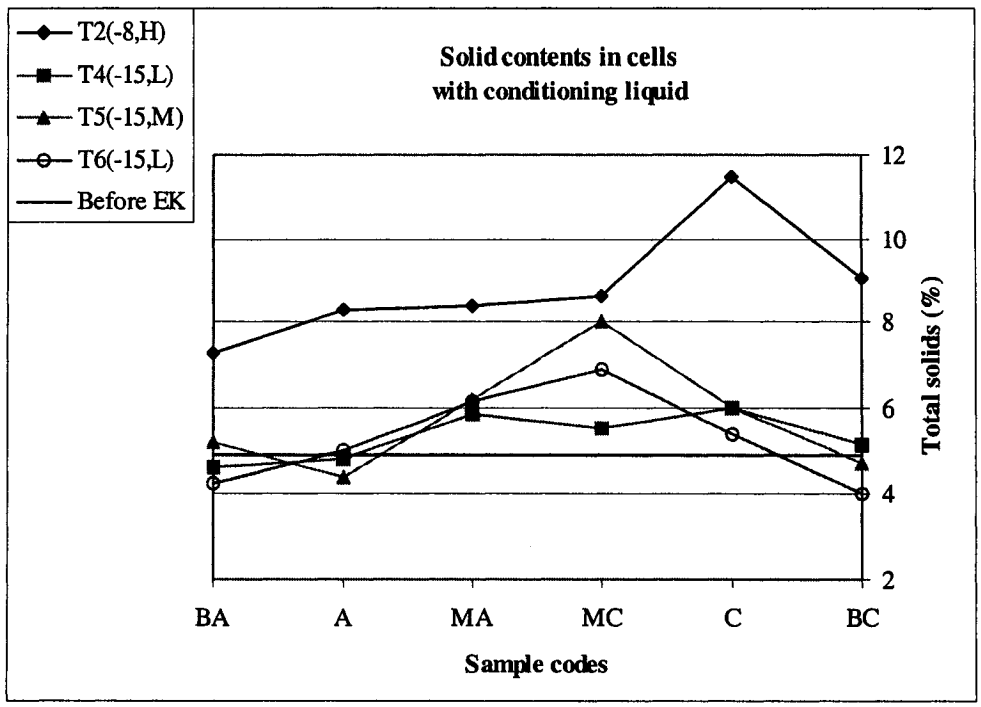

Fig. 4.4 Total solids in cells with conditioning liquid

Average solid contents in areas between the two electrodes in the three cells [T4(-15,L), T5(-15,M) & T6(-15,L)] using conditioning liquid of stage 2 tests were found as 5.6%, 6.1% and 5.9% which were 20.5%, 21.6% and 14.7% higher than the solids content of initial biosolids. The only exception was test T2(-8,H), where average solid content was found as 9.2% in areas between the two electrodes which was 77.8% higher than that of the initial biosolids. This might be due to the prolonged duration that the test ran for.

4.4 Organic Content Distribution

Procedures for the determination of organic content have been delineated in section 3.4.5.2. Organic content data found in various samples of all the tests including the data for the initial biosolids have been presented in Table 4.3. Percentages of organic content in all samples were found lower than the initial value with the only exception of the anode (A) area of test T4(-15,L) which might be due to some unusual circumstances like excessive coagulation or presence of impurities and may be ignored. There is a general trend of decreasing percentages of organic content from the anode towards the cathode areas.

Table 4.3: Percentages of organic contents in samples before and after the application of electrokinetics

Sample code	**Organic content (%)**						**Remarks**
Initial	38.8	54.2	54.0	53.2	54.6	53.9	Before EK
BA	34.4	51.0	53.8	51.2	49.9	46.4	After EK
A	38.0	44.7	53.7	55.2	53.8	51.0	
MA	35.8	38.9	53.4	48.7	47.4	47.3	
MC	33.1	38.6	52.6	48.6	45.0	44.3	
C	30.3	38.8	50.5	49.9	44.8	44.9	
BC	30.8	36.9	50.6	48.2	44.2	46.1	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	**T5(-15,M)**	**T6(-15,L)**	

The maximum organic content reduction of 23.4% from the initial value was observed in test T2(-8,H) considering the average organic content inside the cell, and the minimum reduction was 3.0% in test T3(-15,0). Detailed comparative analyses on the quantities of organic contents in different cells based on the different physical-chemical conditions have been presented in the following sections.

4.4.1 Organic contents in cells without conditioning liquid

Fig. 4.5 and Fig. 4.6 present the organic content distribution in cells tested without using the conditioning liquid. As mentioned in the section above, the figures clearly show that amount of organic contents in samples after the application of electrokinetics gradually decreased toward cathode areas for both tests without conditioning liquid. Percentages of organic contents in all samples of the two tests were found lower than that of the initial biosolids.

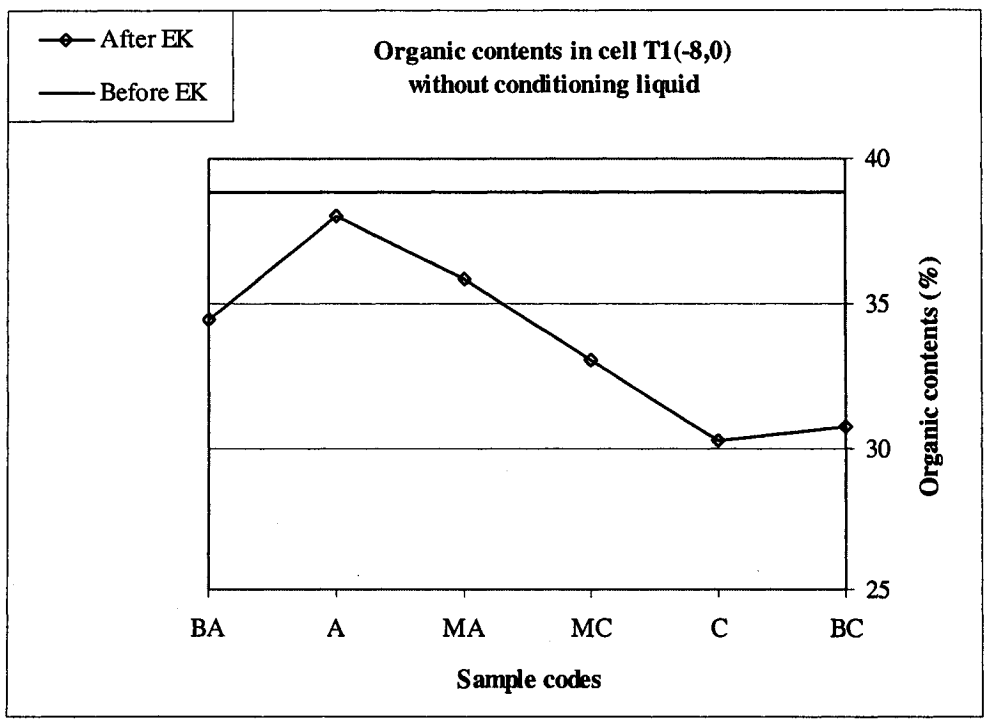

Fig. 4.5 Organic contents in cell T1(-8,0) without conditioning liquid

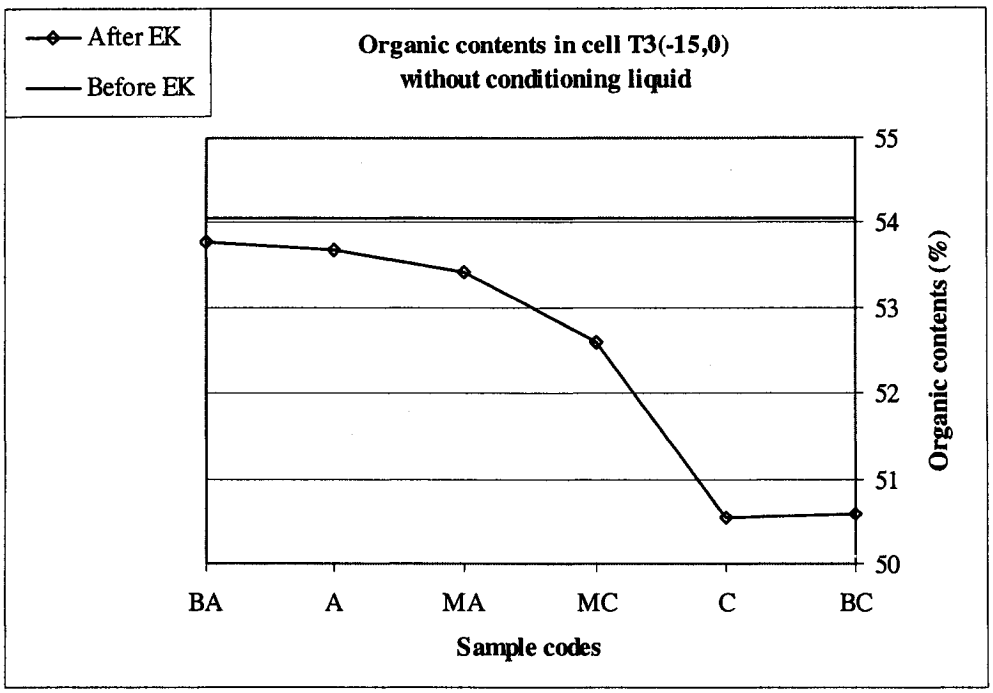

Fig. 4.6 Organic contents in cell T3(-15,0) without conditioning liquid

Test T1(-8,0) had the maximum organic content (38.0%) in anode (A) area, minimum (30.3%) in cathode (C) area and an average (33.7%) for the whole cell area which were respectively 2.1%, 22.0% and 13.1% lower than the organic contents of initial biosolids. The maximum and minimum organic contents for test T3(-15,0) were found as 53.8% and 50.5% respectively in backside of anode (BA) and cathode (C) areas and average for the whole cell area was 52.4% which were respectively 0.5%, 6.5% and 3.0% lower than the initial value.

4.4.2 Organic contents in cells with conditioning liquid

Fig. 4.7 presents organic content distributions in cells tested using conditioning liquid. All tests showed the similar trend of decreasing organic content towards cathode areas as observed during tests without conditioning liquid. Higher organic content reduction was

observed in tests that ran for longer periods. The maximum reduction (31.8%) of organic contents was achieved in test T2(-8,H) that ran for 9 days whereas that for test T4(-15,L) was 9.5% when it ran for 3 days.

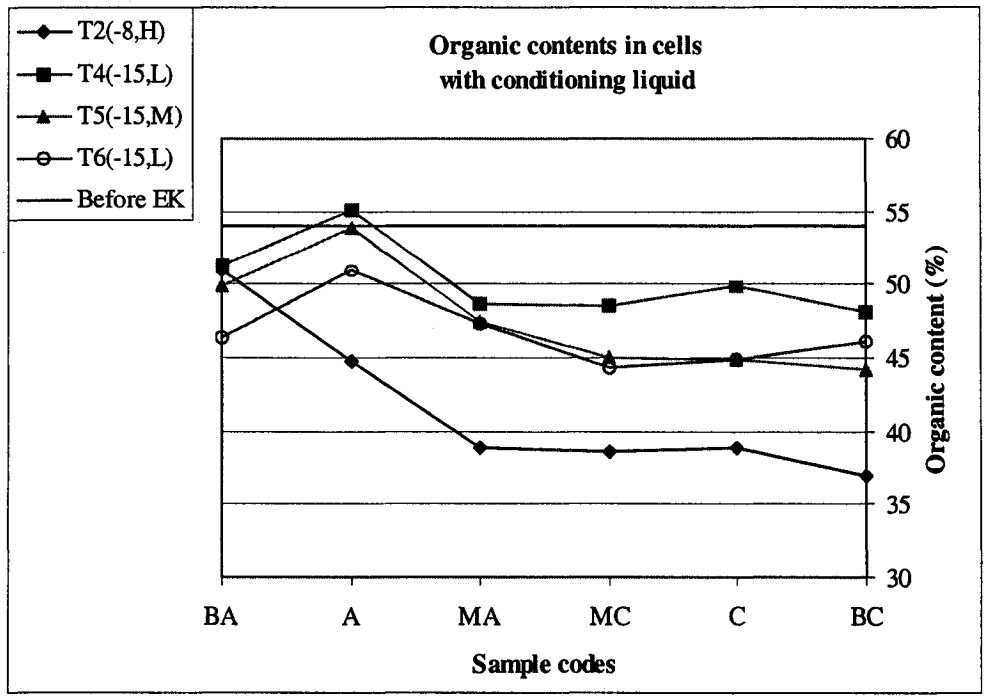

Fig. 4.7 Organic contents in cells with conditioning liquid

Table 4.4 presents the percentages of maximum, minimum and average reduction of organic content from its initial values for the tests with conditioning liquid. The locations of occurrences are easily identifiable from the figure presented above. The average organic content was calculated considering the percentages of organic content of all samples in a cell.

Table 4.4: Percentage reduction with respect to initial organic contents in cells with conditioning liquid.

TEST ID	% Reduction of organic contents			Remarks
	Maximum	Minimum	Average	
T2(-8,H)	31.8	5.8	23.4	With conditioning liquid
T4(-15,L)	9.5	3.8	5.5	
T5(-15,M)	19.0	1.3	12.9	
T6(-15,L)	17.9	5.5	13.5	

4.5 Resistance Development

Section 3.4.3 and section 3.4.5.5 describes the procedures for the measurements of current and voltages during the experiments and calculation of resistances in cells during the freezing process of biosolids.

4.5.1 Resistance in cells without conditioning liquid

The distributions of resistance in cells without conditioning liquid have been presented in Fig. 4.8 and Fig. 4.9. The changes of resistances in cell T1(-8,0) for the all three days it ran at –8°C are shown in Fig. 4.8. The lowest resistance (1605 Ω) was observed in the cathode areas at the beginning of the test and the highest (125.1 kΩ) in the anode areas at the end before current flow stopped totally.

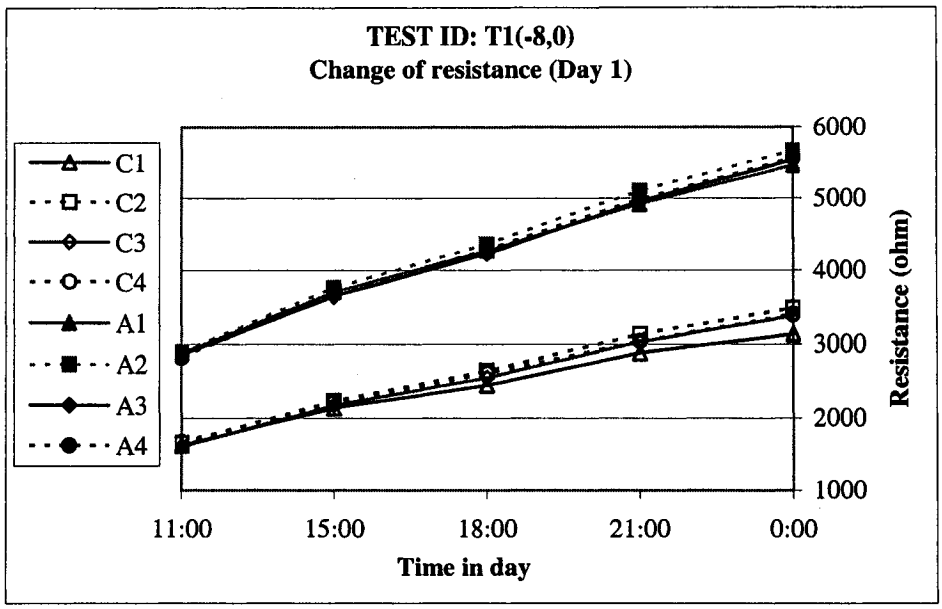

Fig. 4.8(a) Change of resistance (day 1) in cell T1(-8,0)

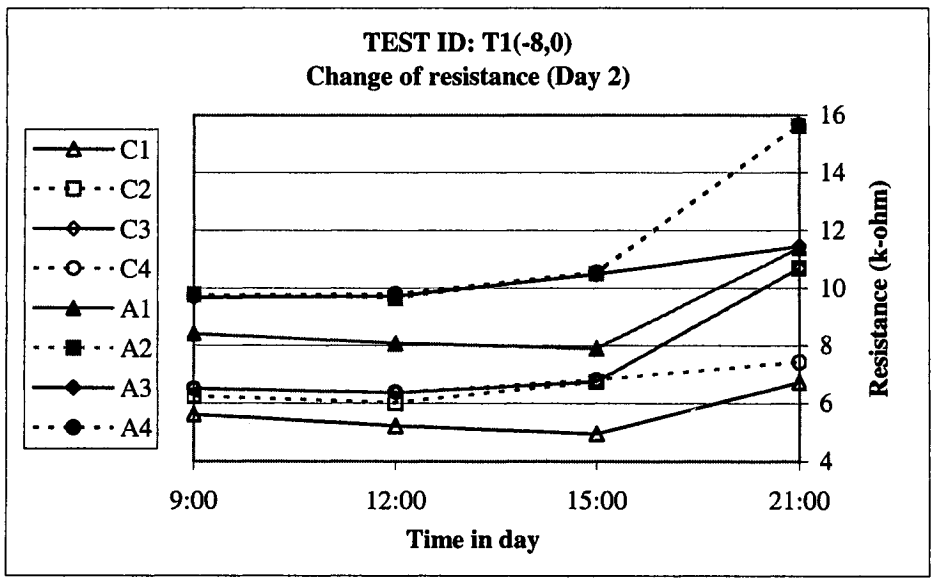

Fig. 4.8(b) Change of resistance (day 2) in cell T1(-8,0)

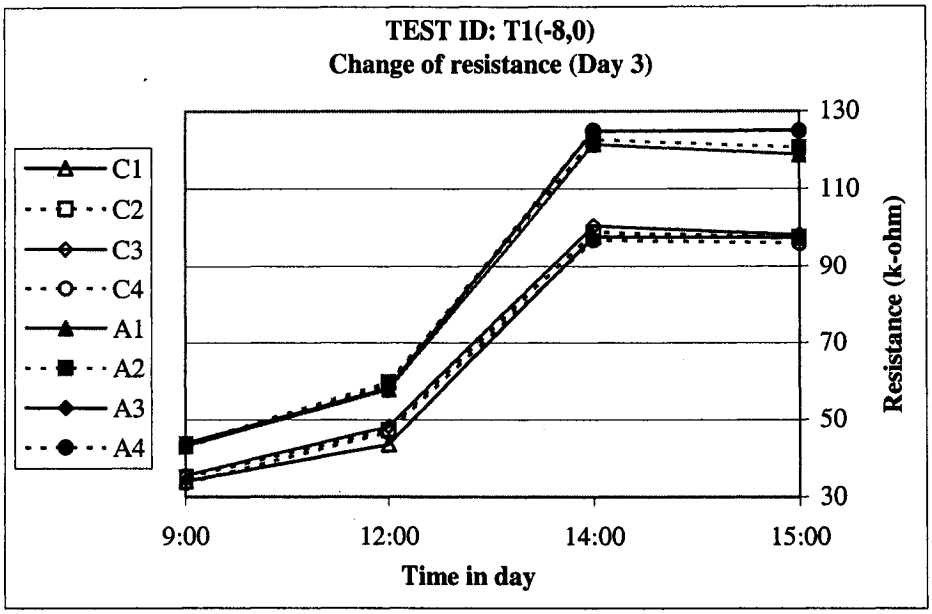

Fig. 4.8(c) Change of resistance (day 3) in cell T1(-8,0)

[Note: C1, C2, C3, C4 and A1, A2, A3, A4 are probes on cathode and anode sides respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell.]

Resistances increased smoothly during the 1st and 2nd day of the experiment. The rate of increment in the cathode and anode areas were respectively 131 Ω/h and 207 Ω/h during the 1st day and 222 Ω/h and 344 Ω/h during the 2nd day. But it increased abruptly at an average rate of 10.5 kΩ/h and 13.2 kΩ/h in cathode and anode areas respectively during the 3rd day.

Fig. 4.9 shows the change of resistances for test T3(-15,0) where the cell was placed at –15°C temperature. Resistances increased much rapidly at an average rate of 2.1 kΩ/h and rose from an average initial value of 17.7 kΩ to 39.0 kΩ in the cathode side during the 1st day of the experiment.

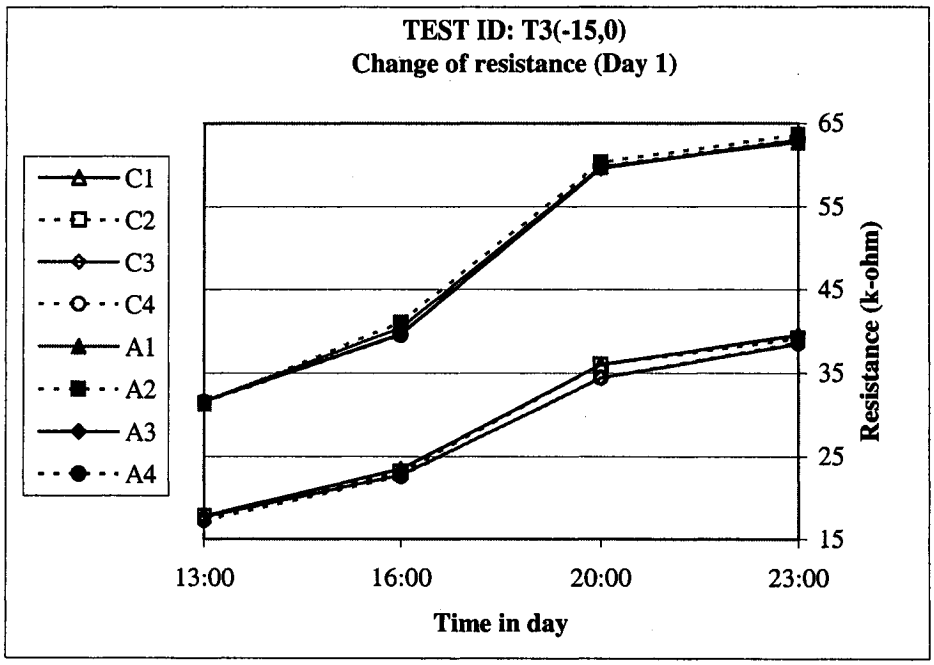

Fig. 4.9(a) Change of resistance (day 1) in cell T3(-15,0)

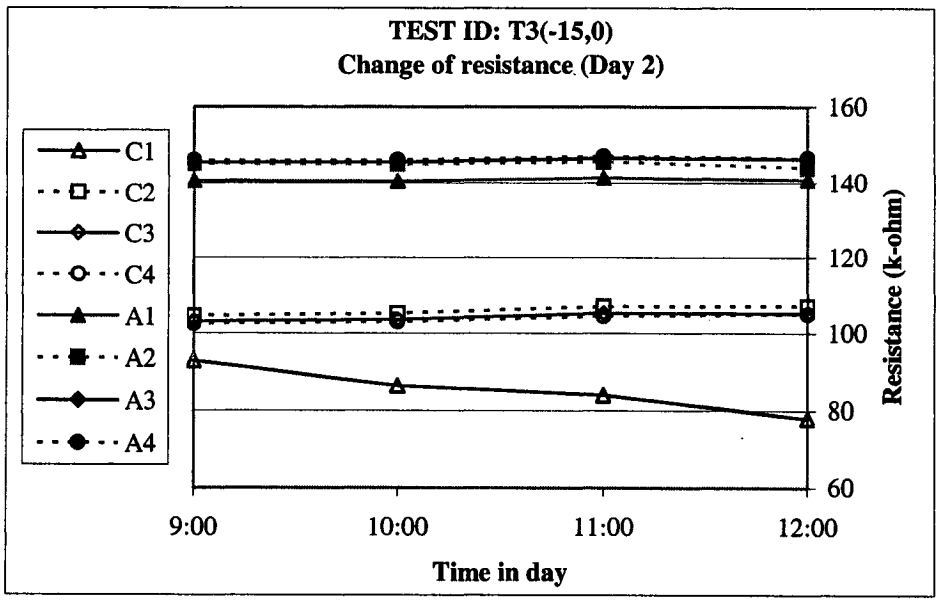

Fig. 4.9(b) Change of resistance (day 2) in cell T3(-15,0)

[Note: C1, C2, C3, C4 and A1, A2, A3, A4 are probes on cathode and anode sides respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell.]

The rate of increase of resistances in anode side was 3.2 kΩ/h and the average values rose from 31.5 kΩ to 63.1 kΩ. In the 2nd day, resistances became almost constant and there was very little current (0.1 mA) flowing and resistance values rose to the maximum of 107.1 kΩ and 147.1 kΩ in cathode and anode sides respectively before current stopped totally.

4.5.2 Resistance in cells with conditioning liquid

Resistance distributions in cells with conditioning liquid have been presented in Fig. 4.10 through Fig. 4.13. All the tests ran for longer periods compared to the previous case of without conditioning liquid and resistances increased at much slower rates. The maximum increment rate of average resistances was 5.7 kΩ/h in anode areas observed during the 8th day of test T2(-8,H), which was 7.5 kΩ/h less than that in test T1(-8,0) without conditioning liquid. Resistances were always higher near the anode areas than the cathode areas and also in bottom layers than the top layers of the cells.

Fig. 4.10 shows resistance distribution in the cell T2(-8,H). This cell was prepared using the highest concentration (40 g/L) of conditioning liquid and ran for the longest period. Change of resistance in the cell as presented in Fig. 4.10, clearly shows that resistance increased gradually from the 1st day to the 4th day at a slower and smooth rate and then remained more or less steady from 5th to 7th day of the experiment. During the 8th day it went up sharply and again became steady until current flow ceased in the 9th day. The lowest resistance (625 Ω) was found in cathode areas during the 1st day and the highest (148 kΩ) in anode areas during the 8th day. The maximum increment rate of average

resistances were 3.6 kΩ/h and 5.7 kΩ/h respectively in cathode and anode areas, also observed during the 8th day.

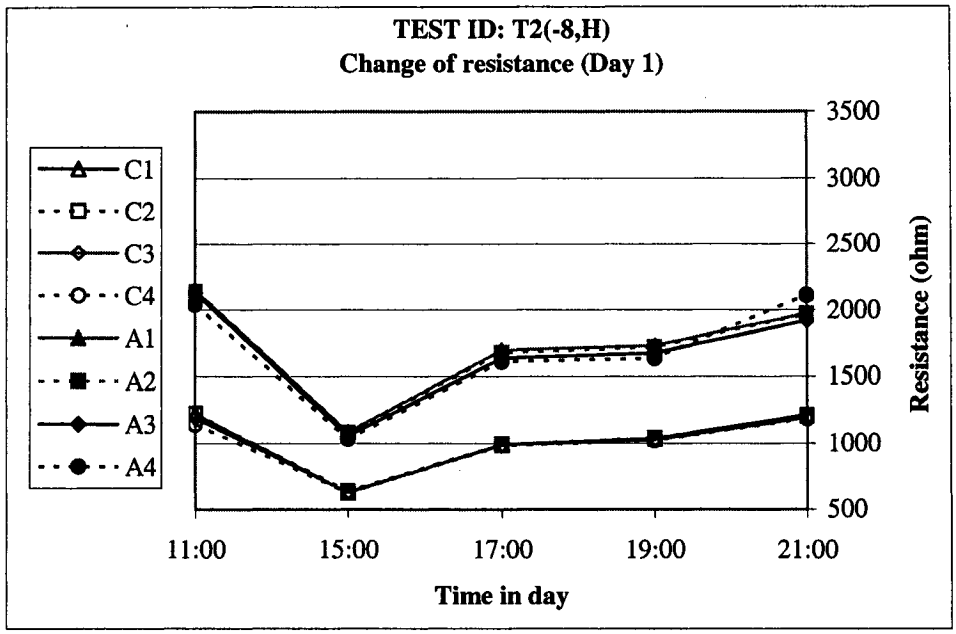

Fig. 4.10(a) Change of resistance (day 1) in cell T2(-8,H)

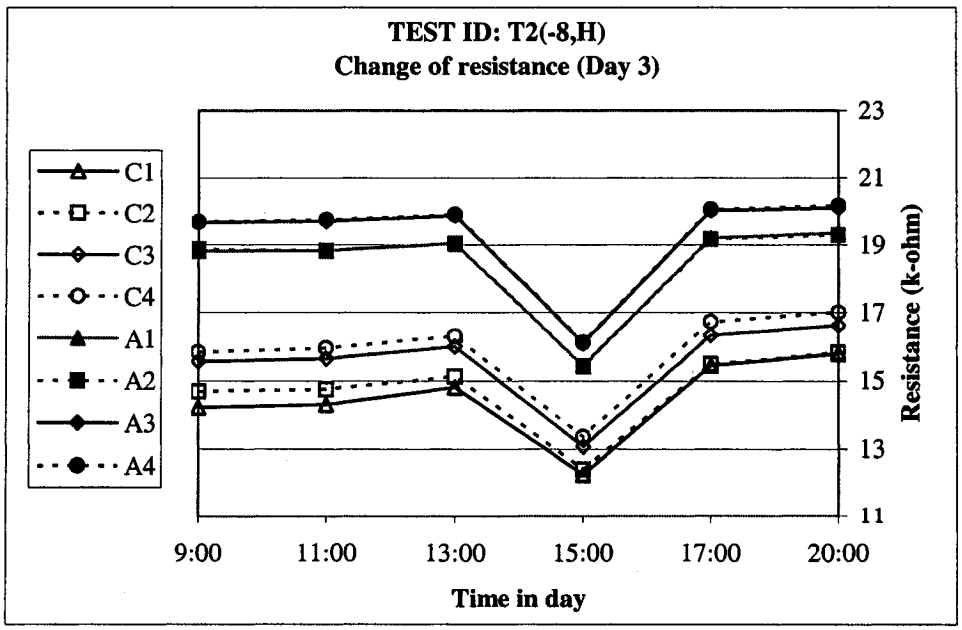

Fig. 4.10(b) Change of resistance (day 3) in cell T2(-8,H)

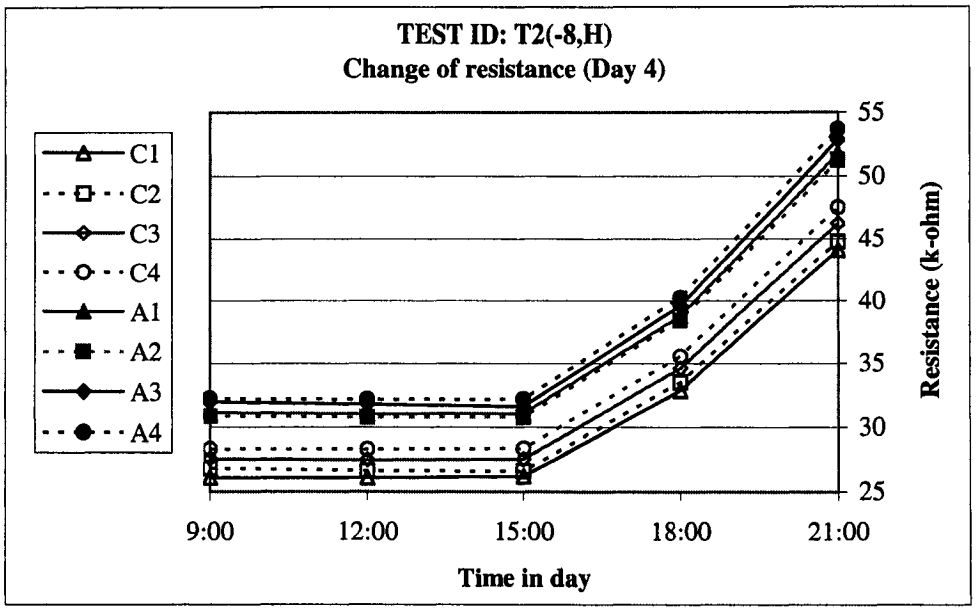

Fig. 4.10(c) Change of resistance (day 4) in cell T2(-8,H)

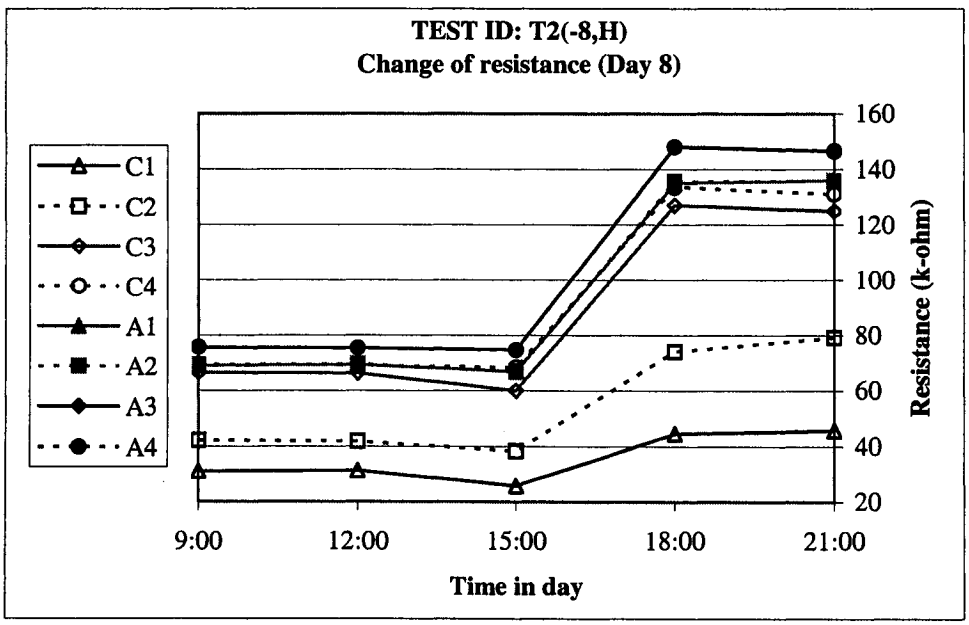

Fig. 4.10(d) Change of resistance (day 8) in cell T2(-8,H)

[Note: C1, C2, C3, C4 and A1, A2, A3, A4 are probes on cathode and anode sides respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell.]

Resistance distributions in the cell of test T4(-15,L) are presented in Fig. 4.11. The cell was prepared using lowest concentration (8 g/L) of conditioning liquid and ran 1 day longer than the test without conditioning liquid. Resistances increased at an average rate of 427 Ω/h and 617 Ω/h respectively in cathode and anode areas during the 1st day and the respective rates for 2nd day were 1193 Ω/h and 2116 Ω/h. The lowest resistance (4925 Ω) was found in the cathode areas during 1st day and the highest (114.8 kΩ) in anode areas during the 3rd day.

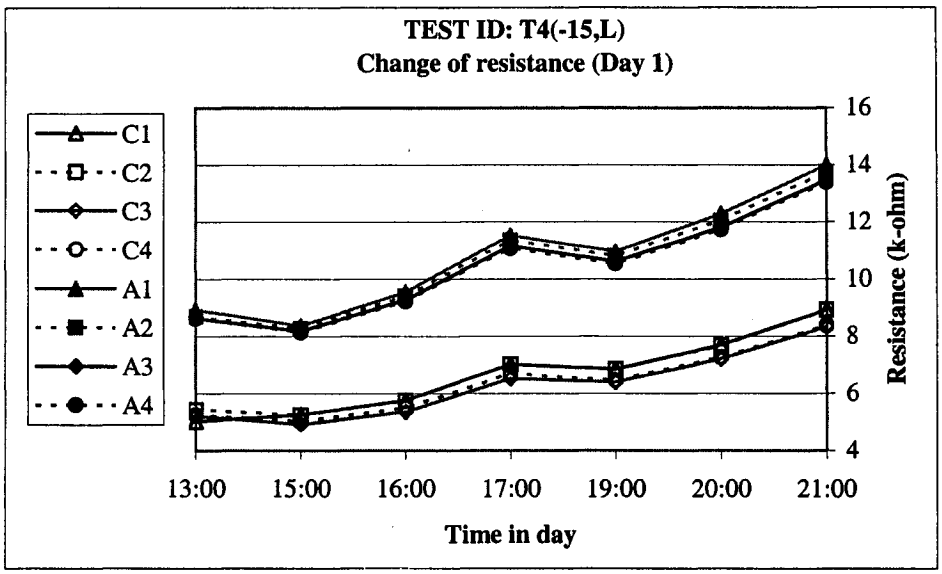

Fig. 4.11(a) Change of resistance (day 1) in cell T4(-15,L)

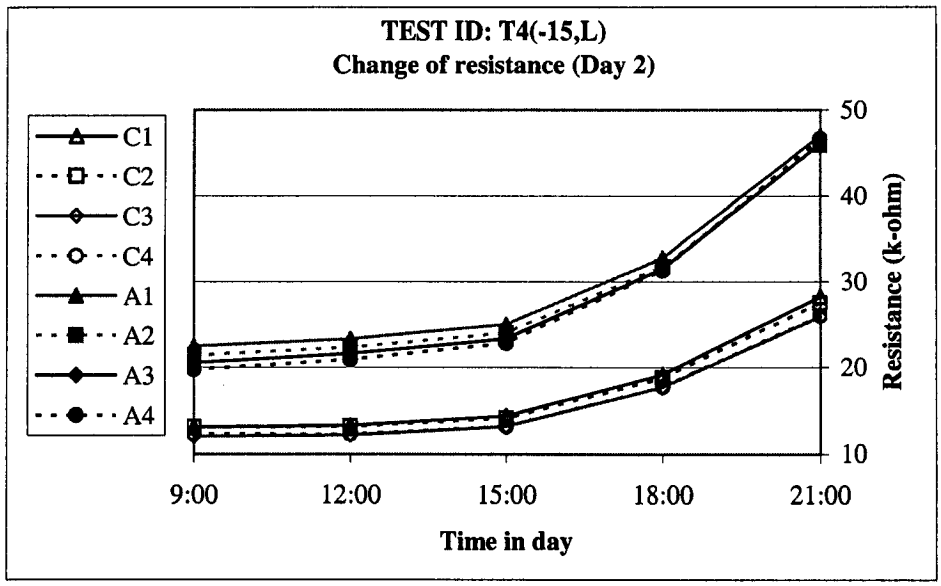

Fig. 4.11(b) Change of resistance (day 2) in cell T4(-15,L)

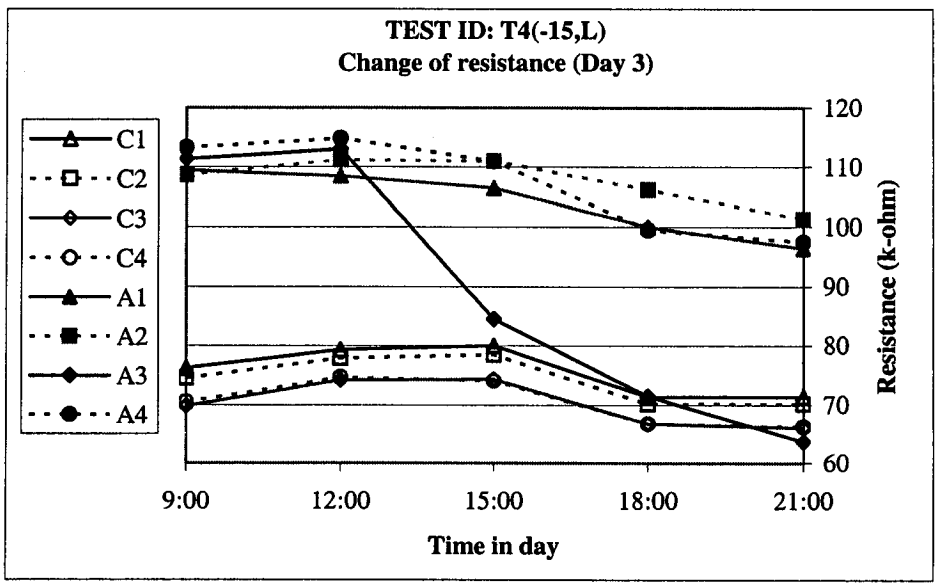

Fig. 4.11(c) Change of resistance (day 3) in cell T4(-15,L)

[Note: C1, C2, C3, C4 and A1, A2, A3, A4 are probes on cathode and anode sides respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell.]

Fig. 4.12 presents the resistance distributions in cell of test T5(-15,M). In this cell conditioning liquid was added at a concentration of 13.4 g/L and it showed a slower and steady increase of resistances all through the 5 days until the final (6^{th}) day when it increased comparatively rapidly and became steady until the current flow ceased completely. The lowest resistance (2000 Ω) was found in cathode areas during the 1^{st} day. The maximum increment rate of average resistances 2.5 kΩ/h and 5.1 kΩ/h respectively in cathode and anode areas and the highest resistance (124.5 kΩ) in anode areas were observed during the 6^{th} day.

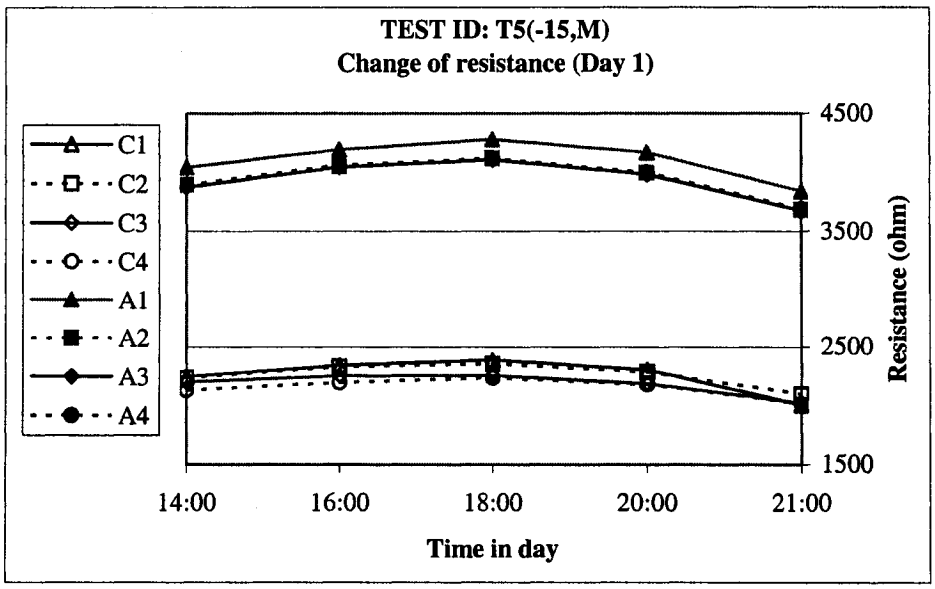

Fig. 4.12(a) Change of resistance (day 1) in cell T5(-15,M)

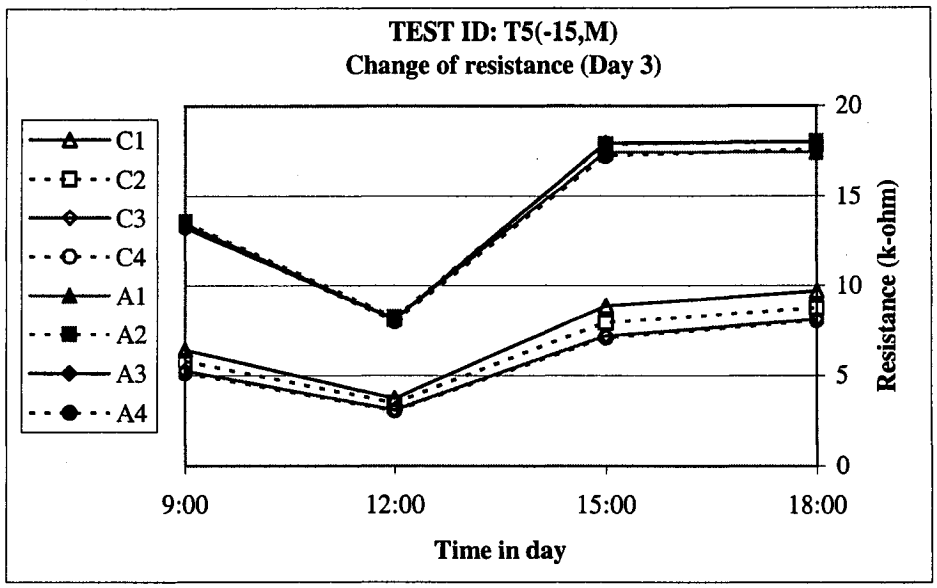

Fig. 4.12(b) Change of resistance (day 3) in cell T5(-15,M)

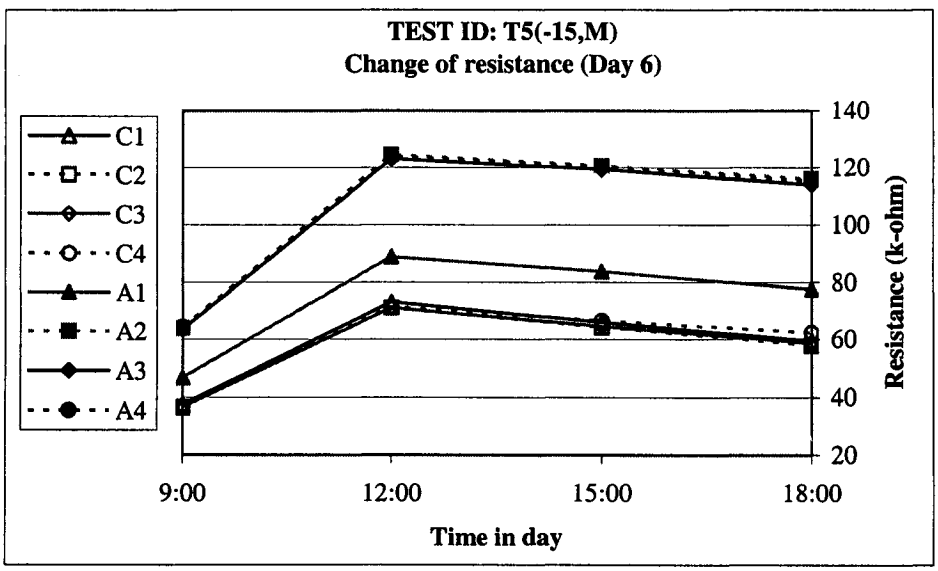

Fig. 4.12(c) Change of resistance (day 6) in cell T5(-15,M)

[Note: C1, C2, C3, C4 and A1, A2, A3, A4 are probes on cathode and anode sides respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell.]

Fig. 4.13 presents the resistance distributions in cell of test T6(-15,L). This cell was prepared using the same concentration (8 g/L) of conditioning liquid as used in test T4(-15,L) but used higher voltage gradient (1.5 V/cm). This induced the duration to be longer than test T4(-15,L) and it ran for 5 days. Resistances increased steadily at a slower rate during the first two days and remained steady throughout the 3rd day. From the 4th day it started to increase at a much higher rate until reached close to the maximum value in the 5th day when it became steady again until current flow ceased completely. The lowest (1653 Ω) and highest (200 kΩ) resistances were found in cathode and anode areas respectively during 1st and 5th days of the experiment. The maximum increment rate of average resistances were 3.0 kΩ/h and 6.1 kΩ/h respectively in cathode and anode areas, observed during the 4th day.

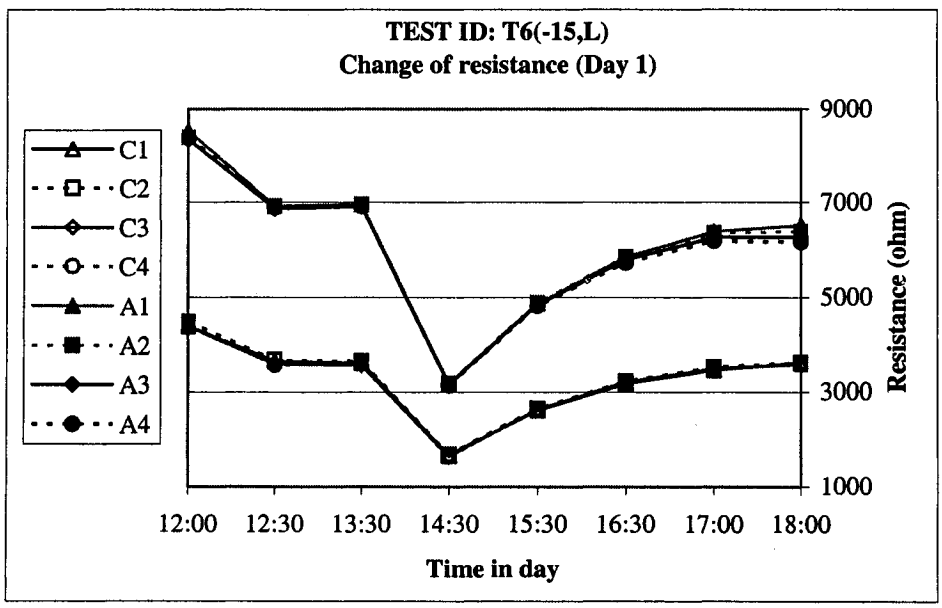

Fig. 4.13(a) Change of resistance (day 1) in cell T6(-15,L)

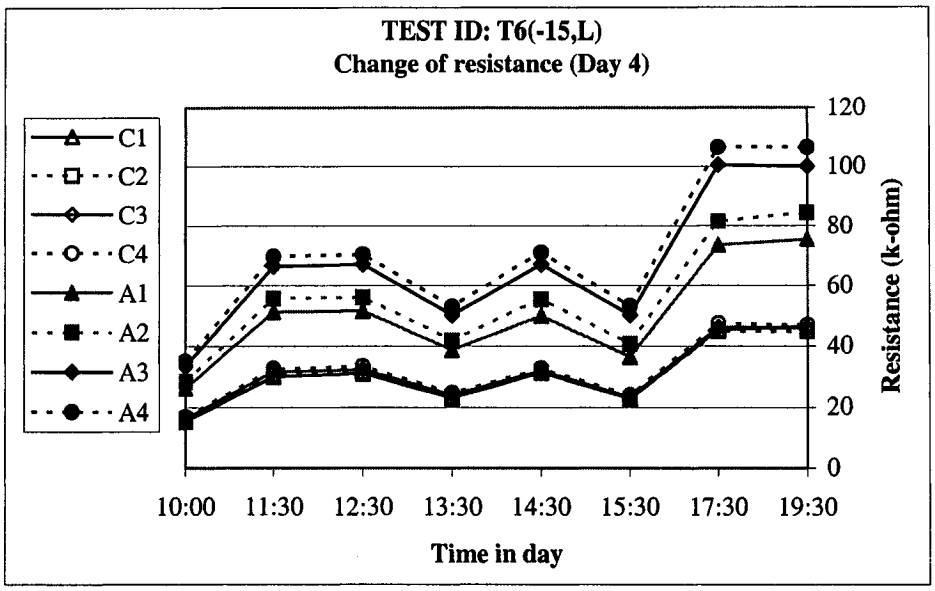

Fig. 4.13(b) Change of resistance (day 4) in cell T6(-15,L)

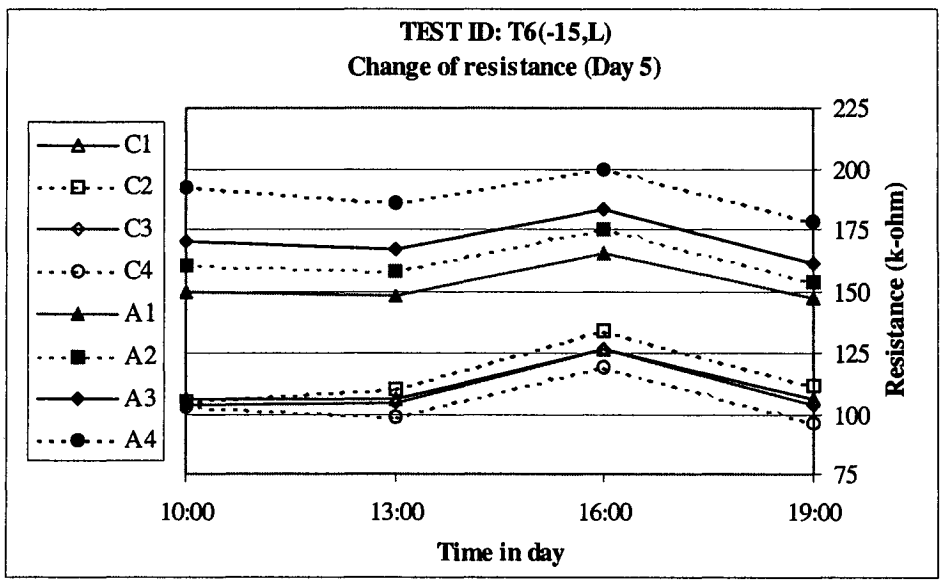

Fig. 4.13(c) Change of resistance (day 5) in cell T6(-15,L)

[Note: C1, C2, C3, C4 and A1, A2, A3, A4 are probes on cathode and anode sides respectively at 3.5 cm, 5.0 cm, 6.5 cm and 8.0 cm depths from the surface of sludge in the cell.]

The tests with conditioning liquid indicate that the increase of the concentration of the conditioning liquid increases the test duration. Use of conditioning liquid perhaps retards the freezing process and helps the system run for longer periods. The tests data indicate that a 10% increase of the concentration of the conditioning liquid increases the duration of the test by 15%. Hence, duration of the electrokinetic processes in freezing biosolids might be controlled using different concentration of the conditioning liquid depending on the movement (or removal) requirement of concerned metals.

4.6 Metal Content Distributions

4.6.1 Cadmium

Procedures for the determination of metal contents have been presented in section 3.4.5.4. Table 4.5 presents concentrations of cadmium in samples before and after the application of electrokinetics. Values represent the mean of three readings by atomic absorption spectrometry for each sample (maximum value of standard deviation was 0.0265). All metal concentration data with standard deviations have been incorporated in Appendix I. Cadmium contents in samples towards the cathode areas were always higher than the anode areas in all of the tests, which indicate transport of cadmium towards cathode areas.

Table 4.5: Mean cadmium concentrations (mg/kg of dry solids) in samples before and after the application of electrokinetics

Sample code	Mean Cd (mg/kg of dry solids)				Remarks
Initial	0.17	0.16	0.53	0.42	Before EK
BC	0.29	0.77	0.79	0.55	After EK
C	0.24	0.49	0.61	0.58	
MC	0.18	0.37	0.54	0.52	
MA	0.22	0.19	0.49	0.46	
A	0.17	0.17	0.43	0.33	
BA	0.35	0.37	0.44	0.26	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	

Test T3(-15,0) shows higher cadmium contents in all samples compared to other tests. This is because of the higher amount of cadmium in the initial biosolids. The highest concentration of cadmium (0.61 mg/kg of dry solids) found in the cathode region of the same test might be related to the higher initial contents. The lowest concentration of cadmium (0.17 mg/kg of dry solids) was observed in the anode region of tests T1(-8,0) and T2(-8,H) which might be attributed to the lower concentration of cadmium in the initial biosolids.

4.6.1.1 Cadmium in cells without conditioning liquid

Cadmium content distributions in cells tested without addition of conditioning liquid have been presented in Fig. 4.14 and Fig. 4.15. In both the figures, higher cadmium concentration towards the cathode region indicates transport of cadmium from the anode area towards the cathode area. Cadmium content in the cathode region of test T1(-8,0) was 145% and that in the same region for test T3(-15,0) was 116% of the respective initial values, which indicates better transport of cadmium during test T1(-8,0).

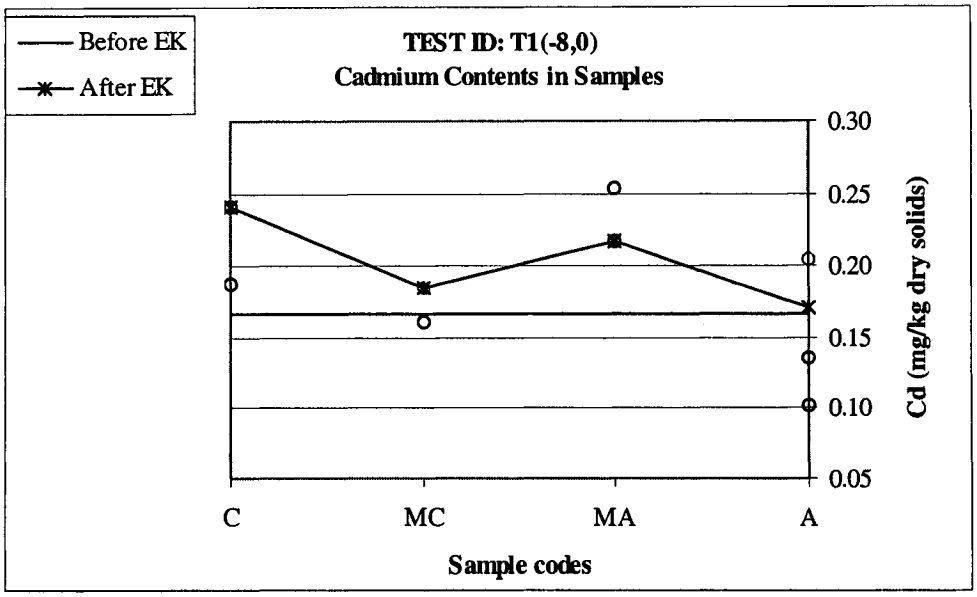

Fig. 4.14 Cadmium in cell T1(-8,0) without conditioning liquid

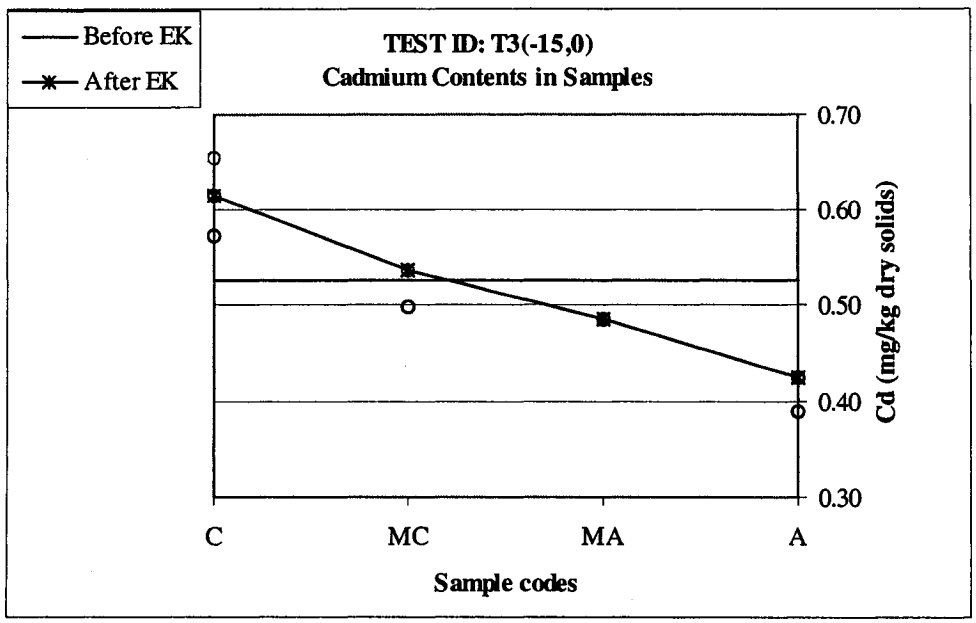

Fig. 4.15 Cadmium in cell T3(-15,0) without conditioning liquid

This might be due to the comparative higher temperature in the cell and the consequent slower rate of ice formation in pore spaces. Moreover, the longer duration of test T1(-8,0) compared to test T3(-15,0) might also have helped better transport of metals in the cell.

4.6.1.2 Cadmium in cells with conditioning liquid

Fig. 4.16 and Fig. 4.17 present cadmium content distributions in cells T2(-8,H) and T4(-15,L) with conditioning liquid. The higher cadmium concentrations towards cathode region in both the figures indicate transport of cadmium in that direction. Test T2(-8,H) was performed at $-8^{o}C$ using the highest concentration of conditioning liquid. The cadmium concentration in the cathode region was 314% of the initial value. This concentration was 138% of the initial for test T4(-15,L) which used the lowest concentration of conditioning liquid and was tested at $-15^{o}C$ temperature. Above data obviously indicate that the transport of cadmium in cathode region was greater in test T2(-8,H) than test T4(-15,L). The prolonged duration of test T2(-8,H) that ran 6 days longer than test T4(-15,L) also support greater transport of metal ions in the cell.

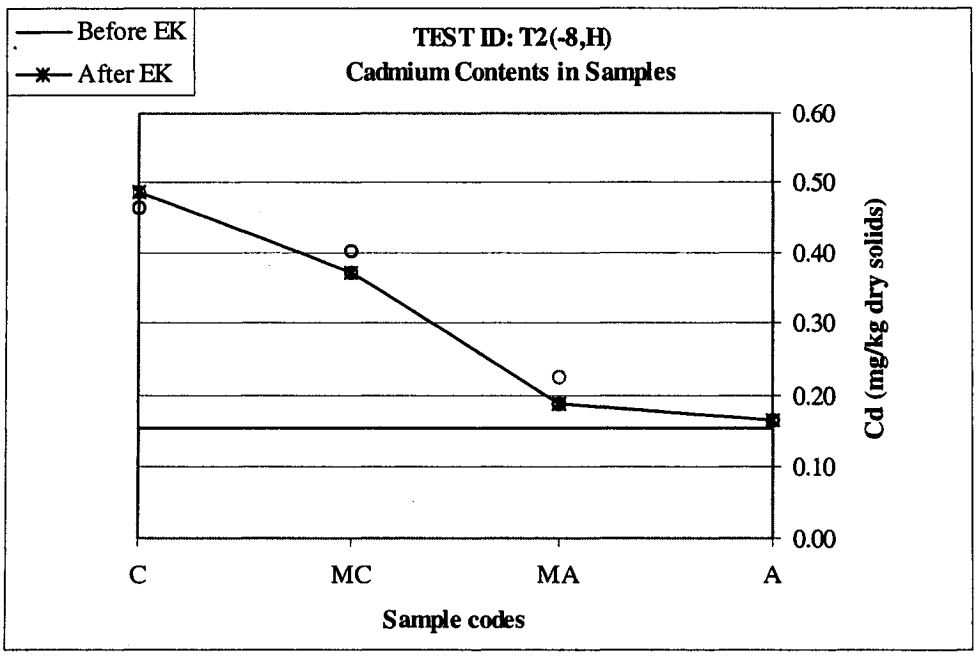

Fig. 4.16 Cadmium in cell T2(-8,H) with conditioning liquid

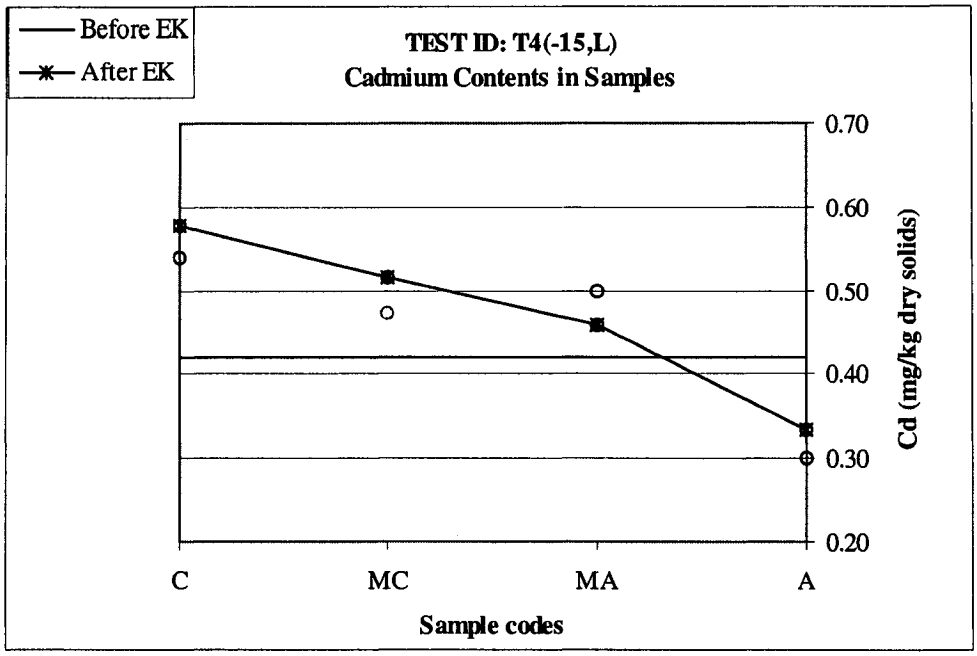

Fig. 4.17 Cadmium in cell T4(-15,L) with conditioning liquid

4.6.2 Copper

Copper concentrations in biosolids samples before and after the application of electrokinetics have been presented in Table 4.6. Values represent the mean of three readings by atomic absorption spectrometry for each sample (maximum value of standard deviation was 0.8838). All metal concentration data with standard deviations have been incorporated in Appendix I. Unlike cadmium, copper concentrations were found higher in anode areas in all of the tests except test T2(-8,H). These higher concentrations in anode areas may be attributed to the corrosion of anode electrodes and the slower mobility of copper in observed pH ranges (Merian, 1991) causing accumulation of copper in the area. In the case of T2(-8,H), the longer duration of the test due to the use of higher concentrations of the conditioning liquid and lower pH in anode areas might have helped

transport of copper ions towards the cathode region causing lower copper concentration in anode area.

Table 4.6: Mean copper concentrations (mg/kg of dry solids) in samples before and after the application of electrokinetics

Sample code	**Mean Cu (mg/kg of dry solids)**				**Remarks**
Initial	79	101	82	102	Before EK
BC	56	77	137	107	After EK
C	42	93	115	106	
MC	40	102	123	102	
MA	56	86	121	100	
A	61	47	133	118	
BA	109	87	148	108	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	

The highest concentration of copper (133 mg/kg of dry solids) was found in the anode region of test T3(-15,0), which might be related to the excessive corrosion of the anode (refer to photo no. 11, Appendix II) of this experiment compared to others. During test T3(-15,0), 56% of the area of the anode submersed in sludge experienced corrosion. The corrosion affected areas during T1(-8,0), T2(-8,H) and T4(-15,L) were respectively 39%, 4% and 1% of the submersed area of the respective anodes. The lowest concentration of copper (40 mg/kg of dry solids) was observed in the mid-cathode region of tests T1(-8,0) which might be related to the lower initial concentrations.

4.6.2.1 Copper in cells without conditioning liquid

Copper distributions in cells without conditioning liquid have been presented in Fig. 4.18 and Fig. 4.19. As explained above, highest copper concentrations were observed in the anode area in both tests T1(-8,0) and T3(-15,0). Lower concentrations towards the

cathode region for both the tests indicate little or slower movement in that direction. pH distributions in the cells, as presented in Fig. 4.1, also show ranges unfavourable for the mobility of copper in the cathode direction.

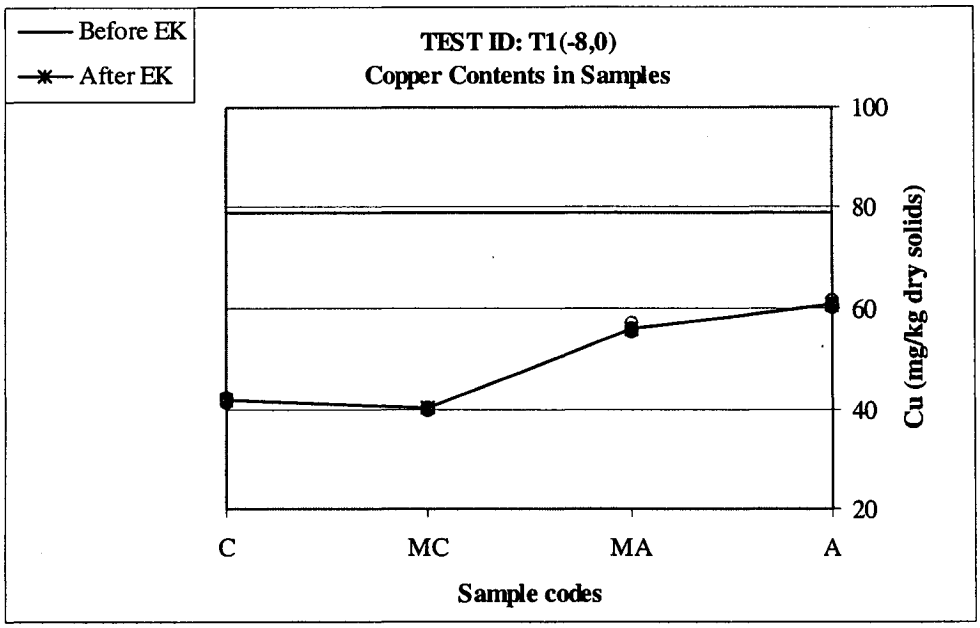

Fig. 4.18 Copper in cell T1(-8,0) without conditioning liquid

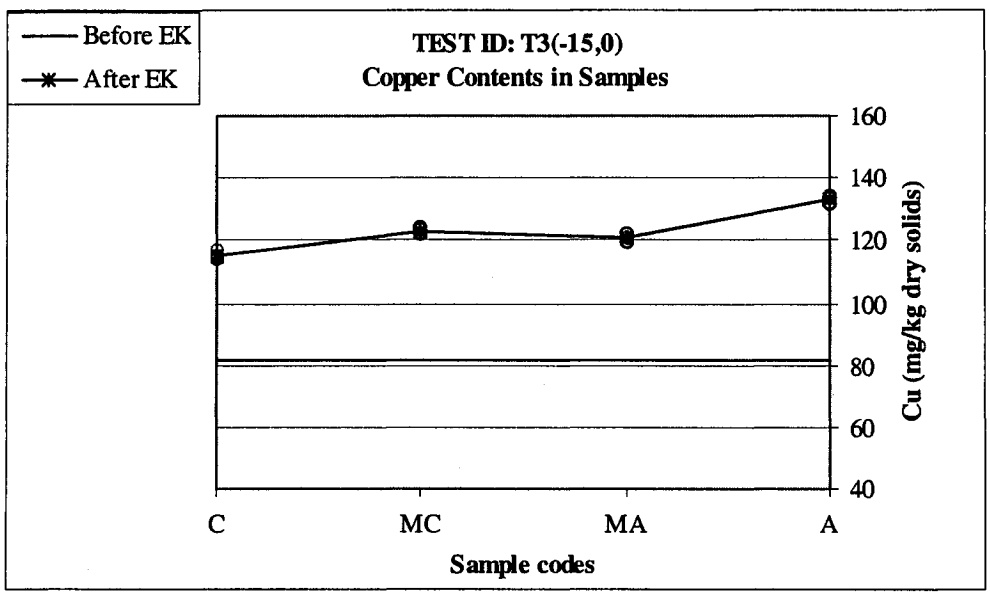

Fig. 4.19 Copper in cell T3(-15,0) without conditioning liquid

As shown in Fig. 4.19 above, copper concentrations in samples of test T3(-15,0) were always found higher than the initial values. These concentrations from anode towards cathode areas were respectively 163%, 147%, 150% and 141% of the initial concentration. This increase of concentrations might be related to the transport of copper ions towards the cathode areas. As already mentioned above, mobility of copper ions being slower in the pH ranges observed in the cell, copper concentration still remains higher in anode area with respect to other areas.

4.6.2.2 Copper in cells with conditioning liquid

Copper content distributions in the cells T2(-8,H) and T4(-15,L) with conditioning liquid have been presented in Fig. 4.20 and Fig. 4.21 respectively. Increasing copper concentrations in samples towards the cathode region with respect to the anode area, as shown in the figures, indicates transport of copper in to the direction of the cathode. This transport was prominent during test T2(-8,H), might be due to the longer duration of the test due to the use of the highest concentration of the conditioning liquid, which provided adequate travel time and facilitated mobility of copper ions. Moreover, pH values in the anode regions of both the tests were found lower than the pH in those regions of tests without conditioning liquid.

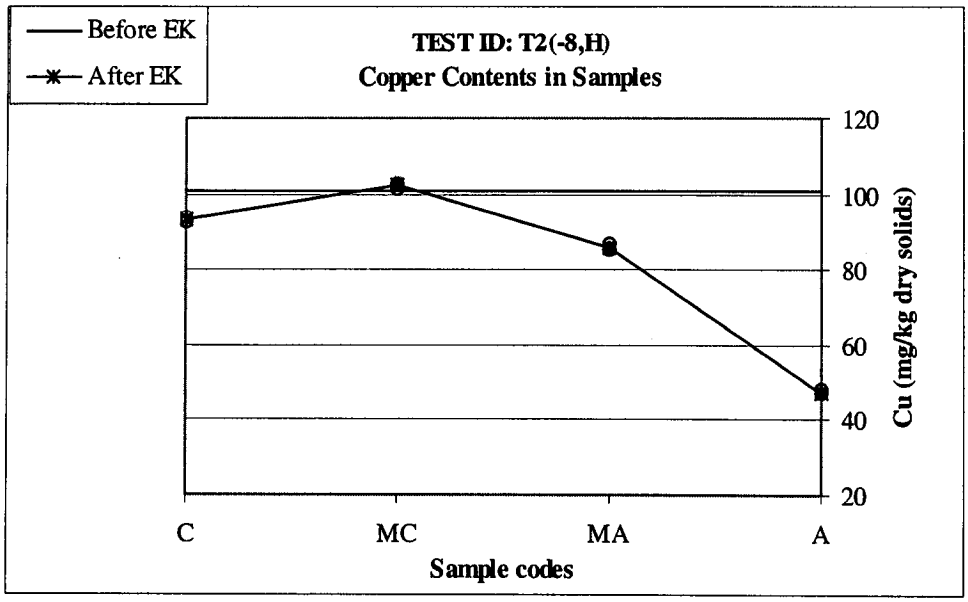

Fig. 4.20 Copper in cell T2(-8,H) with conditioning liquid

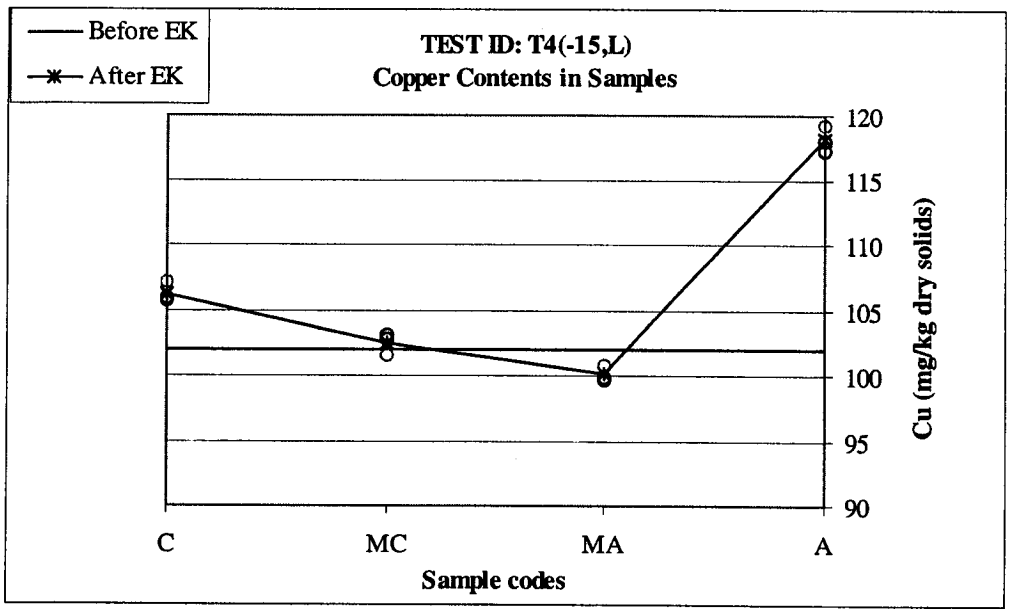

Fig. 4.21 Copper in cell T4(-15,L) with conditioning liquid

A higher copper concentration in the mid-cathode area (102 mg/kg of dry solids) compared to the anode area (47 mg/kg of dry solids) of test T2(-8,H), as shown in Fig. 5.20, clearly indicate better transport of copper ions towards cathode. The concentration

in the cathode area (93 mg/kg of dry solids) indicates both the movement of ions in that direction and the inability of all ions reaching up to that area, at the same time.

The copper distribution in the cell T4(-15,L) presented in Fig. 4.21 indicates a smoother increase of concentration in samples from mid-anode up to cathode areas. The copper concentration in the cathode area was 104% of the initial concentration. The higher copper concentration in the anode area might be related to the corrosion of the anode electrode coupled with inadequate travel time for shorter test duration (3 days) causing accumulation of copper ions in that region.

4.6.3 Lead

The concentrations of lead in biosolids samples before and after the application of electrokinetics for all experiments have been presented in Table 4.7. Values represent the mean of three readings by atomic absorption spectrometry for each sample (maximum value of standard deviation was 0.0700). All metal concentration data with standard deviations have been incorporated in Appendix I. Values show a general trend of higher concentrations in samples towards the cathode region for tests T1(-8,0), T2(-8,H) and T3(-15,0) but test T4(-15,L) does not exhibit any such trend. Lead concentrations in samples after the application of electrokinetics have been found lower than the concentrations in initial biosolids in all of the experiments.

Table 4.7: Mean lead concentrations (mg/kg of dry solids) in samples before and after the application of electrokinetics

Sample code	Mean Pb (mg/kg of dry solids)				Remarks
Initial	3.82	5.09	8.79	9.69	Before EK
BC	3.42	3.05	8.87	7.23	After EK
C	3.54	1.97	8.06	5.43	
MC	3.26	4.75	8.06	7.75	
MA	3.48	4.07	7.60	6.04	
A	2.66	4.04	3.70	8.49	
BA	3.94	3.99	2.52	6.89	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	

A detailed comparative analysis on the distribution of lead contents in different cells based on the different physical-chemical conditions have been presented in the following sections.

4.6.3.1 Lead in cells without conditioning liquid

Fig. 4.22 and Fig. 4.23 present lead distributions in cells T1(-8,0) and T3(-15,0) respectively. The higher lead concentrations in samples towards the cathode areas with respect to the anode areas in both the tests might be due to the transport of lead in that direction. Lead concentrations in cathode, mid-cathode and mid-anode areas of cell T1(-8,0) were respectively 33%, 23% and 31% higher than the anode area. Concentrations in those areas in test T3(-15,0) were respectively 118%, 118% and 105% higher than the concentration in anode area, which indicate better transport of lead ions in cell T3(-15,0) than in cell T1(-8,0).

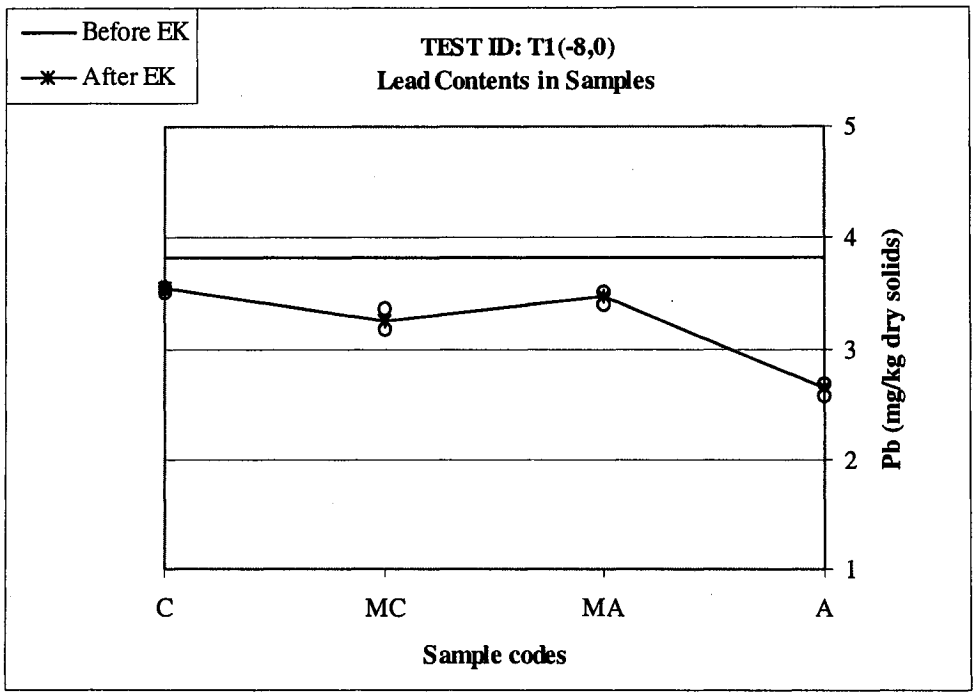

Fig. 4.22 Lead in cell T1(-8,0) without conditioning liquid

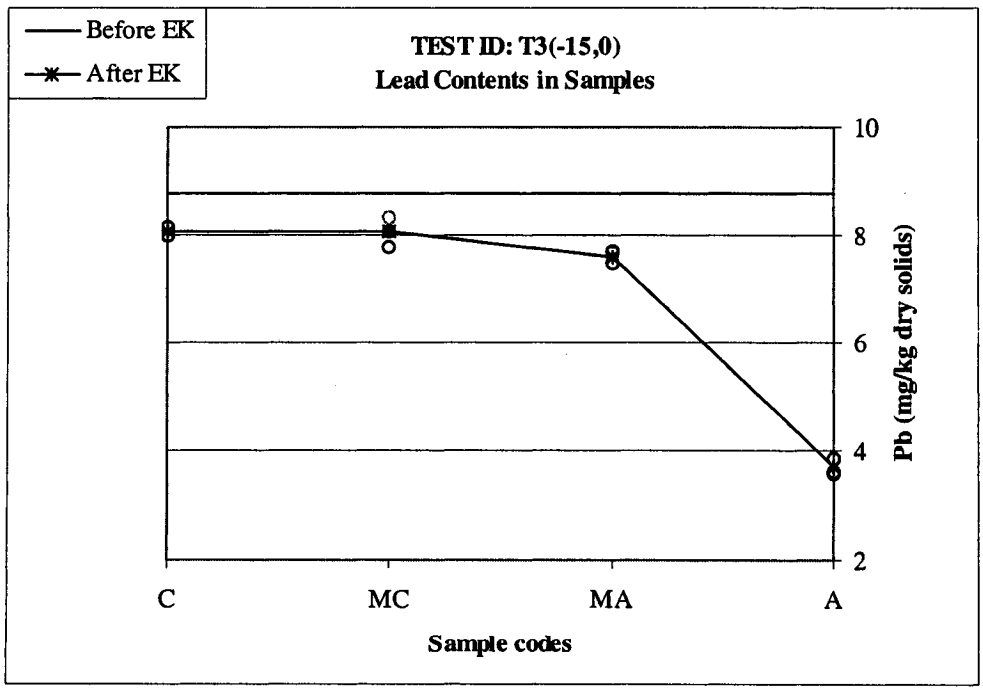

Fig. 4.23 Lead in cell T3(-15,0) without conditioning liquid

The sharp rise of concentration in mid-anode areas with respect to the anode areas during both the tests might be related to the migration of ions in that area and not having sufficient time for traveling further.

4.6.3.2 Lead in cells with conditioning liquid

Lead content distributions in the cells T2(-8,H) and T4(-15,L) with conditioning liquid have been presented in Fig. 4.24 and Fig. 4.25 respectively. Lead is generally found in water as complexes, e.g. $PbCO_3$, $PbCl^+$, $PbCl_2$, $PbCl_3^-$, $PbOH^+$, $Pb(OH)_2$, etc. and can be appreciably adsorbed on particulate matter and form complexes with organic compounds.

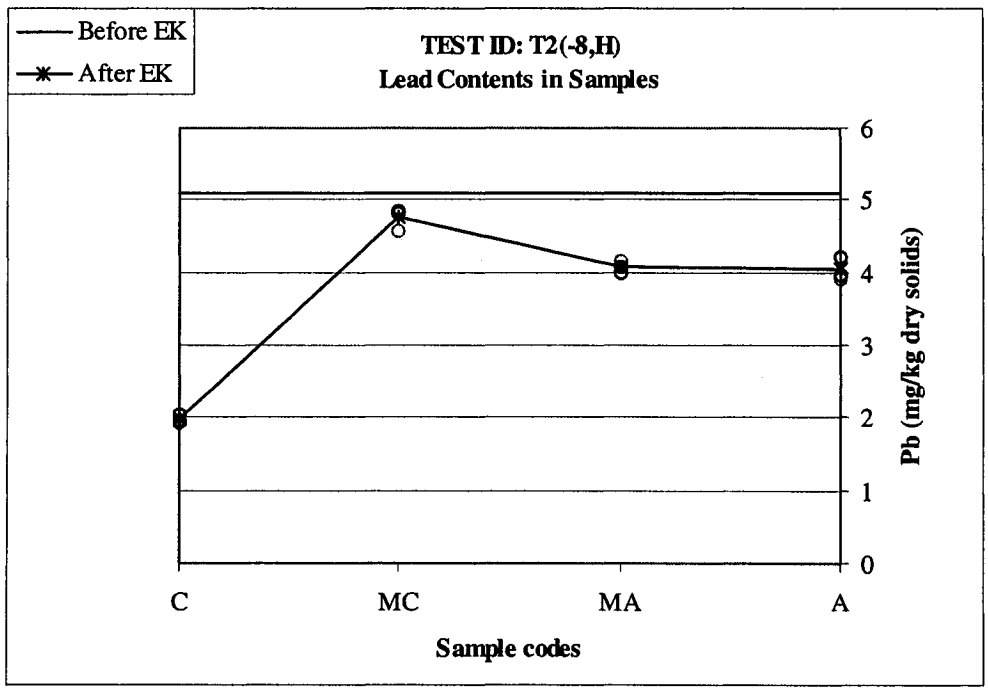

Fig. 4.24 Lead in cell T2(-8,H) with conditioning liquid

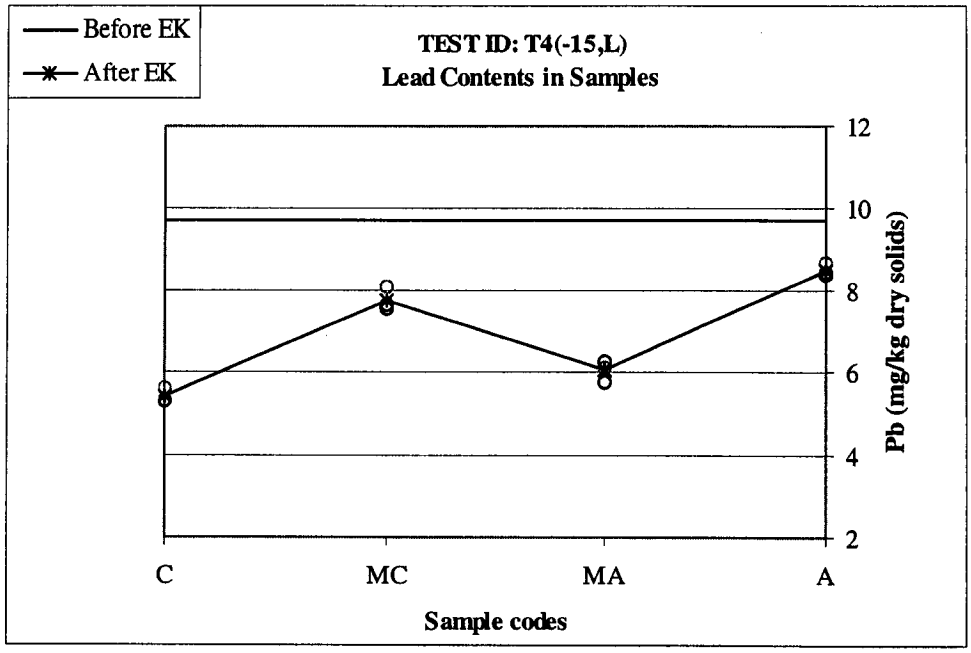

Fig. 4.25 Lead in cell T4(-15,L) with conditioning liquid

Lead distributions in cells with conditioning liquid do not exhibit any clear trend of concentration variations. This might be due to the interference of conditioning liquid on the formation of various lead species and their mobility. Moreover, higher organic content in anode area (Fig. 4.7) and solid content in cathode area (Fig. 4.4) with the influence of the conditioning liquid might have enhanced adsorption of lead species on particulate matter or formation of complexes with organic compounds and influenced mobility of lead species in the cells.

4.6.4 Nickel

Table 4.8 presents nickel concentrations in biosolid samples of all experiments before and after the application of electrokinetics. Values represent the mean of three readings by atomic absorption spectrometry for each sample (maximum value of standard deviation was 12.7827). All metal concentration data with standard deviations have been

incorporated in Appendix I. Nickel concentrations in all of the samples were found much higher than the concentrations in initial biosolids. This may be due to the corrosion of anode electrodes and the consequent release of nickel in the system. The higher nickel concentration values near the anode electrodes in all of the experiments also suggest entry of nickel ions in that location.

Table 4.8: Mean nickel concentrations (mg/kg of dry solids) in samples before and after the application of electrokinetics

Sample code	**Mean Ni (mg/kg of dry solids)**				**Remarks**
Initial	22	12	13	16	Before EK
BC	144	489	229	41	After EK
C	189	396	64	31	
MC	189	470	288	33	
MA	683	210	1155	98	
A	444	315	1593	196	
BA	345	509	768	278	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	

The highest concentration of nickel (1593 mg/kg of dry solids) found in the anode region of test T3(-15,0) might be related to the excessive corrosion of the anode (refer to photo no. 11, Appendix II) of this experiment compared to others. A detailed comparative analysis on the distribution of nickel contents in different cells based on the different physical-chemical conditions have been presented in the following sections.

4.6.4.1 Nickel in cells without conditioning liquid

Fig. 4.26 and Fig. 4.27 present nickel distributions in cells without conditioning liquid of test T1(-8,0) and T3(-15,0) respectively. Nickel concentrations were higher near anode and mid-anode areas of both the tests. This might be due to the entry of nickel ions due to

the corrosion of the anode, as explained earlier and the subsequent migration of ions up to the mid-anode area under favourable pH conditions (refer to Fig. 4.1) for the mobility of nickel ions (refer to Table 2.5). The lower nickel concentrations in mid-cathode and cathode areas might be related to the slower migration of nickel ions from mid-anode areas under the high pH conditions (refer to Fig. 4.1) observed in those areas.

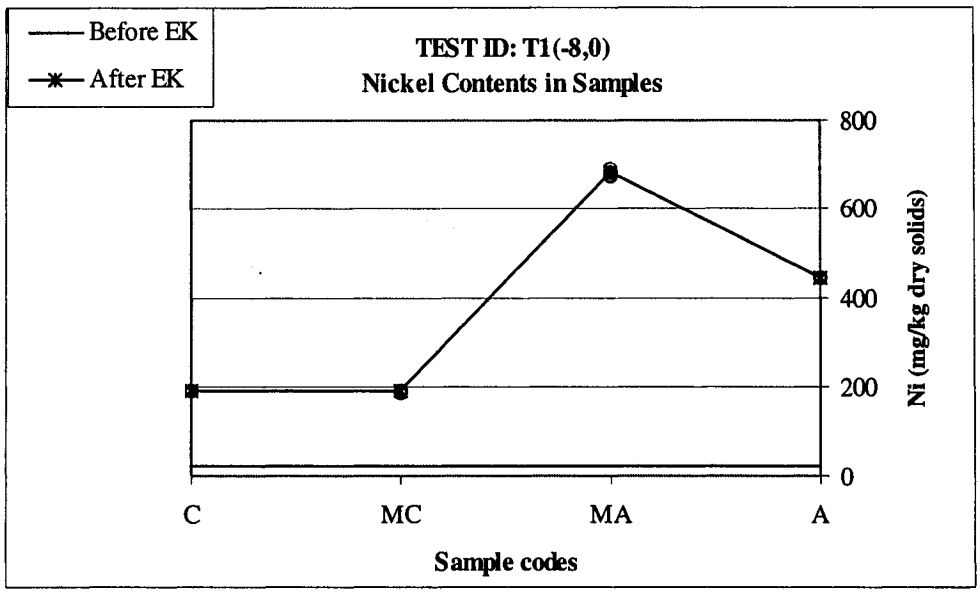

Fig. 4.26 Nickel in cell T1(-8,0) without conditioning liquid

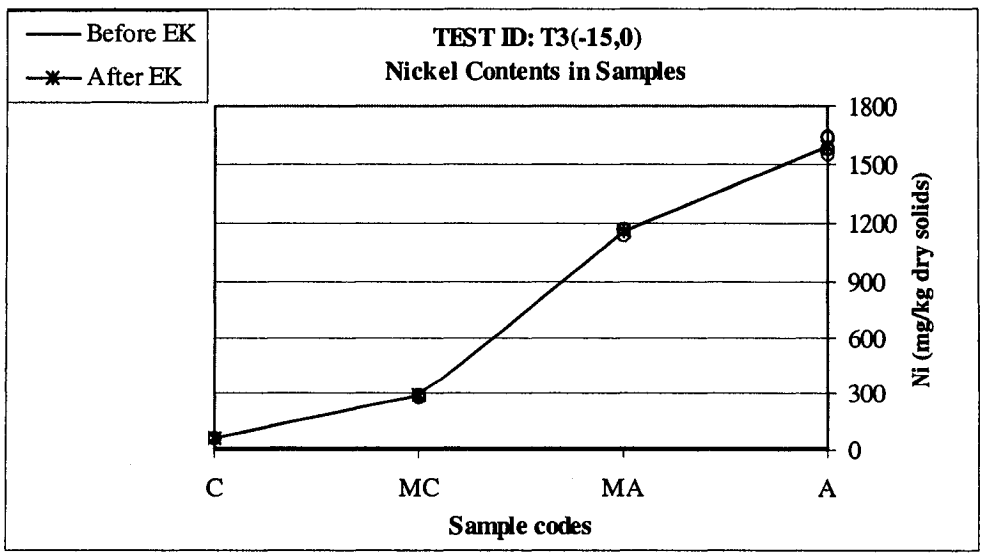

Fig. 4.27 Nickel in cell T3(-15,0) without conditioning liquid

Again, nickel concentrations were found significantly higher than the initial values throughout the cells. This indicates movement of nickel ions all over the cells. Now, considering the overall situations inside the cells, this migration of nickel ions was faster near anode areas and slower near cathode areas due to the development of low and high pH regions (refer to Fig. 4.1).

4.6.4.2 Nickel in cells with conditioning liquid

Fig. 4.28 and Fig. 4.29 present nickel distributions in cells with conditioning liquid T2(-8,H) and T4(-15,L) respectively. Nickel concentrations near mid-cathode and cathode area of test T2(-8,H) were higher than anode area. The test ran for the longest (9 days) period using the highest concentration of the conditioning liquid and pH inside the cell was lowered to acidic ranges (refer to Fig. 4.2), which was favourable for the mobility of nickel ions (refer to Table 2.5). This might have helped migration of nickel ions towards the cathode region resulting in higher concentrations of nickel in that area. In case of test T4(-15,L), the nickel distribution in the cell followed the similar trend as observed during the tests without conditioning liquid. Nickel ions could migrate up to mid-anode area at a faster rate under favourable pH conditions but moved at a slower rate in mid-cathode and cathode areas when pH increased significantly (refer to Fig. 4.2).

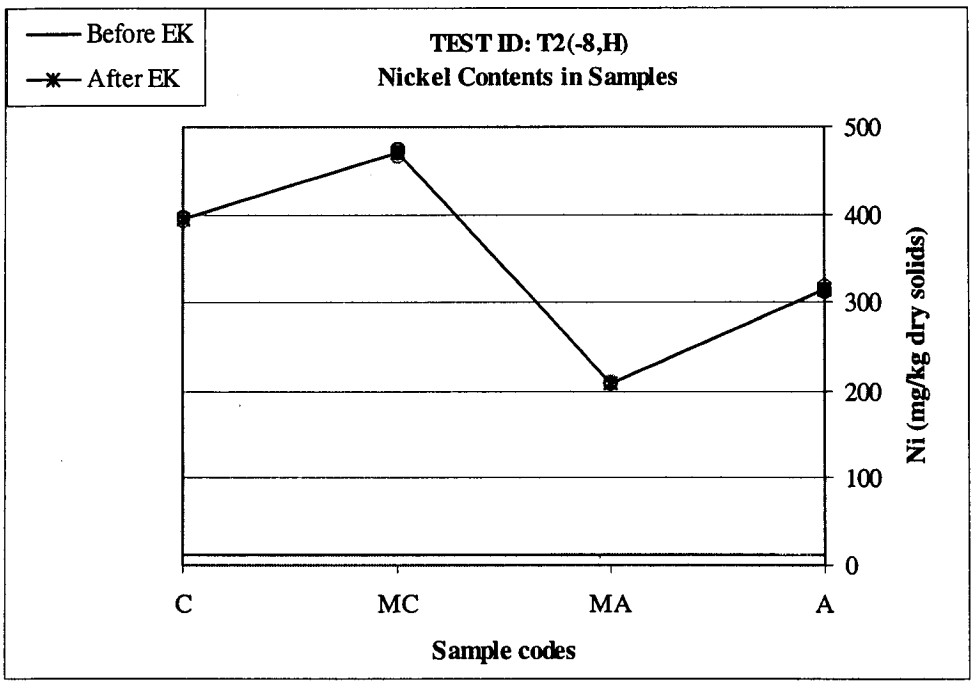

Fig. 4.28 Nickel in cell T2(-8,H) with conditioning liquid

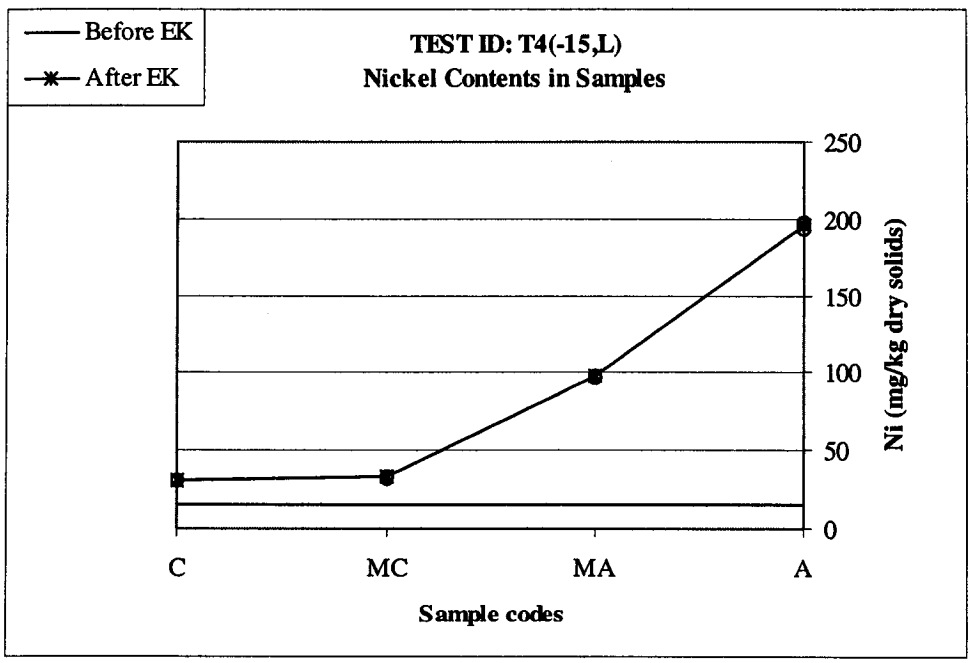

Fig. 4.29 Nickel in cell T4(-15,L) with conditioning liquid

Furthermore, like the previous observation during the tests without conditioning liquid, significantly higher nickel concentrations throughout the cells of both the tests with respect to the initial values indicate movement of nickel ions all over the cells.

4.6.5 Selenium

All the samples were tested for selenium by the atomic absorption spectrometer (Perkin Elmer, Analyst 100) used for the determination of metal contents in samples throughout the study. Selenium was not detected in any of the samples by the spectrometer. It can be concluded that there was no selenium present in the samples or it was below the detection level of the instrument.

4.6.6 Zinc

Table 4.9 presents zinc concentrations in biosolid samples of all experiments before and after the application of electrokinetics. Values represent the mean of three readings by atomic absorption spectrometry for each sample (maximum value of standard deviation was 3.3426). All metal concentration data with standard deviations have been incorporated in Appendix I. Data exhibit a general trend of increasing concentrations toward the cathode regions in all of the experiments. This might be due to the movement of zinc ions towards the cathode areas.

Table 4.9: Mean zinc concentrations (mg/kg of dry solids) in samples before and after the application of electrokinetics

Sample code	Mean Zn (mg/kg of dry solids)				Remarks
Initial	142	166	141	158	Before EK
BC	129	238	200	178	After EK
C	106	139	195	187	
MC	91	53	189	173	
MA	122	15	191	190	
A	111	8	157	96	
BA	207	39	158	144	
TEST ID	**T1(-8,0)**	**T2(-8,H)**	**T3(-15,0)**	**T4(-15,L)**	

Zinc exists in water mainly as $ZnOH^+$, $Zn(OH)_2$, $ZnCl^+$, $ZnCl_2$, $ZnCO_3$, etc., depending on pH and can be in colloidal forms, adsorbed on particulate matter or form organic complexes. The highest concentration of zinc (195 mg/kg of dry solids) and lowest (8 mg/kg of dry solids) was found in the cathode and anode area in test T3(-15,0) and test T2(-8,H) respectively. A detailed comparative analysis on the distribution of zinc contents in different cells based on the different physical-chemical conditions have been presented in the following sections.

4.6.6.1 Zinc in cells without conditioning liquid

Fig. 4.30 and Fig. 4.31 present zinc contents in cells without conditioning liquid of test T1(-8,0) and T3(-15,0) respectively. The higher zinc concentrations in the mid-anode areas compared to the anode areas in both cells clearly indicate movement of zinc up to the mid-anode areas. This might be due to the favourable pH conditions (refer to Fig. 4.1) in these regions. Concentrations of zinc beyond mid-anode area though show a tendency to increase but at a slower rate; perhaps the high pH conditions (refer to Fig. 4.1) in these

areas inhibited movement of zinc ions. Zinc concentrations increased smoothly from anode to cathode areas in cell T3(-15,0) but these concentrations were scattered in cell T1(-8,0).

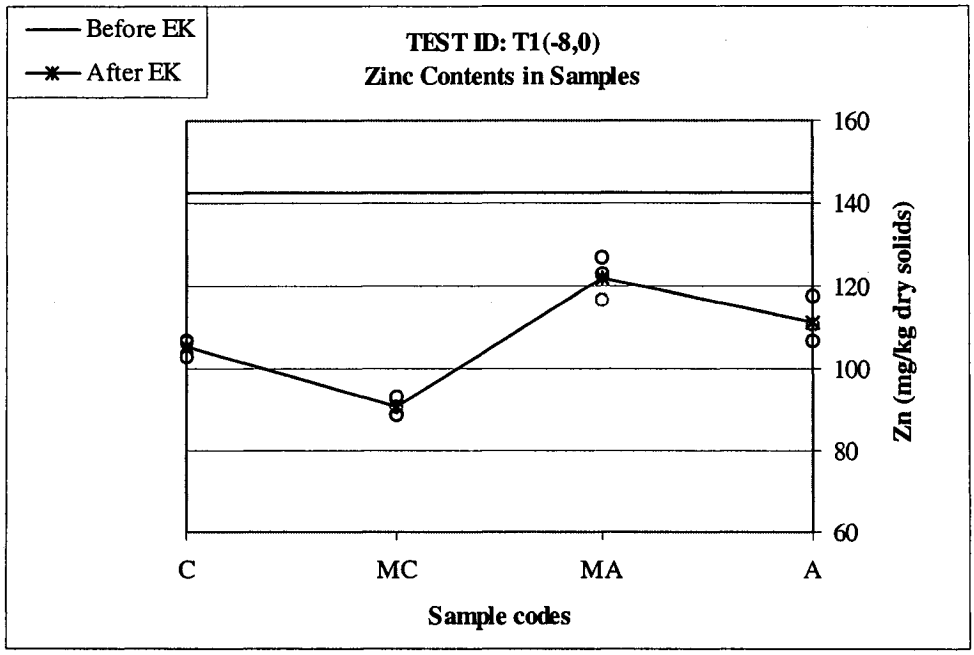

Fig. 4.30 Zinc in cell T1(-8,0) without conditioning liquid

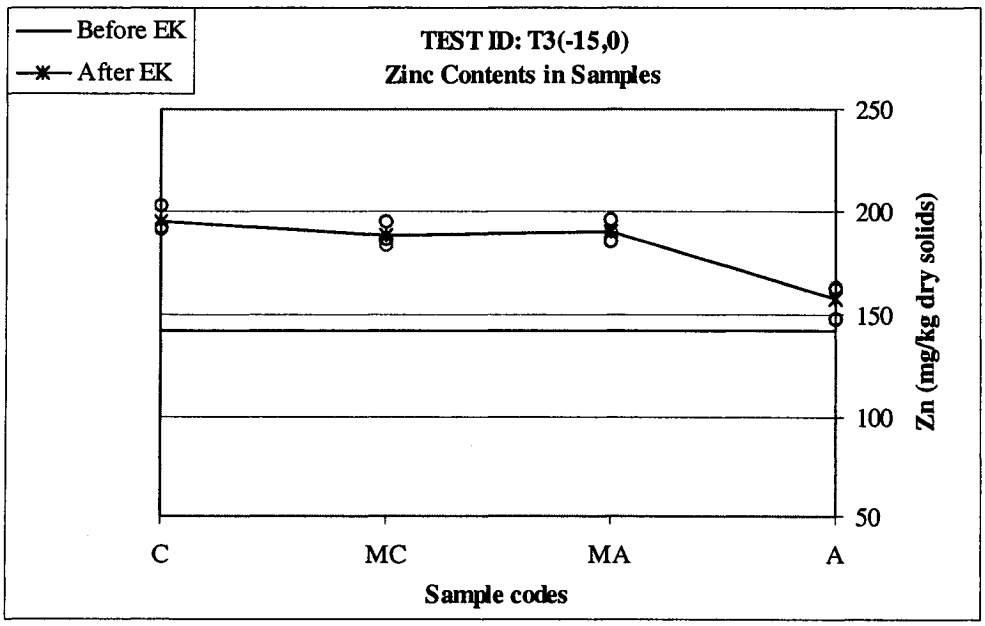

Fig. 4.31 Zinc in cell T3(-15,0) without conditioning liquid

4.6.6.2 Zinc in cells with conditioning liquid

Fig. 4.32 and Fig. 4.33 present zinc distributions in cells with conditioning liquid of test T2(-8,H) and T4(-15,L) respectively. The higher zinc concentrations toward cathode areas in both the cells clearly indicate movement of zinc towards the cathode. This movement was prominent throughout the cell T2(-8,H). Perhaps the longer test duration due to the use of higher concentration of the conditioning liquid and low pH conditions (refer to Fig. 4.2) favoured the movement of zinc ions in this cell. During test T4(-15,L), the significantly higher zinc concentration in mid-anode area compared to anode area indicates faster migration of zinc ions. The low pH conditions in these zones also support faster movement of zinc ions. On the other hand, the high pH conditions (refer to Fig. 4.2) in mid-cathode and cathode areas induced slower movement of zinc ions in these areas causing accumulation of zinc in mid-anode area. But, as a whole, there was movement of zinc ions towards the cathode area. This movement was faster in anode and mid-anode areas and slower in cathode and mid-cathode area.

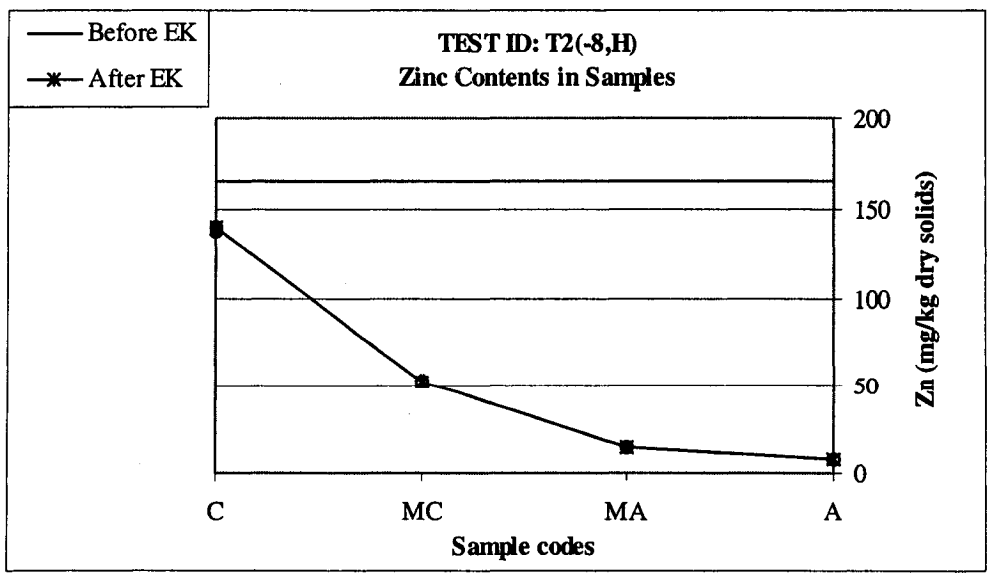

Fig. 4.32 Zinc in cell T2(-8,H) with conditioning liquid

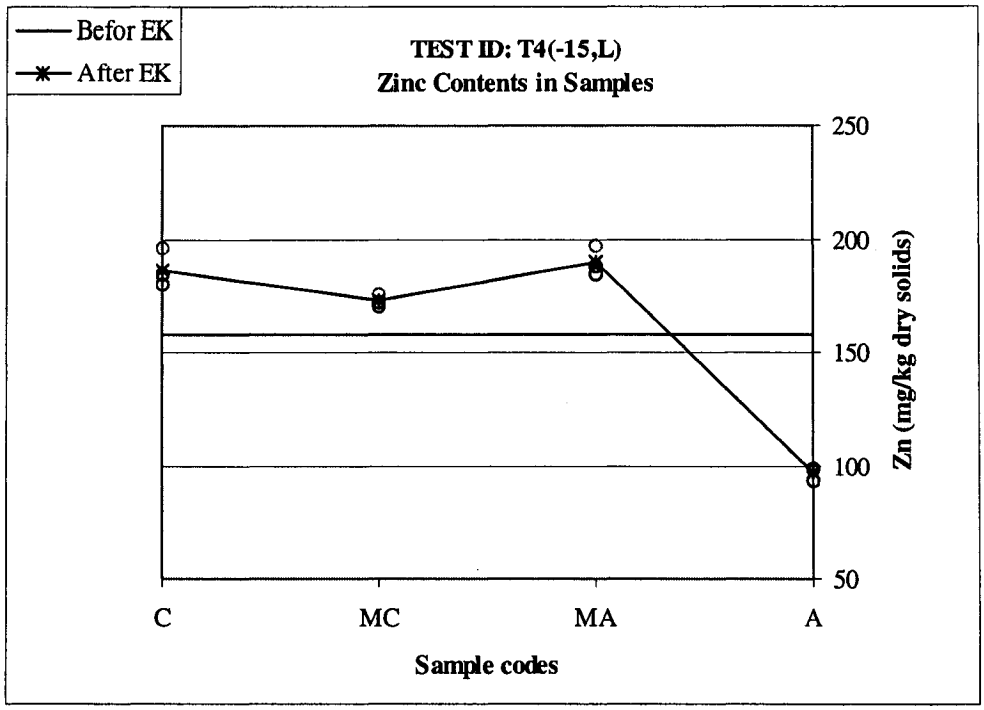

Fig. 4.33 Zinc in cell T4(-15,L) with conditioning liquid

4.7 Discussion Based on the Experiment Variables

4.7.1 Biosolids freezing in the observed cold ambient temperatures

The cold environment is directly related to the freezing of biosolids in cells and the rapid increase of resistances. The increments of resistances in all six cells under different conditions have been presented in Fig. 4.34 through Fig. 4.39. The figures clearly show that the resistance increased gradually at the initial stages of the experiments and that the rate of increment of resistances increased dramatically as the experiments progressed and especially during the last days of each experiment. This happened mainly due to the rapid freezing of biosolids in the cells after a certain period of time because of the cold ambient temperatures. Resistances on the anode side of the cells were always higher than the cathode side. This is primarily due to the increased distance from cathode and also the oxidation process near the anode areas (Hakimipour, 2001; Choudhury, 1998). Moreover,

resistances near the bottom of the cells were generally higher than that near the top, which may be attributed to the settlement of solids from the sludge solution to the bottom of the cells and the consequent increase of resistances to the flow of electricity. In cells without conditioning liquid (Fig. 4.34 and Fig. 4.35), biosolids freezes comparatively rapidly and resistances rise at a much faster rate than the cells with conditioning liquid (Fig. 4.36 to Fig. 4.39).

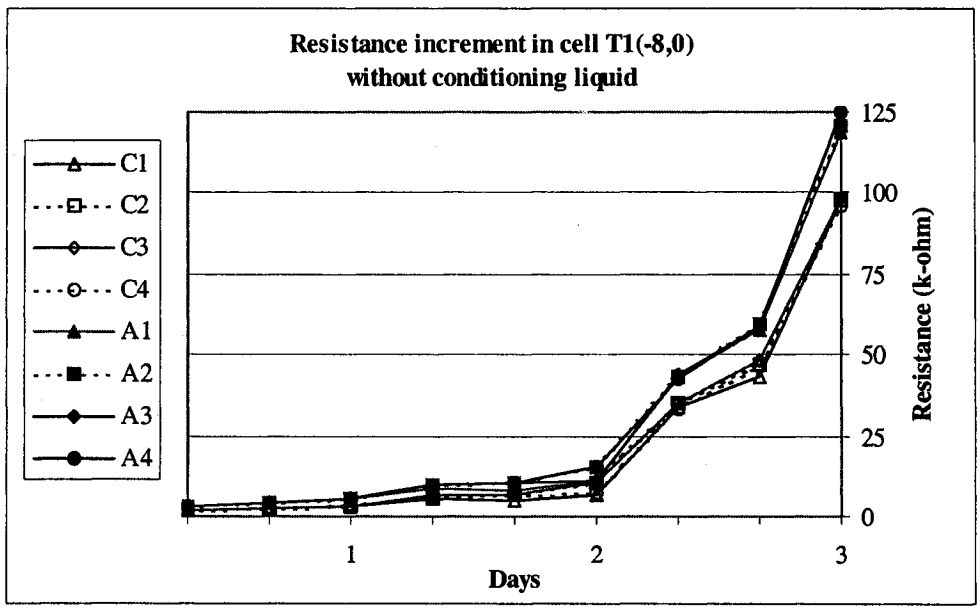

Fig. 4.34 Resistance increment in cell T1(-8,0) without conditioning liquid

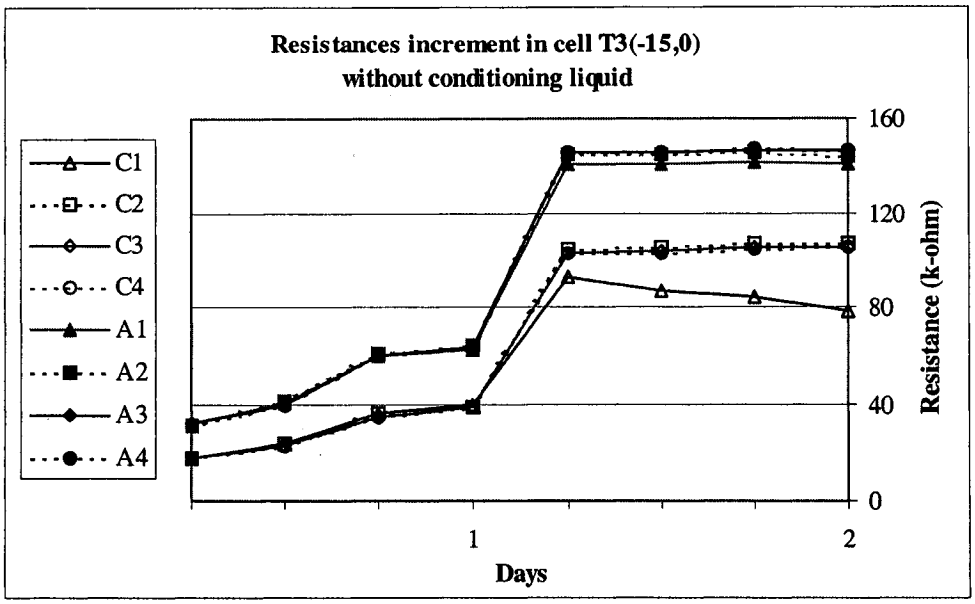

Fig. 4.35 Resistance increment in cell T3(-15,0) without conditioning liquid

Use of conditioning liquid retards the freezing process and helps to keep resistances low. Higher concentration of conditioning liquid helps to run the system for comparatively longer periods.

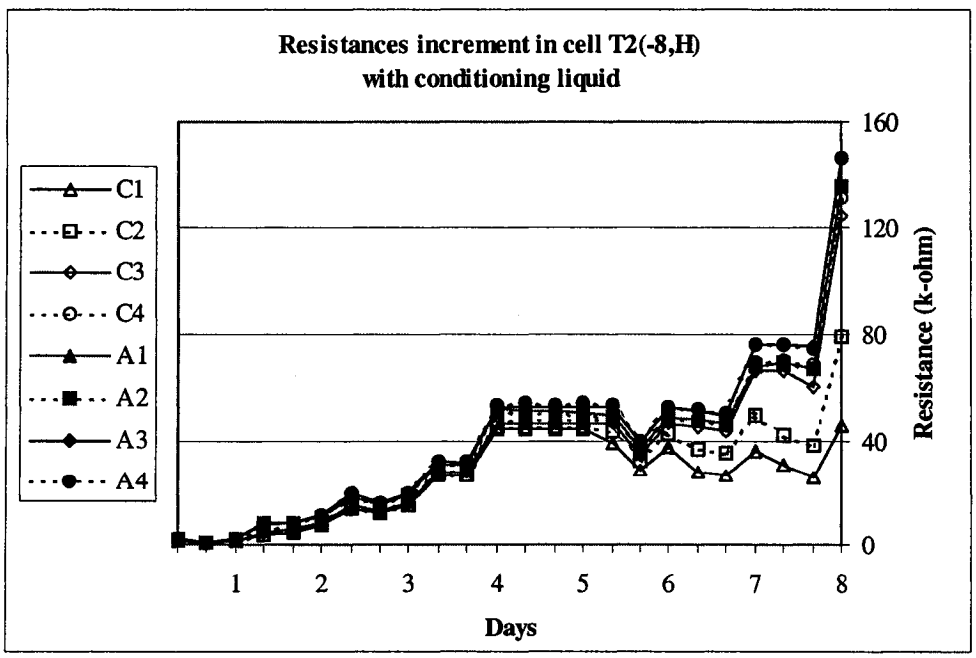

Fig. 4.36 Resistance increment in cell T2(-8,H) with conditioning liquid

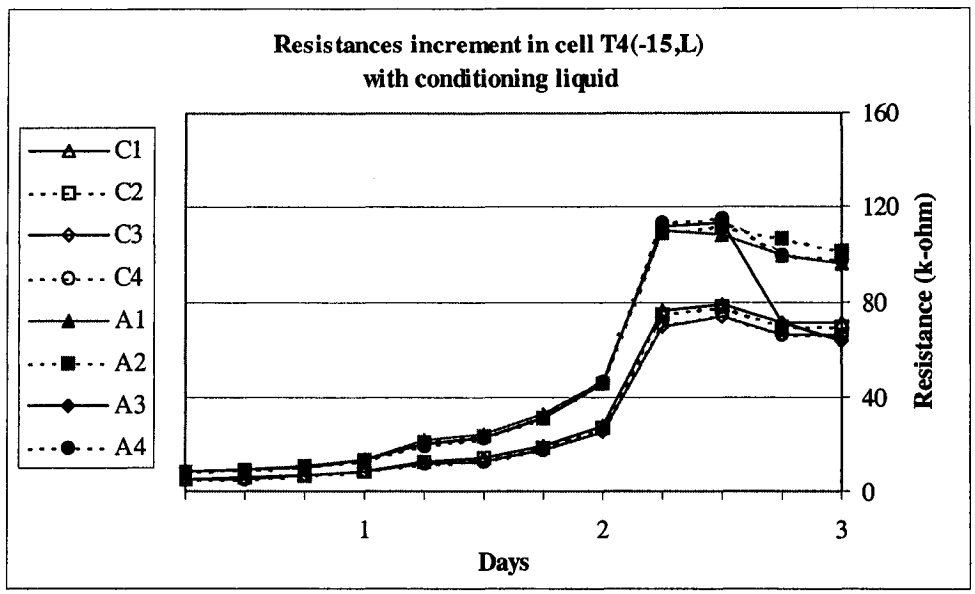

Fig. 4.37 Resistance increment in cell T4(-15,L) with conditioning liquid

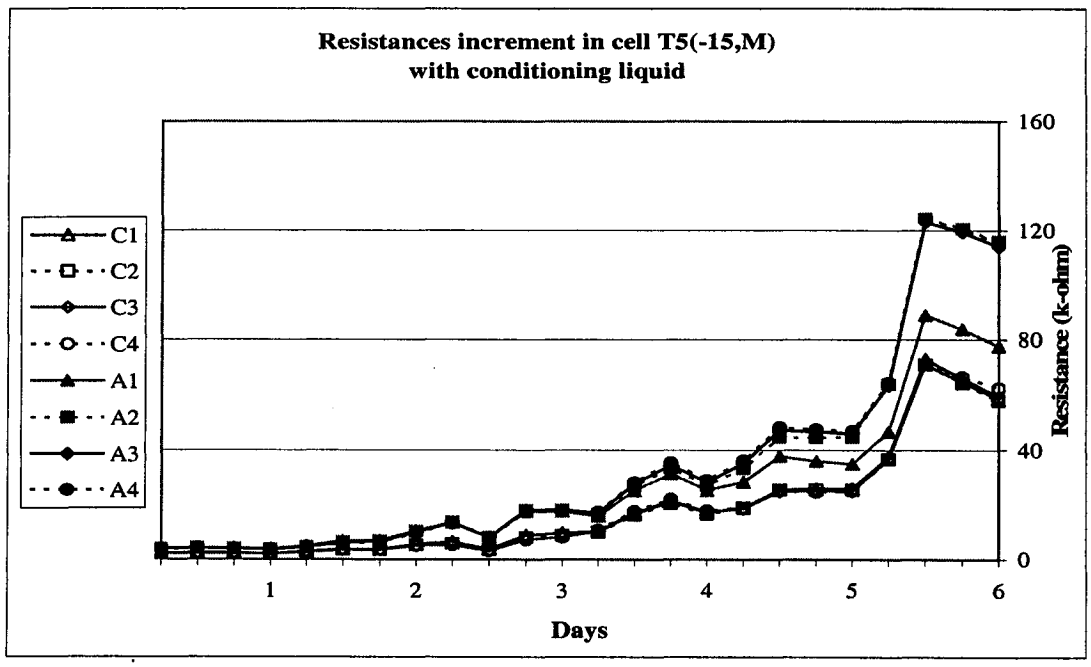

Fig. 4.38 Resistance increment in cell T5(-15,M) with conditioning liquid

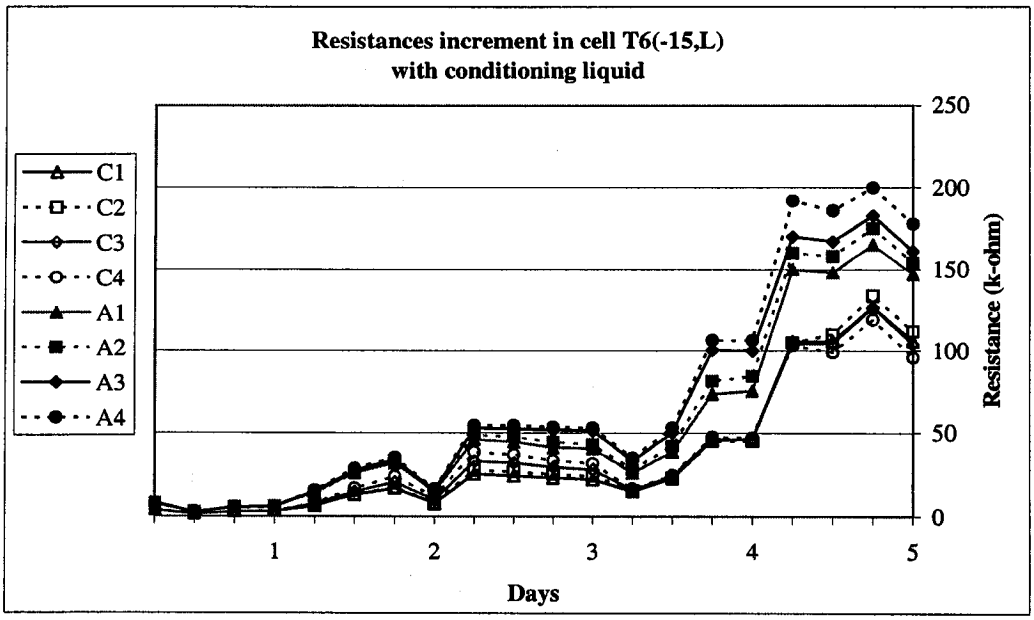

Fig. 4.39 Resistance increment in cell T6(-15,L) with conditioning liquid

Working periods of electrokinetic processes, to achieve the required movement of metals depending on the removal requirements from biosolids in extreme low temperature conditions, might be optimized varying concentrations of conditioning liquid. Thus, the rapid increase of resistances due to the indirect impact of biosolids freezing in low ambient temperatures could be avoided offsetting the rate of increment of resistances through the use of different concentrations of conditioning liquid as required.

4.7.2 Effect of cold ambient temperature on pH, total solids and organic contents

It is obvious from the previous discussions in section 4.2 and the pH distributions obtained in different cell conditions as presented in Fig. 4.1 and Fig. 4.2 that low ambient temperatures have no direct impact on pH values. Cold ambient condition is directly related to the freezing of biosolids in the cells and reduces the test duration. Broader differences between the highest and lowest pH values were obtained as the tests ran for

longer periods either due to the addition of conditioning liquid or introduction of higher voltage gradient (Fig. 4.2).

The data and discussions on total solids and its distributions in the cells as presented in section 4.3 and shown in figures 4.3 and 4.4 clearly indicate that low ambient temperature has no direct impact on solids content distribution other than the indirect freezing effect of biosolids inside the cells and the consequent immobilization of water as well as solid particles. The lower rate of solids content increment in the three cells T4(-15,L), T5(-15,M) and T6(-15,L)) might be related to the use of conditioning liquid rather than the low ambient temperature as discussed in section 4.3.2.

The discussions on organic contents and the data and figures presented in section 4.4, clearly illustrate that low ambient temperature has no direct impact on the distribution of organic contents in the cells. Rather it is related to the freezing of biosolids inside the cells and the consequent duration of experiments. Regarding the reduction of organic contents, as already shown in section 4.4.1 and section 4.4.2, higher reductions of organic contents were achieved in cells when the experiments ran for longer periods.

4.7.3 Effect of cold ambient temperature on metal content distributions

Metal content distributions presented in section 4.6 clearly indicate movement of metals towards the cathode for all of the selected metals (Cd, Cu, Pb, Ni and Zn) at both the low ambient temperatures (-8°C and –15°C) at which the tests were carried out, with the only exception of copper in cells without conditioning liquid. This movement was prominent in cells with highest concentration of conditioning liquid at –8°C for all of the selected

metals except lead. Considering the cell conditions and the metals concentration data of various samples of different tests, it can be concluded that cold ambient temperature indirectly affects the system through freezing biosolids thereby shutting the whole system. Movement of metals can be achieved as long as biosolids are not completely frozen.

Additionally as observed in the literature review (Mazus, 1993), the ion concentration in unfrozen water around biosolid particles might have been increased during the freezing process and enhanced the movement of metals under imposed electric field. Literature also suggest that dense and smaller volume colloidal particles settle to the bottom of the cell near the anode area and in a lower electrical potential the velocity of settling is lower and the solids produce a more compact residue as a result of slow coagulation between the particles. So the resistance in anode area increases dramatically (Habibi, 2004) which is consistent with our results. All these phenomena might have significant impact on the movement of metals as observed in this study. Direct comparison of the metal movement data of this study with the only available previous study (Esmaeily, 2002) on the removal of metals from biosolids by electrokinetics at laboratory temperature exhibit similar trend of movement of metals towards the cathode. However, the previous system was equipped with drainage facilities for metal removal, therefore, the concentration distribution was different. Yet, cadmium and zinc distribution in all cells during this study showed better movement than the previous study; copper and nickel in cells with conditioning liquid showed better results as before. In the case of lead, better movement was observed in cells without conditioning liquid, which is in contrary to the results obtained in the previous study where higher lead removal was observed in cells with conditioning liquid.

CHAPTER 5 CONCLUSIONS

5.1 Conclusions

This research work has pioneered the application of electrokinetic phenomena in cold weather conditions and revealed valuable information on the movement of heavy metals in biosolids. In this research, application of a new technique for the removal of heavy metals from biosolids in low temperatures has been examined. Electrokinetics has been applied in cells with biosolids at –8 and –15 °C temperatures, with current and voltage monitored continuously across the cells. At the end of each test, biosolids were sampled and analyzed for pH, total solids, organic and metal contents. Tests were carried out both biosolids alone and biosolids mixed with conditioning liquid. Based on the obtained results and analysis, the fulfillment of the objectives of the research can be delineated as mentioned below.

Electrokinetic process and its effect on the movement of metals:

1) Considering the overall cell conditions and the metals concentrations in different locations in the cells after the application of electrokinetics in different tests, it can be concluded that electrokinetic processes could be used for the removal of metals from biosolids in extreme low temperatures.
2) Higher metal concentrations observed in the cathode region with respect to the anode region in most of the tests indicate transport of metals towards the cathode areas.
3) This movement of metals was more obvious in tests that ran for longer periods, which justifies the use of conditioning liquid with a required

concentration to permit functioning of the electrokinetic processes for a period permitting an adequate movement (or removal) of concerned metals.

4) Cadmium in the cell with highest concentration of conditioning liquid at –8°C showed the best results. 195% more cadmium was found in the cathode than in the anode region.

5) In the same cell copper concentrations also exhibited better movement with increasing concentrations towards the cathode. Copper concentration in the cathode area was 97% higher than in the anode area. Higher concentration of copper in the mid-cathode area might be related to the relative numbers of ions able to move up to cathode area depending on the migration velocity and time.

6) Lead in cell without conditioning liquid at –15°C temperature showed better movement of lead ions towards the cathode region. Lead concentration in the cathode area was 118% higher than in the anode area.

7) Mobility of nickel showed the best results in the cell with highest concentration of the conditioning liquid at –8°C. Nickel concentrations in the cathode and mid-cathode areas were respectively 26% and 49% higher than the concentration in anode area.

8) Zinc also showed better movement towards the cathode region in the cell with the highest concentration of the conditioning liquid at –8°C. Zinc concentration in cathode area (139 mg/kg of dry solids) was 1686% higher than the concentration in anode area (8 mg/kg of dry solids).

9) Cadmium and zinc showed better movement in all the cells under all different condition. Though the best results were achieved in the cell with the highest concentration of the conditioning liquid for both metals.

10) Copper and nickel showed better movement in cells with conditioning liquid. Again, the best results were obtained in the cell with the highest concentration of the conditioning liquid. In the case of lead, cells without conditioning liquid showed better movement.

11) Corrosion of the stainless steel anode electrodes necessitate selection of suitable other materials as electrodes to prevent introduction of additional metals in biosolids.

Effect of conditioning liquid:

12) Use of conditioning liquid helps the system run for longer periods retarding the freezing process, thus enhances the movement of metals in biosolids under electrokinetic processes.

13) Duration of the electrokinetic processes in freezing biosolids can be controlled varying the concentrations of conditioning liquid depending on the movement (or removal) requirement. A 10% increase of the concentration of the conditioning liquid increases the duration by 15%.

14) Resistance increases at a much slower rate (7.5 kΩ/h less than cells WOCL considering maximum increment rates) in cells with conditioning liquid.

15) Much less corrosion of the electrodes occur in cells with conditioning liquid (4% and 1% of submersed area) than in cells without conditioning liquid (39%

and 56% of submersed area) is another advantage of using conditioning liquids.

Impacts on biosolids characteristics and freezing:

16) Reduction of organic content was observed in all experiments. The highest average (23.4%) reduction of organic content occurred in the cell with highest concentration of conditioning liquid at $-8^{o}C$.

17) Total solid contents increased towards cathode regions in all experiments. The highest average (88.3%) increment was observed in cell without conditioning liquid at $-8^{o}C$.

18) Though pH increased in the cathode regions in all experiments, the highest values maintained an upper limit and rarely exceeded 9.0. This indicates slower rise of pH in the cathode region, which might have facilitated a better movement of metal ions towards the cathode regions with the propagation of an acid front.

19) Resistances increased at a slower rate during the initial stages of the experiments but the increment rate rose dramatically during the last day indicating the freezing of biosolids. The maximum increment rates were 13.2 kΩ/h in cells without conditioning liquid and 5.7 kΩ/h in cells with conditioning liquid.

5.2 Contributions

The major contributions of this research work are:

1) Assessment of the functionality of electrokinetic processes in biosolids in cold environments.
2) Generation of a large amount of data on the physical-chemical properties of biosolids in cold conditions under the application of electrokinetics.
3) Assessment of the movement of metals in biosolids in cold conditions under electrokinetics processes and the introduction of data on such movement of metals.
4) Development of the resistance variation databases during the freezing processes and the freezing profiles of biosolids for two temperatures (-8°C and –15°C).
5) Information on the influence of the conditioning liquid on biosolids freezing, physical-chemical properties of biosolids and the movement of contaminants in biosolids through electrokinetic processes in cold conditions.
6) Development protocols for the study of electrokinetic application into biosolids in cold conditions.
7) Initiation of an electrokinetic procedure to contaminant removal from biosolids in cold environments.

5.3 Recommendations for Further Research

The following future work might be recommended to enrich the knowledge in this field:

- Additional research using other types of biosolids.
- Studies on metal species formation.
- Studies on metal collection after the application of EK.
- Detailed studies about the loss of organic matters and production of biogases.
- Studies on biosolids dewatering by electrokinetics in conjunction with freezing and thawing.
- Pilot studies in the field before going for large-scale application.
- Large scale experiments, especially in cells with increased depths.

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Website named Envirotools, A collaborative effort between the Hazardous Substances Research Center (HSRC) and the Superfund Basic Research Program (SBRP) and produced at Michigan State University.

APPENDIX I

MEASURED DATA AND CALCULATIONS

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T1(-8,0)

Day 1:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
11:00	4.3	7.00	7.12	6.90	7.20	12.38	12.44	12.28	12.14	
15:00	3.3	7.05	7.38	7.19	7.30	12.20	12.40	12.01	12.14	
18:00	2.8	6.86	7.40	7.14	7.30	11.96	12.21	11.84	11.99	
21:00	2.4	6.92	7.52	7.27	7.30	11.80	12.25	11.89	11.96	
0:00	2.2	6.90	7.66	7.44	7.48	12.02	12.47	12.18	12.24	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
11:00	4.3	1628	1656	1605	1674	2879	2893	2856	2823	
15:00	3.3	2136	2236	2179	2212	3697	3758	3639	3679	
18:00	2.8	2450	2643	2550	2607	4271	4361	4229	4282	
21:00	2.4	2883	3133	3029	3042	4917	5104	4954	4983	
0:00	2.2	3136	3482	3382	3400	5464	5668	5536	5564	

Day 2:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	1.4	7.86	8.74	9.13	9.12	11.78	13.68	13.55	13.64	
12:00	1.4	7.32	8.44	8.92	8.95	11.31	13.51	13.60	13.71	
15:00	1.3	6.43	8.78	8.78	8.86	10.28	13.65	13.63	13.71	
21:00	0.9	6.06	9.62	9.62	6.70	10.25	14.06	10.30	14.08	Temp: -8°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	1.4	5614	6243	6521	6514	8414	9771	9679	9743	
12:00	1.4	5229	6029	6371	6393	8079	9650	9714	9793	
15:00	1.3	4946	6754	6754	6815	7908	10500	10485	10546	
21:00	0.9	6733	10689	10689	7444	11389	15622	11444	15644	Temp: -8°C

Day 3:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	10.20	10.53	10.64	10.04	12.92	13.07	13.11	12.88	
12:00	0.2	8.70	9.45	9.63	9.33	11.54	11.94	11.63	11.80	
14:00	0.1	9.77	9.89	10.05	9.69	12.14	12.26	12.48	12.50	
15:00	0.1	9.75	9.76	9.82	9.60	11.88	12.06	12.51	12.49	Temp: -8°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T1(-8,0)

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	34000	35100	35467	33467	43067	43567	43700	42933	
12:00	0.2	43500	47250	48150	46650	57700	59700	58150	59000	
14:00	0.1	97700	98900	100500	96900	121400	122600	124800	125000	
15:00	0.1	97500	97600	98200	96000	118800	120600	125100	124900	Temp: -8°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T2(-8,H)

Day 1:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
11:00	5.2	6.35	6.35	6.20	5.94	11.18	11.10	11.07	10.60	
15:00	9.7	6.08	6.18	6.11	6.06	10.53	10.50	10.25	10.03	
17:00	6.3	6.24	6.26	6.23	6.20	10.68	10.56	10.31	10.13	
19:00	6.3	6.53	6.55	6.47	6.44	10.90	10.82	10.54	10.29	
21:00	5.6	6.81	6.77	6.69	6.64	11.06	11.02	10.74	11.81	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
11:00	5.2	1221	1221	1192	1142	2150	2135	2129	2038	
15:00	9.7	627	637	630	625	1086	1082	1057	1034	
17:00	6.3	990	994	989	984	1695	1676	1637	1608	
19:00	6.3	1037	1040	1027	1022	1730	1717	1673	1633	
21:00	5.6	1216	1209	1195	1186	1975	1968	1918	2109	

Day 2:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	1.8	6.50	6.15	7.83	10.73	14.16	14.57	15.06	15.17	Temp: -8°C
12:00	1.4	6.66	7.47	10.50	11.30	14.25	14.40	15.07	15.16	
15:00	1.8	8.36	10.12	11.38	11.56	14.22	14.23	14.94	15.05	
18:00	1.2	10.03	10.60	11.25	11.43	14.20	14.21	14.93	15.00	
21:00	1.3	9.91	10.00	10.70	10.89	14.00	14.02	14.76	14.77	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	1.8	3611	3417	4350	5961	7867	8094	8367	8428	Temp: -8°C
12:00	1.4	4757	5336	7500	8071	10179	10286	10764	10829	
15:00	1.8	4644	5622	6322	6422	7900	7906	8300	8361	
18:00	1.2	8358	8833	9375	9525	11833	11842	12442	12500	
21:00	1.3	7623	7692	8231	8377	10769	10785	11354	11362	

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T2(-8,H)

Day 3:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.8	10.97	11.35	12.05	12.26	14.66	14.70	15.33	15.35	
11:00	0.8	11.04	11.40	12.12	12.36	14.67	14.67	15.36	15.40	Temp: -8°C
13:00	0.8	11.45	11.70	12.40	12.64	14.83	14.84	15.50	15.52	
15:00	1.0	11.77	11.92	12.58	12.86	14.93	14.93	15.59	15.62	
17:00	0.8	11.96	11.99	12.66	12.98	14.97	14.94	15.62	15.64	
20:00	0.8	12.24	12.26	12.90	13.21	15.09	15.04	15.68	15.73	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.8	13713	14188	15063	15325	18325	18375	19163	19188	
11:00	0.8	13800	14250	15150	15450	18338	18338	19200	19250	Temp: -8°C
13:00	0.8	14313	14625	15500	15800	18538	18550	19375	19400	
15:00	1.0	11770	11920	12580	12860	14930	14930	15590	15620	
17:00	0.8	14950	14988	15825	16225	18713	18675	19525	19550	
20:00	0.8	15300	15325	16125	16513	18863	18800	19600	19663	

Day 4:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.5	13.05	13.42	13.78	14.15	15.57	15.43	15.99	16.12	
12:00	0.5	13.05	13.31	13.75	14.15	15.52	15.40	15.90	16.10	
15:00	0.5	13.10	13.30	13.77	14.18	15.54	15.39	15.82	16.10	
18:00	0.4	13.15	13.40	13.85	14.23	15.51	15.38	15.83	16.10	
21:00	0.3	13.22	13.43	13.86	14.25	15.53	15.37	15.85	16.11	Temp: -8°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.5	26100	26840	27560	28300	31140	30860	31980	32240	
12:00	0.5	26100	26620	27500	28300	31040	30800	31800	32200	
15:00	0.5	26200	26600	27540	28360	31080	30780	31640	32200	
18:00	0.4	32875	33500	34625	35575	38775	38450	39575	40250	
21:00	0.3	44067	44767	46200	47500	51767	51233	52833	53700	Temp: -8°C

Day 5:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	13.28	13.50	14.00	14.40	15.40	15.15	15.85	16.15	Temp: -8°C
12:00	0.3	13.28	13.44	14.00	14.44	15.37	15.13	15.85	16.12	
15:00	0.3	13.34	13.47	14.03	14.48	15.32	15.07	15.85	16.11	
18:00	0.3	13.19	13.45	14.05	14.44	15.25	15.00	15.85	16.10	
21:00	0.3	13.30	13.45	14.06	14.51	15.21	14.97	15.88	16.14	Temp: -8°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T2(-8,H)

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	44267	45000	46667	48000	51333	50500	52833	53833	Temp: -8°C
12:00	0.3	44267	44800	46667	48133	51233	50433	52833	53733	
15:00	0.3	44467	44900	46767	48267	51067	50233	52833	53700	
18:00	0.3	43967	44833	46833	48133	50833	50000	52833	53667	
21:00	0.3	44333	44833	46867	48367	50700	49900	52933	53800	Temp: -8°C

Day 6:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	11.83	13.05	13.89	14.33	14.78	14.56	15.68	16.00	Temp: -8°C
12:00	0.2	11.80	12.98	13.87	14.39	14.77	14.58	15.71	16.05	
15:00	0.4	11.40	12.80	13.88	14.40	14.72	14.56	15.67	16.02	
18:00	0.3	11.56	12.85	13.99	14.48	14.80	14.63	15.71	15.99	
21:00	0.3	11.30	12.74	13.98	14.50	14.75	14.58	15.69	15.85	Temp: -8°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	39433	43500	46300	47767	49267	48533	52267	53333	Temp: -8°C
12:00	0.2	59000	64900	69350	71950	73850	72900	78550	80250	
15:00	0.4	28500	32000	34700	36000	36800	36400	39175	40050	
18:00	0.3	38533	42833	46633	48267	49333	48767	52367	53300	
21:00	0.3	37667	42467	46600	48333	49167	48600	52300	52833	Temp: -8°C

Day 7:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	8.42	10.98	13.58	14.32	14.45	14.30	15.38	15.55	Temp: -8°C
12:00	0.3	8.37	10.80	13.46	14.08	14.13	14.12	15.26	15.32	
15:00	0.3	8.00	10.52	13.12	13.81	13.88	13.90	14.97	15.00	
18:00	0.2	7.60	10.13	13.40	14.00	13.79	13.82	15.19	15.20	
21:00	0.2	7.24	9.91	13.22	13.88	13.59	13.69	15.12	15.16	Temp: -8°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.3	28067	36600	45267	47733	48167	47667	51267	51833	Temp: -8°C
12:00	0.3	27900	36000	44867	46933	47100	47067	50867	51067	
15:00	0.3	26667	35067	43733	46033	46267	46333	49900	50000	
18:00	0.2	38000	50650	67000	70000	68950	69100	75950	76000	
21:00	0.2	36200	49550	66100	69400	67950	68450	75600	75800	Temp: -8°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T2(-8,H)

Day 8:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.2	6.22	8.45	13.28	13.92	13.80	13.86	15.12	15.14	Temp: -8°C
12:00	0.2	6.27	8.37	13.24	13.82	13.86	13.91	15.07	15.06	
15:00	0.2	5.16	7.69	12.00	13.67	13.36	13.40	14.95	14.92	
18:00	0.1	4.47	7.40	12.71	13.35	13.50	13.57	14.80	14.80	
21:00	0.1	4.58	7.92	12.50	13.12	13.60	13.59	14.65	14.65	Temp: -8°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.2	31100	42250	66400	69600	69000	69300	75600	75700	Temp: -8°C
12:00	0.2	31350	41850	66200	69100	69300	69550	75350	75300	
15:00	0.2	25800	38450	60000	68350	66800	67000	74750	74600	
18:00	0.1	44700	74000	127100	133500	135000	135700	148000	148000	
21:00	0.1	45800	79200	125000	131200	136000	135900	146500	146500	Temp: -8°C

Day 9:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.1	5.22	8.47	11.88	12.49	13.58	13.74	14.27	14.22	Temp: -8°C
12:00	0.1	4.85	7.98	11.65	12.30	13.50	13.65	14.22	14.16	
15:00	0.1	4.87	7.46	10.86	11.57	13.18	13.39	13.88	13.80	
18:00	0.1	4.93	7.10	10.35	11.07	13.14	13.29	13.70	13.59	Temp: -8°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.1	52200	84700	118800	124900	135800	137400	142700	142200	Temp: -8°C
12:00	0.1	48500	79800	116500	123000	135000	136500	142200	141600	
15:00	0.1	48700	74600	108600	115700	131800	133900	138800	138000	
18:00	0.1	49300	71000	103500	110700	131400	132900	137000	135900	Temp: -8°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T3(-15,0)

Day 1:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
13:00	0.4	7.14	7.13	7.09	6.92	12.65	12.55	12.64	12.62	
16:00	0.3	7.05	6.95	6.83	6.80	12.10	12.30	11.87	11.86	
20:00	0.2	7.20	7.20	6.88	6.89	11.95	12.06	11.92	11.95	
23:00	0.2	7.91	7.83	7.70	7.72	12.54	12.72	12.60	12.61	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
13:00	0.4	17850	17825	17725	17300	31625	31375	31600	31550	
16:00	0.3	23500	23167	22767	22667	40333	41000	39567	39533	
20:00	0.2	36000	36000	34400	34450	59750	60300	59600	59750	
23:00	0.2	39550	39150	38500	38600	62700	63600	63000	63050	

Day 2:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.1	9.29	10.45	10.31	10.25	14.06	14.52	14.55	14.60	
10:00	0.1	8.64	10.52	10.36	10.30	14.05	14.50	14.56	14.61	
11:00	0.1	8.40	10.70	10.53	10.45	14.14	14.57	14.66	14.71	
12:00	0.1	7.80	10.71	10.52	10.50	14.08	14.40	14.64	14.66	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.1	92900	104500	103100	102500	140600	145200	145500	146000	
10:00	0.1	86400	105200	103600	103000	140500	145000	145600	146100	
11:00	0.1	84000	107000	105300	104500	141400	145700	146600	147100	
12:00	0.1	78000	107100	105200	105000	140800	144000	146400	146600	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T4(-15,L)

Day 1:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
13:00	1.3	6.53	7.05	6.78	6.82	11.61	11.31	11.21	11.22	
15:00	1.2	6.31	6.30	5.91	6.05	10.05	9.93	9.82	9.78	
16:00	1.0	5.76	5.75	5.36	5.50	9.55	9.41	9.28	9.23	
17:00	0.8	5.62	5.62	5.22	5.35	9.21	9.07	8.92	8.86	
19:00	0.8	5.48	5.48	5.12	5.17	8.77	8.64	8.49	8.43	
20:00	0.7	5.39	5.38	5.05	5.09	8.59	8.42	8.26	8.21	
21:00	0.6	5.36	5.36	5.00	5.03	8.40	8.25	8.09	8.04	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
13:00	1.3	5023	5423	5215	5246	8931	8700	8623	8631	
15:00	1.2	5258	5250	4925	5042	8375	8275	8183	8150	
16:00	1.0	5760	5750	5360	5500	9550	9410	9280	9230	
17:00	0.8	7025	7025	6525	6688	11513	11338	11150	11075	
19:00	0.8	6850	6850	6400	6463	10963	10800	10613	10538	
20:00	0.7	7700	7686	7214	7271	12271	12029	11800	11729	
21:00	0.6	8933	8933	8333	8383	14000	13750	13483	13400	Temp: -15°C

Day 2:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.4	5.22	5.22	4.80	4.92	8.99	8.56	8.21	7.91	Temp: -15°C
12:00	0.4	5.30	5.25	4.87	4.91	9.32	8.93	8.63	8.37	
15:00	0.4	5.74	5.64	5.25	5.26	10.00	9.60	9.33	9.12	
18:00	0.3	5.75	5.63	5.31	5.32	9.83	9.53	9.45	9.39	
21:00	0.2	5.65	5.50	5.18	5.20	9.41	9.19	9.22	9.33	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.4	13050	13050	12000	12300	22475	21400	20525	19775	Temp: -15°C
12:00	0.4	13250	13125	12175	12275	23300	22325	21575	20925	
15:00	0.4	14350	14100	13125	13150	25000	24000	23325	22800	
18:00	0.3	19167	18767	17700	17733	32767	31767	31500	31300	
21:00	0.2	28250	27500	25900	26000	47050	45950	46100	46650	

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T4(-15,L)

Day 3:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.1	7.63	7.46	6.98	7.05	10.95	10.87	11.14	11.33	Temp: -15°C
12:00	0.1	7.93	7.79	7.42	7.47	10.85	11.12	11.30	11.48	
15:00	0.1	8.00	7.85	7.44	7.41	10.65	11.10	8.45	11.10	
18:00	0.1	7.14	7.02	6.68	6.68	10.00	10.62	7.15	9.95	
21:00	0.1	7.14	7.02	6.61	6.63	9.64	10.13	6.37	9.75	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.1	76300	74600	69800	70500	109500	108700	111400	113300	Temp: -15°C
12:00	0.1	79300	77900	74200	74700	108500	111200	113000	114800	
15:00	0.1	80000	78500	74400	74100	106500	111000	84500	111000	
18:00	0.1	71400	70200	66800	66800	100000	106200	71500	99500	
21:00	0.1	71400	70200	66100	66300	96400	101300	63700	97500	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T5(-15,M)

Day 1:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
14:00	2.8	6.28	6.25	6.15	5.95	11.32	10.90	10.85	10.90	Temp: -15°C
16:00	2.6	6.08	6.05	5.85	5.70	10.90	10.53	10.52	10.57	
18:00	2.5	5.96	5.88	5.63	5.58	10.70	10.30	10.27	10.30	
20:00	2.5	5.75	5.70	5.46	5.44	10.42	9.99	9.96	10.00	
21:00	2.7	5.40	5.65	5.45	5.43	10.37	9.95	9.92	9.96	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
14:00	2.8	2243	2232	2196	2125	4043	3893	3875	3893	Temp: -15°C
16:00	2.6	2338	2327	2250	2192	4192	4050	4046	4065	
18:00	2.5	2384	2352	2252	2232	4280	4120	4108	4120	
20:00	2.5	2300	2280	2184	2176	4168	3996	3984	4000	
21:00	2.7	2000	2093	2019	2011	3841	3685	3674	3689	Temp: -15°C

Day 2:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	2.0	5.75	5.58	5.42	5.39	9.90	9.23	9.03	9.02	Temp: -15°C
12:00	1.7	5.69	5.53	5.34	5.31	10.18	9.28	8.93	8.91	
15:00	1.6	5.93	5.75	5.57	5.53	11.02	10.33	9.72	9.38	
18:00	1.6	5.96	5.75	5.52	5.50	11.30	10.84	10.33	9.90	
21:00	1.1	6.02	5.75	5.50	5.49	11.56	11.30	11.00	10.70	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	2.0	2875	2790	2710	2695	4950	4615	4515	4510	Temp: -15°C
12:00	1.7	3347	3253	3141	3124	5988	5459	5253	5241	
15:00	1.6	3706	3594	3481	3456	6888	6456	6075	5863	
18:00	1.6	3725	3594	3450	3438	7063	6775	6456	6188	
21:00	1.1	5473	5227	5000	4991	10509	10273	10000	9727	Temp: -15°C

Day 3:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.9	5.77	5.20	4.72	4.62	12.10	12.20	11.91	11.95	Temp: -15°C
12:00	1.5	5.60	5.24	4.66	4.60	12.20	12.36	12.16	12.00	
15:00	0.7	6.20	5.55	5.03	4.96	12.20	12.50	12.55	12.06	
18:00	0.7	6.79	6.13	5.68	5.63	12.20	12.62	12.61	12.32	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T5(-15,M)

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.9	6411	5778	5244	5133	13444	13556	13233	13278	Temp: -15°C
12:00	1.5	3733	3493	3107	3067	8133	8240	8107	8000	
15:00	0.7	8857	7929	7186	7086	17429	17857	17929	17229	
18:00	0.7	9700	8757	8114	8043	17429	18029	18014	17600	Temp: -15°C

Day 4:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.8	8.20	7.95	8.30	8.52	12.52	13.20	13.53	13.78	Temp: -15°C
12:00	0.5	8.30	8.03	8.48	8.72	12.52	13.29	13.72	14.00	
15:00	0.4	8.40	8.10	8.57	8.81	12.50	13.35	13.84	14.21	
18:00	0.5	8.50	8.21	8.65	8.88	12.60	13.42	14.00	14.41	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.8	10250	9938	10375	10650	15650	16500	16913	17225	Temp: -15°C
12:00	0.5	16600	16060	16960	17440	25040	26580	27440	28000	
15:00	0.4	21000	20250	21425	22025	31250	33375	34600	35525	
18:00	0.5	17000	16420	17300	17760	25200	26840	28000	28820	Temp: -15°C

Day 5:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.4	7.50	7.50	7.37	7.52	11.30	13.27	14.15	14.48	Temp: -15°C
12:00	0.3	7.60	7.60	7.43	7.53	11.36	13.39	14.17	14.47	
15:00	0.3	7.62	7.62	7.48	7.57	11.15	13.36	14.09	14.38	
18:00	0.3	7.72	7.62	7.48	7.32	10.80	13.38	13.98	14.26	Temp: -15°C
21:00	0.3	7.75	7.60	7.45	7.50	10.49	13.44	13.83	14.07	

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.4	18750	18750	18425	18800	28250	33175	35375	36200	Temp: -15°C
12:00	0.3	25333	25333	24767	25100	37867	44633	47233	48233	
15:00	0.3	25400	25400	24933	25233	37167	44533	46967	47933	
18:00	0.3	25733	25400	24933	24400	36000	44600	46600	47533	Temp: -15°C
21:00	0.3	25833	25333	24833	25000	34967	44800	46100	46900	

Day 6:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.2	7.50	7.32	7.32	7.29	9.35	12.78	12.69	12.85	Temp: -15°C
12:00	0.1	7.30	7.10	7.10	7.13	8.89	12.45	12.30	12.40	
15:00	0.1	6.59	6.43	6.45	6.65	8.38	12.06	11.93	12.03	
18:00	0.1	5.94	5.80	5.87	6.24	7.76	11.60	11.40	11.54	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T5(-15,M)

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	0.2	37500	36600	36600	36450	46750	63900	63450	64250	Temp: -15°C
12:00	0.1	73000	71000	71000	71300	88900	124500	123000	124000	
15:00	0.1	65900	64300	64500	66500	83800	120600	119300	120300	
18:00	0.1	59400	58000	58700	62400	77600	116000	114000	115400	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T6(-15,L)

Day 1:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
12:00	2.1	9.20	9.40	9.20	9.30	17.90	17.60	17.50	17.60	Temp: -15°C
12:30	2.4	8.77	8.83	8.60	8.55	16.60	16.61	16.48	16.54	
13:30	2.3	8.30	8.40	8.20	8.30	16.00	16.00	15.90	15.90	
14:30	4.9	8.20	8.30	8.10	8.20	15.60	15.60	15.50	15.40	
15:30	3.1	8.12	8.22	8.15	8.17	15.07	15.13	15.03	14.92	
16:30	2.5	7.94	8.07	8.02	8.00	14.61	14.61	14.44	14.29	
17:00	2.3	7.98	8.11	8.04	8.04	14.69	14.62	14.41	14.23	
18:00	2.3	8.30	8.34	8.24	8.25	14.99	14.68	14.42	14.18	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
12:00	2.1	4381	4476	4381	4429	8524	8381	8333	8381	Temp: -15°C
12:30	2.4	3654	3679	3583	3563	6917	6921	6867	6892	
13:30	2.3	3609	3652	3565	3609	6957	6957	6913	6913	
14:30	4.9	1673	1694	1653	1673	3184	3184	3163	3143	
15:30	3.1	2619	2652	2629	2635	4861	4881	4848	4813	
16:30	2.5	3176	3228	3208	3200	5844	5844	5776	5716	
17:00	2.3	3470	3526	3496	3496	6387	6357	6265	6187	
18:00	2.3	3609	3626	3583	3587	6517	6383	6270	6165	Temp: -15°C

Day 2:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	1.2	8.24	8.34	9.47	10.00	17.14	17.49	18.29	19.14	Temp: -15°C
10:30	0.8	8.50	8.60	10.10	10.60	17.40	17.70	18.60	19.40	
11:00	1.0	8.60	8.70	10.20	10.80	17.40	17.70	18.60	19.50	
12:00	0.8	8.80	9.00	10.20	11.40	17.80	18.00	19.00	19.80	
13:00	0.7	9.20	9.30	10.60	11.90	18.20	18.30	19.40	20.10	
14:00	1.5	9.50	9.70	11.15	12.60	18.60	18.80	19.70	20.30	
15:00	1.7	9.90	10.10	11.70	13.30	18.90	19.60	20.00	20.60	
16:00	1.3	10.00	10.20	12.00	13.80	19.00	19.80	20.10	20.70	
17:00	0.6	10.20	10.50	12.45	14.40	19.20	20.00	20.30	21.10	
21:00	1.3	10.50	10.80	13.30	15.80	19.30	20.20	20.80	21.70	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T6(-15,L)

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
9:00	1.2	6867	6950	7892	8333	14283	14575	15242	15950	Temp: -15°C
10:30	0.8	10625	10750	12625	13250	21750	22125	23250	24250	
11:00	1.0	8600	8700	10200	10800	17400	17700	18600	19500	
12:00	0.8	11000	11250	12750	14250	22250	22500	23750	24750	
13:00	0.7	13143	13286	15143	17000	26000	26143	27714	28714	
14:00	1.5	6333	6467	7433	8400	12400	12533	13133	13533	
15:00	1.7	5824	5941	6882	7824	11118	11529	11765	12118	
16:00	1.3	7692	7846	9231	10615	14615	15231	15462	15923	
17:00	0.6	17000	17500	20750	24000	32000	33333	33833	35167	
21:00	1.3	8077	8308	10231	12154	14846	15538	16000	16692	Temp: -15°C

Day 3:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
10:30	0.4	10.30	11.10	13.25	15.40	18.40	19.50	21.10	21.80	Temp: -15°C
13:30	0.4	9.80	10.80	12.80	14.80	17.80	19.10	21.00	21.80	
18:00	0.4	9.30	10.20	11.80	13.40	16.40	17.80	20.70	21.40	
20:00	0.4	8.90	9.80	11.25	12.70	16.30	17.20	20.50	21.20	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
10:30	0.4	25750	27750	33125	38500	46000	48750	52750	54500	Temp: -15°C
13:30	0.4	24500	27000	32000	37000	44500	47750	52500	54500	
18:00	0.4	23250	25500	29500	33500	41000	44500	51750	53500	
20:00	0.4	22250	24500	28125	31750	40750	43000	51250	53000	Temp: -15°C

Day 4:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
10:00	0.6	9.20	9.50	9.80	10.10	15.70	17.00	20.00	21.00	Temp: -15°C
11:30	0.3	9.00	9.20	9.50	9.80	15.40	16.70	19.90	20.90	
12:30	0.3	9.30	9.40	9.70	10.00	15.50	16.80	20.10	21.10	
13:30	0.4	9.20	9.30	9.60	9.90	15.50	16.80	20.10	21.20	
14:30	0.3	9.40	9.40	9.60	9.80	15.00	16.60	20.10	21.30	
15:30	0.4	9.10	9.10	9.30	9.60	14.60	16.30	20.10	21.30	
17:30	0.2	9.10	9.00	9.25	9.50	14.70	16.30	20.10	21.30	
19:30	0.2	9.30	9.00	9.20	9.40	15.10	16.90	20.00	21.30	Temp: -15°C

ELECTRICAL MEASUREMENT DATA AND ANALYSIS

TEST ID: T6(-15,L)

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
10:00	0.6	15333	15833	16333	16833	26167	28333	33333	35000	Temp: -15°C
11:30	0.3	30000	30667	31667	32667	51333	55667	66333	69667	
12:30	0.3	31000	31333	32333	33333	51667	56000	67000	70333	
13:30	0.4	23000	23250	24000	24750	38750	42000	50250	53000	
14:30	0.3	31333	31333	32000	32667	50000	55333	67000	71000	
15:30	0.4	22750	22750	23250	24000	36500	40750	50250	53250	
17:30	0.2	45500	45000	46250	47500	73500	81500	100500	106500	
19:30	0.2	46500	45000	46000	47000	75500	84500	100000	106500	Temp: -15°C

Day 5:

Time	Current	Voltage (V)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
10:00	0.1	10.60	10.50	10.40	10.30	15.00	16.00	17.00	19.20	Temp: -15°C
13:00	0.1	10.60	11.00	10.45	9.90	14.80	15.80	16.70	18.60	
16:00	0.1	12.70	13.40	12.65	11.90	16.50	17.50	18.30	20.00	
19:00	0.1	10.60	11.20	10.40	9.60	14.70	15.40	16.10	17.80	Temp: -15°C

Time	Current	Resistance (ohm)								Remarks
	(mA)	C1	C2	C3	C4	A1	A2	A3	A4	
10:00	0.1	106000	105000	104000	103000	150000	160000	170000	192000	Temp: -15°C
13:00	0.1	106000	110000	104500	99000	148000	158000	167000	186000	
16:00	0.1	127000	134000	126500	119000	165000	175000	183000	200000	
19:00	0.1	106000	112000	104000	96000	147000	154000	161000	178000	Temp: -15°C

Metal Concentration Data by AAS

Test ID	Sample Code	dig. soln V2 (mL)	Sample volume (mL)	Sample (wet) wt. (g)	%TS	Metals Concentrations (mg/L)									
						Cu					Ni				
						AAS Readings									
						1st	2nd	3rd	Mean	SD	1st	2nd	3rd	Mean	SD
T1(-8,0)	BEK	25	20	20.10	5.25	5.01	5.01	4.96	4.99	0.0289	1.42	1.11	1.34	1.29	0.1609
	BEK(DUP)	25	60	63.44	4.74	9.46	9.49	9.40	9.45	0.0458	2.62	2.68	2.61	2.64	0.0379
	BC	20	60	62.15	10.15	17.87	17.68	17.69	17.75	0.1069	45.94	44.81	45.33	45.36	0.5656
	C	19.5	70	75.63	9.61	15.66	15.74	15.48	15.62	0.1332	70.08	70.66	70.30	70.35	0.2928
	MC	19	70	75.61	10.89	17.55	17.54	17.31	17.46	0.1358	81.86	82.49	80.74	81.69	0.8864
	MA	25	70	76.50	9.02	15.75	15.42	15.36	15.51	0.2100	191.00	185.97	188.69	188.53	2.5178
	A	25	70	71.40	10.28	18.03	17.70	17.82	17.85	0.1670	130.12	130.19	130.60	130.30	0.2593
	BA	28.5	50	51.89	9.35	18.80	18.56	18.49	18.61	0.1626	58.60	58.64	59.08	58.77	0.2663
T2(-8,H)	BEK	13.5	70	73.84	5.17	32.13	32.14	31.93	32.06	0.1185	3.52	3.35	3.34	3.41	0.1012
	BEK(DUP)	12	70	74.82	5.17	32.79	32.56	31.99	32.45	0.4119	3.13	2.98	3.14	3.08	0.0896
	BC	20.5	70	76.51	9.06	26.19	26.11	26.10	26.13	0.0493	164.31	167.17	164.87	165.44	1.5157
	C	20.5	70	76.92	11.49	40.59	40.08	40.05	40.24	0.3035	169.50	171.49	170.78	170.59	1.0085
	MC	20.5	70	76.36	8.64	33.22	33.04	32.69	32.98	0.2695	149.71	151.03	152.79	151.16	1.5452
	MA	22.5	70	71.25	8.38	22.76	22.71	23.12	22.86	0.2237	56.15	55.15	55.62	55.64	0.5003
	A	25.5	70	74.65	8.28	11.46	11.37	11.62	11.48	0.1266	77.30	75.47	76.22	76.32	0.9199
	BA	22	70	73.11	7.24	21.03	21.06	20.94	21.01	0.0624	121.64	122.26	123.09	122.33	0.7275
T3(-15,0)	BEK	9	70	72.99	4.03	30.22	29.63	29.80	29.88	0.3037	4.29	4.03	3.97	4.10	0.1701
	BEK(DUP)	9	70	72.45	4.48	29.81	29.65	29.57	29.68	0.1222	2.96	2.95	3.26	3.05	0.1762
	BC	24	70	69.25	7.42	29.48	29.39	28.92	29.27	0.3007	48.71	49.74	48.70	49.05	0.5976
	C	22.5	70	74.68	7.37	28.53	28.10	27.97	28.20	0.2931	15.62	15.47	15.61	15.57	0.0839
	MC	20	70	72.78	7.16	32.15	32.25	31.76	32.05	0.2589	75.44	74.98	74.44	74.95	0.5005
	MA	18	70	74.76	6.43	32.32	32.57	32.03	32.31	0.2702	302.51	312.53	310.70	308.52	5.3358
	A	15.5	70	69.67	6.26	37.74	37.12	37.64	37.50	0.3329	437.12	462.27	445.72	448.12	12.7827
	BA	10	70	71.79	4.43	47.06	46.60	47.18	46.94	0.3062	250.47	241.79	240.64	244.22	5.3742
T4(-15,L)	BEK	10.5	70	70.58	4.61	32.50	31.92	30.76	31.72	0.8860	5.34	4.98	4.68	5.00	0.3305
	BEK(DUP)	12	70	70.88	4.70	30.79	30.25	30.28	30.44	0.3035	2.94	2.87	2.80	2.87	0.0700
	BC	15	70	74.45	5.13	27.17	27.05	27.24	27.15	0.0961	10.37	10.31	10.31	10.33	0.0346
	C	17	70	73.74	5.98	27.76	27.42	27.47	27.55	0.1836	8.19	8.19	8.12	8.17	0.0404
	MC	17	70	71.51	5.52	23.59	23.94	23.87	23.80	0.1852	7.89	7.56	7.73	7.73	0.1650
	MA	18	70	73.56	5.87	24.17	23.95	23.90	24.01	0.1436	23.54	23.29	23.62	23.48	0.1721
	A	11	70	68.38	4.83	35.80	35.22	35.42	35.48	0.2946	59.49	58.22	59.15	58.95	0.6574
	BA	12.5	70	71.02	4.65	28.24	28.62	28.40	28.42	0.1908	73.29	73.67	73.14	73.37	0.2732

Metal Concentration Data by AAS

Test ID	Sample Code	Metals Concentrations (mg/L)															
		Pb					Zn					Cd					Se
		AAS Readings															
		1st	2nd	3rd	Mean	SD	1st	2nd	3rd	Mean	SD	1st	2nd	3rd	Mean	SD	
T1(-8,0)	BEK	1.30	1.43	1.32	1.35	0.0700	6.91	6.96	6.70	6.86	0.1380	0.62	0.61	0.66	0.63	0.0265	<DL
	BEK(DUP)	0.45	0.47	0.44	0.46	0.0153	15.59	18.40	17.59	17.12	1.4464	0.02	0.02	0.03	0.02	0.0058	<DL
	BC	1.16	1.05	1.03	1.08	0.0700	42.04	39.48	40.79	40.74	1.2801	0.09	0.09	0.08	0.09	0.0058	<DL
	C	1.33	1.31	1.32	1.32	0.0100	39.70	39.92	38.43	39.34	0.8043	0.09	0.09	0.07	0.09	0.0115	<DL
	MC	1.38	1.38	1.46	1.41	0.0462	39.20	40.30	38.36	39.27	0.9729	0.08	0.07	0.07	0.08	0.0058	<DL
	MA	0.97	0.94	0.97	0.96	0.0173	32.23	33.87	34.98	33.66	1.3835	0.06	0.06	0.07	0.06	0.0058	<DL
	A	0.79	0.76	0.79	0.78	0.0173	32.48	34.45	31.34	32.71	1.5734	0.06	0.04	0.03	0.05	0.0153	<DL
	BA	0.69	0.66	0.68	0.67	0.0153	36.26	36.17	33.48	35.26	1.5797	0.06	0.06	0.07	0.06	0.0058	<DL
T2(-8,H)	BEK	1.46	1.47	1.40	1.44	0.0379	52.96	52.68	51.99	52.54	0.4992	0.10	0.10	0.10	0.10	0.0000	<DL
	BEK(DUP)	0.74	0.73	0.64	0.70	0.0551	54.03	54.92	51.51	53.45	1.7687	0.03	0.04	0.04	0.05	0.0058	<DL
	BC	1.03	1.01	1.04	1.03	0.0153	84.33	78.97	78.19	80.41	3.3426	0.27	0.26	0.26	0.26	0.0058	<DL
	C	0.83	0.88	0.84	0.85	0.0265	60.40	59.45	60.35	60.06	0.5346	0.21	0.20	0.20	0.21	0.0058	<DL
	MC	1.47	1.56	1.55	1.53	0.0493	17.15	17.08	16.74	16.99	0.2193	0.12	0.13	0.12	0.12	0.0058	<DL
	MA	1.10	1.06	1.08	1.08	0.0200	3.94	3.87	3.86	3.89	0.0436	0.06	0.05	0.05	0.05	0.0058	<DL
	A	0.95	0.96	1.02	0.98	0.0379	1.92	1.89	1.87	1.89	0.0252	0.04	0.04	0.04	0.04	0.0000	<DL
	BA	0.98	0.97	0.92	0.96	0.0321	9.26	9.47	9.63	9.45	0.1856	0.08	0.09	0.08	0.09	0.0058	<DL
T3(-15,0)	BEK	3.13	3.02	3.03	3.06	0.0608	47.35	49.62	52.46	49.73	2.5603	0.19	0.18	0.18	0.18	0.0058	<DL
	BEK(DUP)	3.12	3.13	3.24	3.17	0.0666	51.67	50.30	51.07	51.01	0.6868	0.18	0.19	0.19	0.19	0.0058	<DL
	BC	1.94	1.91	1.84	1.90	0.0513	43.88	41.97	42.63	42.81	0.9701	0.17	0.16	0.18	0.17	0.0100	<DL
	C	1.96	1.96	1.99	1.97	0.0173	46.74	49.55	46.97	47.73	1.5602	0.16	0.15	0.14	0.15	0.0100	<DL
	MC	2.17	2.03	2.10	2.10	0.0700	47.87	50.98	48.64	49.13	1.6197	0.14	0.13	0.13	0.14	0.0058	<DL
	MA	2.05	2.06	2.00	2.03	0.0321	50.89	49.48	52.46	50.92	1.4907	0.13	0.13	0.13	0.13	0.0000	<DL
	A	1.02	1.08	1.01	1.04	0.0379	45.88	45.63	41.38	44.20	2.5290	0.12	0.12	0.11	0.12	0.0058	<DL
	BA	0.86	0.75	0.79	0.80	0.0557	49.72	47.70	54.17	50.40	3.3102	0.14	0.14	0.14	0.14	0.0000	<DL
T4(-15,L)	BEK	2.98	3.00	3.01	3.00	0.0153	47.23	48.30	51.25	48.87	2.0820	0.14	0.13	0.13	0.13	0.0058	<DL
	BEK(DUP)	2.34	2.23	2.32	2.30	0.0586	43.49	43.25	44.43	43.72	0.6236	0.14	0.13	0.12	0.13	0.0100	<DL
	BC	1.84	1.84	1.84	1.84	0.0000	43.98	44.45	47.91	45.39	2.1462	0.14	0.14	0.13	0.14	0.0058	<DL
	C	1.46	1.38	1.39	1.41	0.0436	50.88	46.72	47.84	48.42	2.1526	0.15	0.15	0.14	0.15	0.0058	<DL
	MC	1.88	1.75	1.77	1.80	0.0700	40.72	39.56	40.09	40.12	0.5807	0.11	0.12	0.12	0.12	0.0058	<DL
	MA	1.47	1.38	1.50	1.45	0.0624	47.21	44.22	45.04	45.46	1.5450	0.11	0.11	0.12	0.11	0.0058	<DL
	A	2.60	2.53	2.52	2.55	0.0436	29.33	27.93	29.71	28.97	0.9374	0.09	0.10	0.09	0.10	0.0058	<DL
	BA	1.84	1.81	1.80	1.82	0.0208	36.26	40.68	37.32	38.00	2.3076	0.08	0.07	0.07	0.07	0.0058	<DL

Calculated Metal Concentrations in mg/kg of dry solids

Test ID	Sample Code	Metals Concentrations (mg/kg dry solids)							
		Cu				Ni			
		1st	2nd	3rd	Mean	1st	2nd	3rd	Mean
T1(-8,0)	BEK	119	119	118	118	34	26	32	31
	BEK(DUP)	79	79	78	79	22	22	22	22
	BC	57	56	56	56	146	142	144	144
	C	42	42	42	42	188	190	189	189
	MC	41	40	40	40	189	190	186	189
	MA	57	56	56	56	692	674	684	683
	A	61	60	61	61	443	443	445	444
	BA	110	109	109	109	344	345	347	345
T2(-8,H)	BEK	114	114	113	113	12	12	12	12
	BEK(DUP)	102	101	99	101	10	9	10	10
	BC	77	77	77	77	486	494	488	489
	C	94	93	93	93	393	398	396	396
	MC	103	103	102	102	465	469	475	470
	MA	86	86	87	86	212	208	210	210
	A	47	47	48	47	319	311	314	315
	BA	87	88	87	87	506	508	512	509
T3(-15,0)	BEK	92	91	91	91	13	12	12	13
	BEK(DUP)	83	82	82	82	8	8	9	8
	BC	138	137	135	137	227	232	227	229
	C	117	115	114	115	64	63	64	64
	MC	123	124	122	123	290	288	286	288
	MA	121	122	120	121	1132	1170	1163	1155
	A	134	132	134	133	1554	1643	1585	1593
	BA	148	147	148	148	788	760	757	768
T4(-15,L)	BEK	105	103	99	102	17	16	15	16
	BEK(DUP)	111	109	109	110	11	10	10	10
	BC	107	106	107	107	41	40	40	41
	C	107	106	106	106	32	32	31	31
	MC	102	103	103	102	34	33	33	33
	MA	101	100	100	100	98	97	98	98
	A	119	117	118	118	198	194	197	196
	BA	107	108	107	108	277	279	277	278

Calculated Metal Concentrations in mg/kg of dry solids

Test ID	Sample Code	Metals Concentrations (mg/kg dry solids)							
		Pb				Zn			
		1st	2nd	3rd	Mean	1st	2nd	3rd	Mean
T1(-8,0)	BEK	31	34	31	32.00	164	165	159	163
	BEK(DUP)	4	4	4	3.82	130	153	146	142
	BC	4	3	3	3.42	133	125	129	129
	C	4	4	4	3.54	106	107	103	106
	MC	3	3	3	3.26	90	93	89	91
	MA	4	3	4	3.48	117	123	127	122
	A	3	3	3	2.66	111	117	107	111
	BA	4	4	4	3.94	213	213	197	207
T2(-8,H)	BEK	5	5	5	5.09	187	186	184	186
	BEK(DUP)	2	2	2	2.17	168	170	160	166
	BC	3	3	3	3.05	249	234	231	238
	C	2	2	2	1.97	140	138	140	139
	MC	5	5	5	4.75	53	53	52	53
	MA	4	4	4	4.07	15	15	15	15
	A	4	4	4	4.04	8	8	8	8
	BA	4	4	4	3.99	39	39	40	39
T3(-15,0)	BEK	10	9	9	9.36	145	152	160	152
	BEK(DUP)	9	9	9	8.79	143	139	142	141
	BC	9	9	9	8.87	205	196	199	200
	C	8	8	8	8.06	191	203	192	195
	MC	8	8	8	8.06	184	196	187	189
	MA	8	8	7	7.60	190	185	196	191
	A	4	4	4	3.70	163	162	147	157
	BA	3	2	2	2.52	156	150	170	158
T4(-15,L)	BEK	10	10	10	9.69	153	156	166	158
	BEK(DUP)	8	8	8	8.29	157	156	160	158
	BC	7	7	7	7.23	173	175	188	178
	C	6	5	5	5.43	196	180	184	187
	MC	8	8	8	7.75	175	170	173	173
	MA	6	6	6	6.04	197	184	188	190
	A	9	8	8	8.49	98	93	99	96
	BA	7	7	7	6.89	137	154	141	144

Calculated Metal Concentrations in mg/kg of dry solids

Test ID	Sample Code	Metals Concentrations (mg/kg dry solids)				
		Cd				Se
		1st	2nd	3rd	Mean	
T1(-8,0)	BEK	14.70	14.46	15.65	14.93	<DL
	BEK(DUP)	0.17	0.17	0.25	0.17	<DL
	BC	0.29	0.29	0.25	0.29	<DL
	C	0.24	0.24	0.19	0.24	<DL
	MC	0.18	0.16	0.16	0.18	<DL
	MA	0.22	0.22	0.25	0.22	<DL
	A	0.20	0.14	0.10	0.17	<DL
	BA	0.35	0.35	0.41	0.35	<DL
T2(-8,H)	BEK	0.35	0.35	0.35	0.35	<DL
	BEK(DUP)	0.09	0.12	0.12	0.16	<DL
	BC	0.80	0.77	0.77	0.77	<DL
	C	0.49	0.46	0.46	0.49	<DL
	MC	0.37	0.40	0.37	0.37	<DL
	MA	0.23	0.19	0.19	0.19	<DL
	A	0.17	0.17	0.17	0.17	<DL
	BA	0.33	0.37	0.33	0.37	<DL
T3(-15,0)	BEK	0.58	0.55	0.55	0.55	<DL
	BEK(DUP)	0.50	0.53	0.53	0.53	<DL
	BC	0.79	0.75	0.84	0.79	<DL
	C	0.65	0.61	0.57	0.61	<DL
	MC	0.54	0.50	0.50	0.54	<DL
	MA	0.49	0.49	0.49	0.49	<DL
	A	0.43	0.43	0.39	0.43	<DL
	BA	0.44	0.44	0.44	0.44	<DL
T4(-15,L)	BEK	0.45	0.42	0.42	0.42	<DL
	BEK(DUP)	0.50	0.47	0.43	0.47	<DL
	BC	0.55	0.55	0.51	0.55	<DL
	C	0.58	0.58	0.54	0.58	<DL
	MC	0.47	0.52	0.52	0.52	<DL
	MA	0.46	0.46	0.50	0.46	<DL
	A	0.30	0.33	0.30	0.33	<DL
	BA	0.30	0.26	0.26	0.26	<DL

APPENDIX II

PHOTOGRAPHS

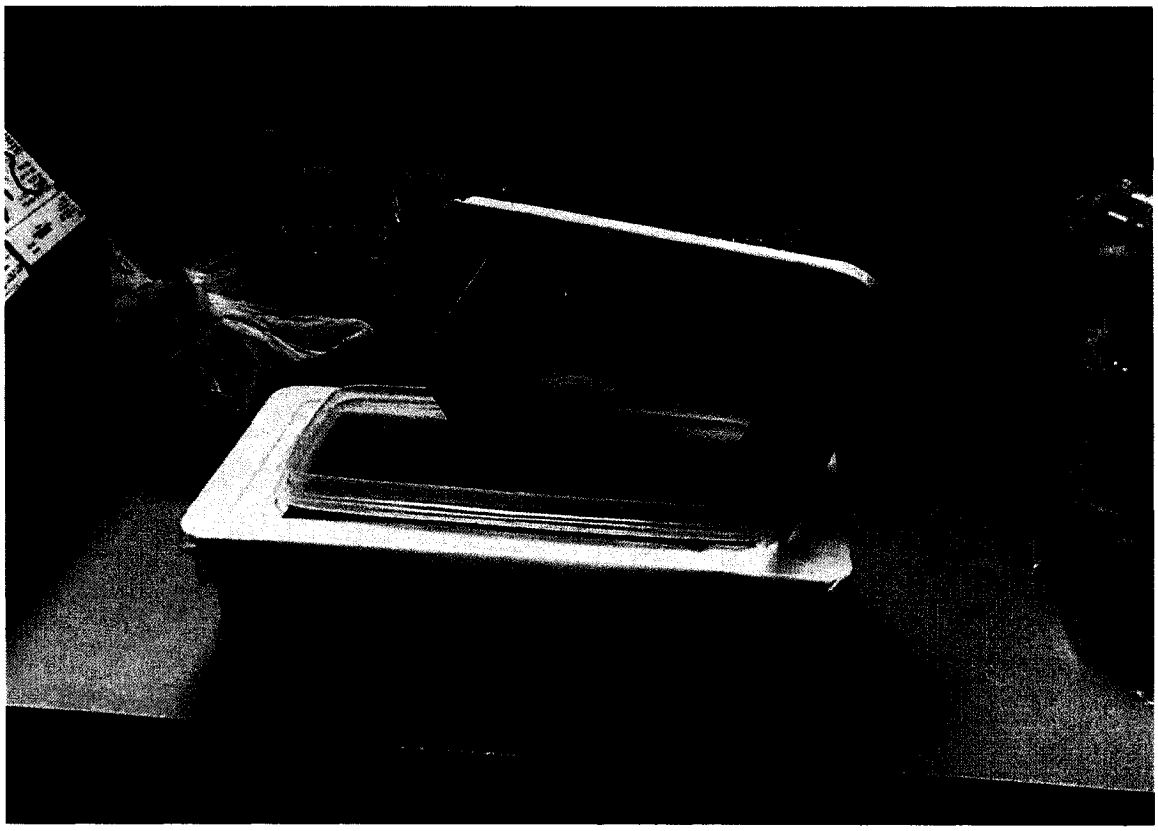

Photo No. 1: The electrokinetic cell with electrodes ready to start experiment

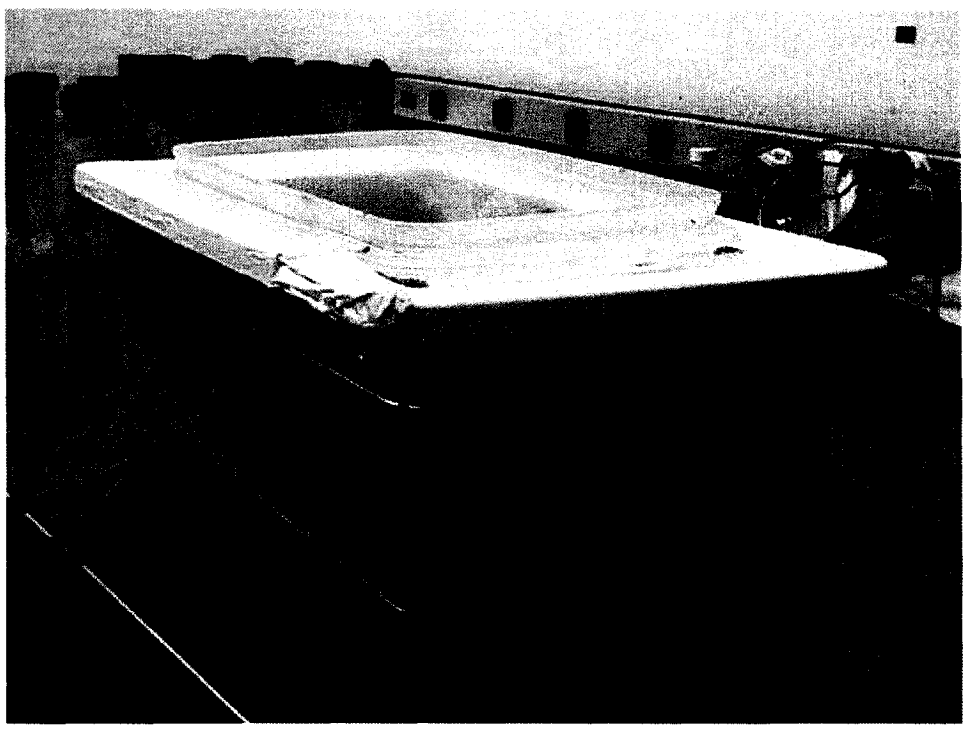

Photo No. 2: The electrokinetic cell – as it looks from the side

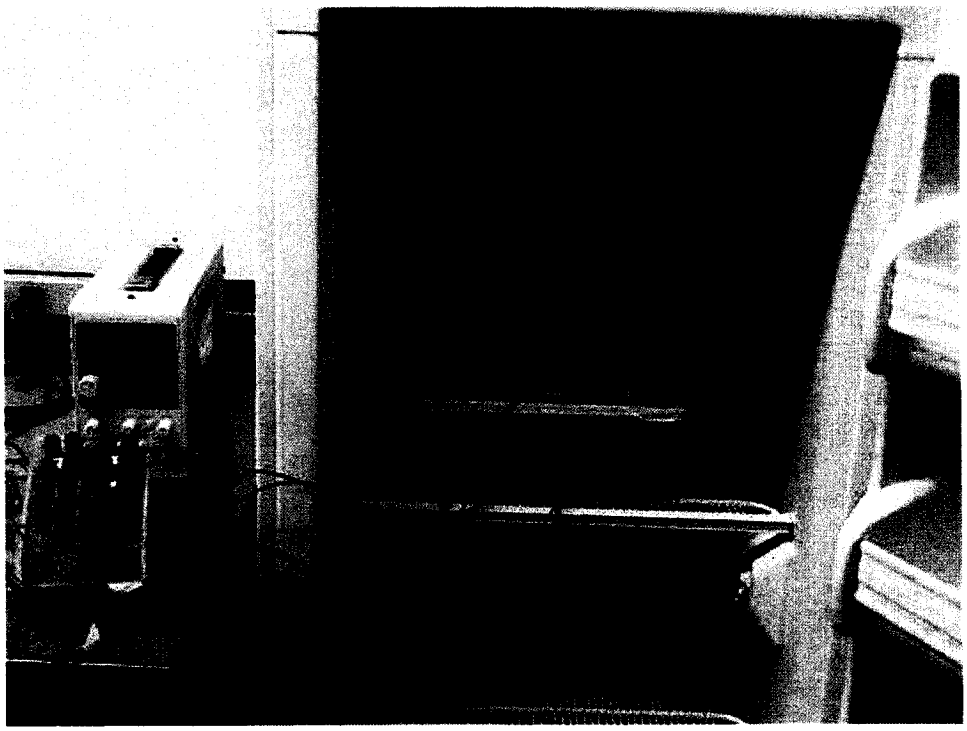

Photo No. 3: The EK cell with biosolids placed at the desired low temperature

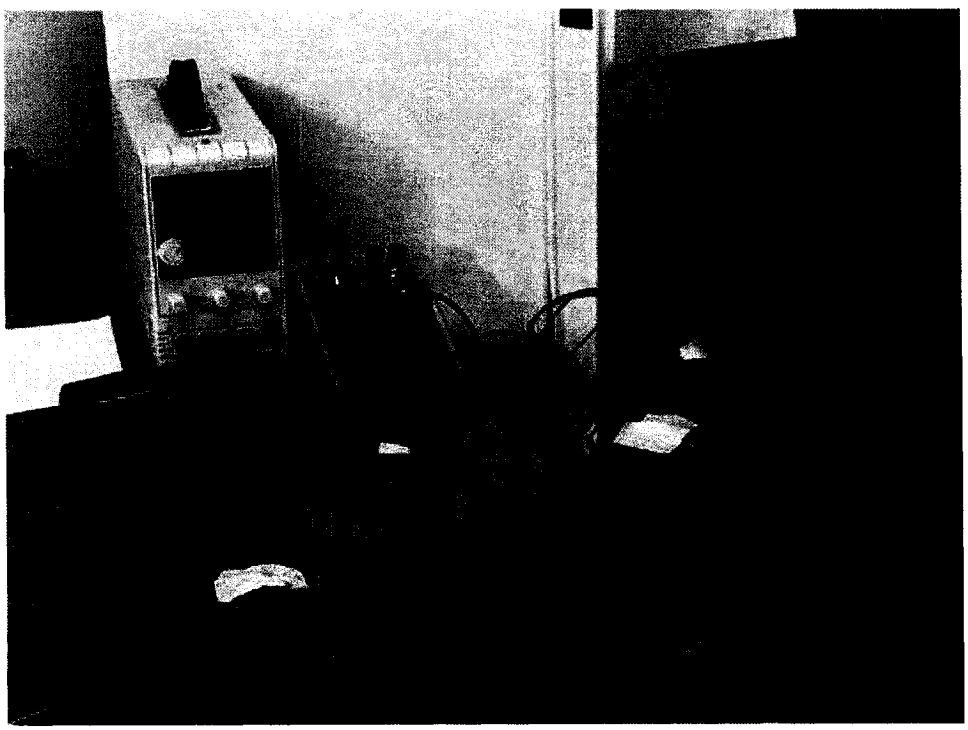

Photo No. 4: Experiment in progress

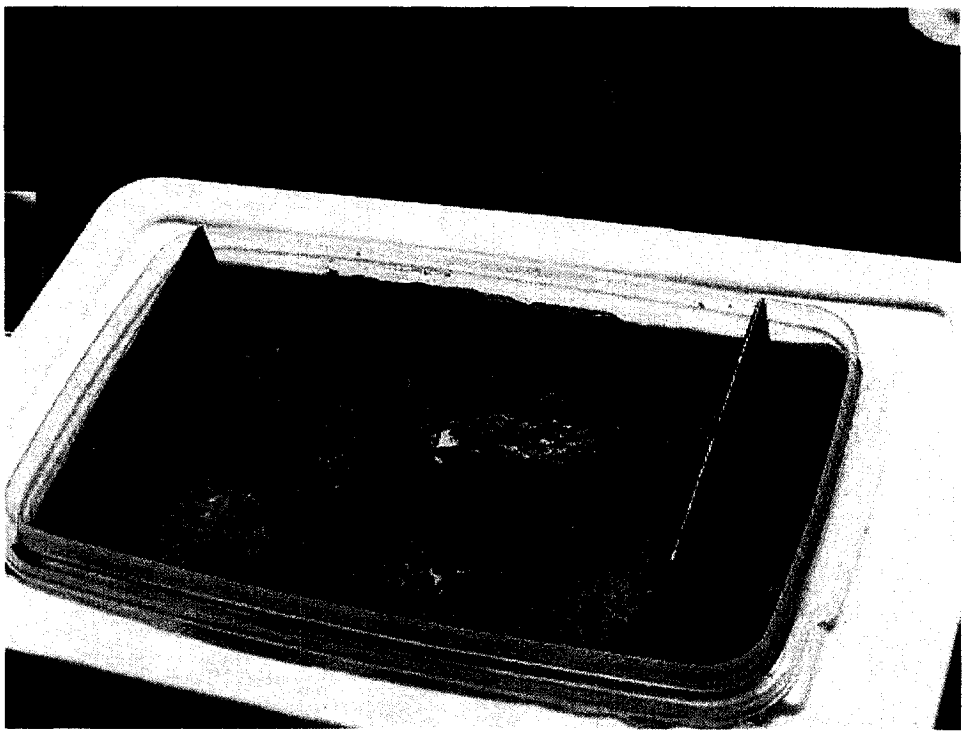

Photo No. 5: Frozen biosolids in the cell after test T1(-8,0)

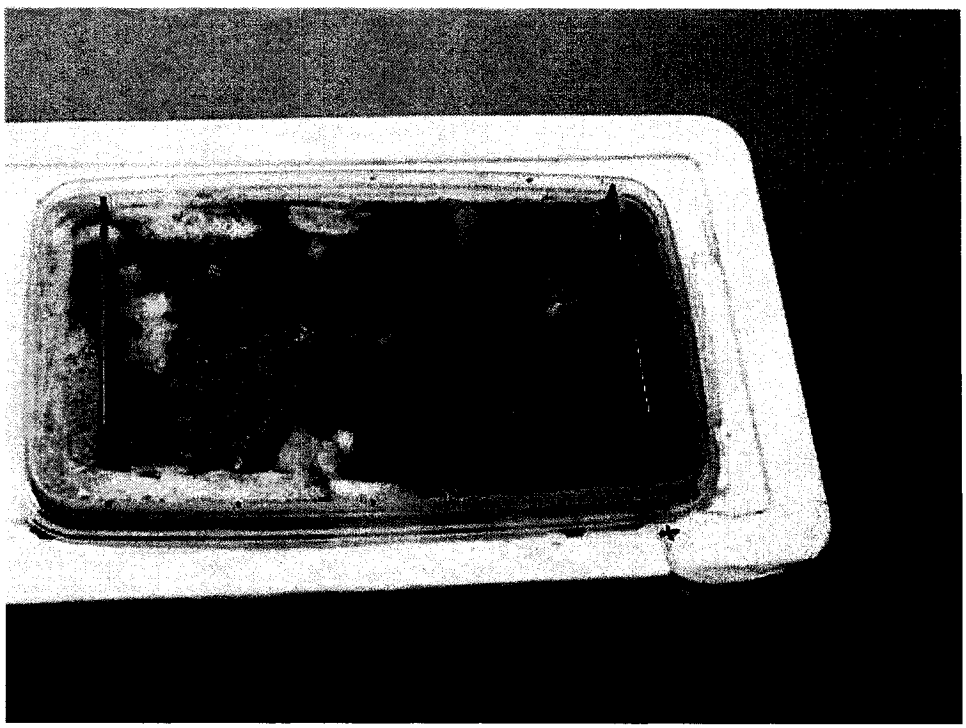

Photo No. 6: Frozen biosolids in the cell after test T2(-8,H)

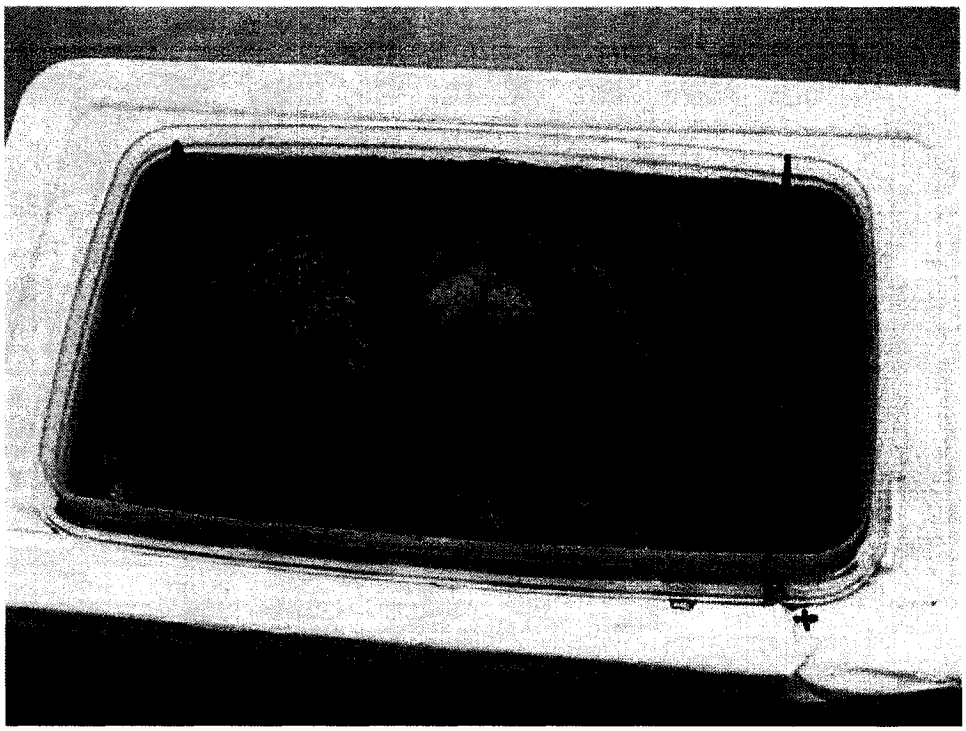

Photo No. 7: Frozen biosolids in the cell after test T4(-15,L)

Photo No. 8: Frozen biosolids in the cell after test T5(-15,M)

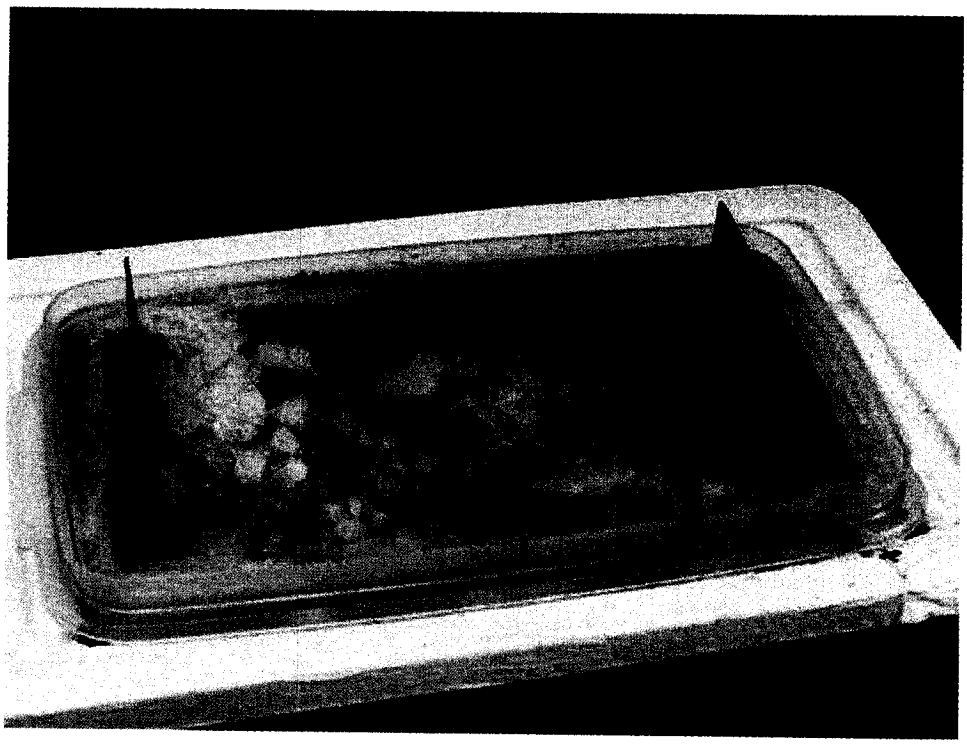

Photo No. 9: Frozen biosolids in the cell after test T6(-15,L)

Photo No. 10: Biosolids samples after application of electrokinetics

Photo No. 11: Heavily corroded anode during test T3(-15,0)

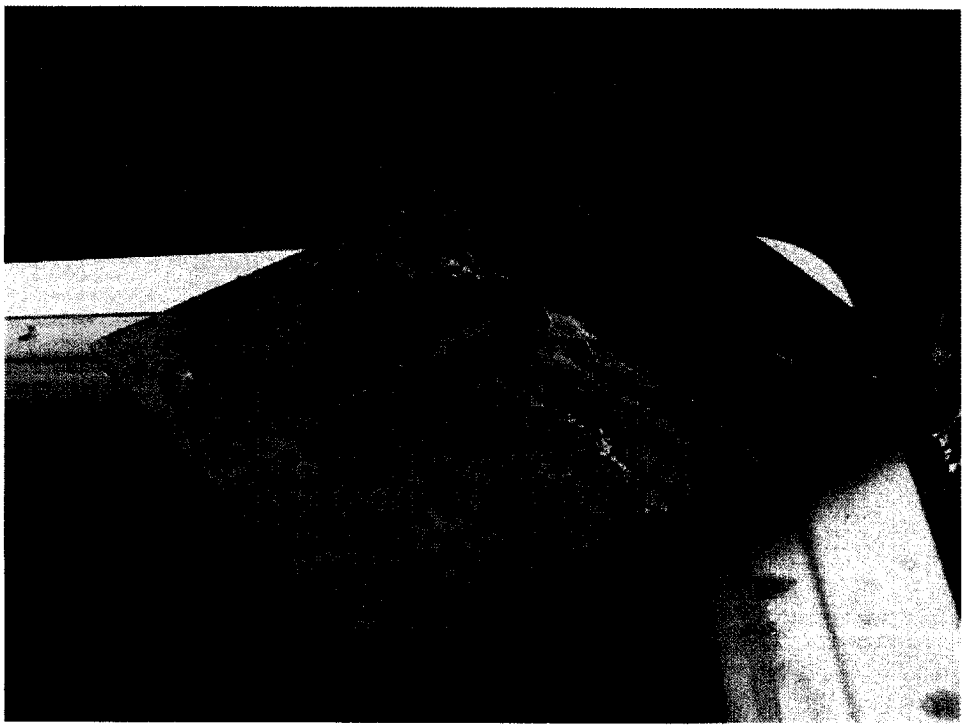

Photo No. 12: Slightly corroded anode during test T2(-8,H)

Photo No. 13: Filtration in progress for metal content analysis

Photo No. 14: The Atomic Absorption Spectrometer used in this study