CHARACTERIZATION AND STABILIZATION OF CHEMICALLY ASSISTED PRIMARY SEDIMENTATION PROCESS (CAPS) SLUDGE

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Abstract

Chemically assisted primary sedimentation process (CAPS) is adopted as Stage I of the Strategic Sewage Disposal Scheme (SSDS) implemented by the Hong Kong government. CAPS, using chemical coagulants to treat wastewater, is employed in a new sewage treatment plant (STP) on Stonecutters Island. The production of these large quantities of CAPS sludge creates disposal and utilization problems and stabilization of sludge before land disposal is one of the development trends for the disposal of sludge.

In the present study, the effect of different coagulants on the performance of CAPS was investigated by jar tests and a large scale test. The various physical and chemical properties of chemically-treated sludge and the biologically-treated sludges collected from different STPs were compared. Then, the effect of pulverized fuel ash (PFA) and lime (CaO) stabilisation on the CAPS sludge was studied. The suitability of the alkaline stabilized sludge for land application purposes was also evaluated by (i) short -term cup trials on growing two edible crops, Chinese radish and barley, in stabilized-sludge amended soil mixtures; (ii) long-term pot trials on planting tall wheat grass in amended soil. Lastly, the impact of disposing stabilized sludge in landfill was studied by lysimeter tests.

The jar test and pilot-scale results showed that CAPS could achieve better removal efficiencies of suspended solids, total nitrogen and phosphorous. It was found that there were significantly differences in both physical and chemical properties between the

chemically modified sludge and the biological treated sludges. Also, the use of PFA and lime was able to render the stabilized sewage sludge meeting the USEPA's criteria for Process to Further Reduce Pathogens (PFRP) in addition to producing a final product with improved handling characteristics. The results from plant bioassay indicated that it was feasible to plant on a mixture of natural soil and stabilized sewage sludge provided the type of soil used is carefully selected. Lastly, liming in sludge delayed the gas production by maintaining high pH levels.

All in all, alkaline stabilization can be viewed as an alternative to treat sewage sludge. Besides, the stabilized product has potential to be used as a soil conditioner in landscaping purposes. But more work needs to be done on the detailed microbiological and geotechnical properties of the CAPS sludge, the optimum application dosage of applying stabilized sludge to soil, and the long-term behavior of the stabilized sludge when disposed of in the landfill environment.

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CHAPTER 1: INTRODUCTION

1.1 Overview

Tonnes of domestic and industrial wastewater is generated each day in Hong Kong. With the implementation of Strategic Sewage Disposal Scheme (SSDS), which targeting at providing proper treatment for the sewage generated around Victoria Harbor, the pollution problem in the harbor can be temporary solved. A review on this project by an International Review Panel concluded that Chemically Enhanced Primary Treatment (CEPT) or Chemically Assisted Sedimentation Process (CAPS) should be adopted to produce an effluent that almost can be comparable to that achieved with biological treatment, which can also be readily disinfected. CAPS, using ferric chloride together with an anionic polymer to induce coagulation or flocculation and the finely-divided particles form large floc, is being used in the new sewage treatment plant on Stonecutters Island.

It is expected that sludge produced in Hong Kong will be between 250,000 and 400,000 tonnes dry solids per year by the year 2000. And the estimates of future sludge production are dominated by the very large amount of sludge expected to be produced at the sewage treatment works on Stonecutters Island. The production of these large quantities of CAPS sludge give create new problems in proper treatment method and disposal outlets.

Sludge stabilization is commonly used to reduce the number and prevent regrowth of pathogenic organisms, and thereby minimize nuisance conditions created during sludge disposal. Lime stabilization, defined as 'sufficient lime is added to produce a pH of 12 after two hours of contact', qualifies as a Process to Further Reduce Pathogens (PFRP). Pulverized fuel ash (PFA) is the solid by-product generated at coal fired power stations. It is known that the addition of PFA and CaO has the potential to reduce heavy metal leaching and reduce total coliform content of the stabilized sewage sludge. Besides, alkaline ash can provide a high alkaline buffering capacity which in terms reduce heavy metal availability in sludge during its composting.

Because of the presence of beneficial organic compounds in sludge, planting crops on sludge-amended soil becomes a common agricultural practice. For instance, soil mixed with fly ash and sewage sludge can increase the dry weight yields of tall wheat grass while reducing the uptake of Zn, Cu and Cd. Besides, liming the soils to pH 7 can significantly reduce heavy metal concentrations in carrots and spinach.

The co-disposal of sewage sludge with municipal solid waste in a sanitary landfill in viewed is an environmentally friendly disposal option. The high organic matter content in sludge, the presence of methanogenic bacteria, particularly for sludge which had already been anaerobically digested were the basis for the capacity of accelerating biostabilization. It is widely known that sludge causes a speed-up of the landfill stabilization process by a greater methane production.

1.2 Objectives

i. To investigate the combined effect of ferric chloride and an anionic polymer on the performance of CAPS

ii. To characterize and compare raw, digested and CAPS sludges collected from 3 sewage treatment plants in Hong Kong

iii. To investigate the effect of stabilization of CAPS sludge with PFA and CaO

iv. To evaluate the stabilized sludge-amended soil on the short-term growth of two edible crops and the long-term growth of a grass.

v. To monitor and evaluate leachate and gas production from sludge only and sludge-solid waste codisposal landfills

The whole project is divided into five parts. The first part focuses on CAPS and the second part provides a detailed characterization of sewage sludge. The third experiment investigates the effectiveness of alkaline stabilization of sludge. The last two parts evaluate the feasibility of stabilized sludge for agricultural and landfill disposal.

CHAPTER 2: SEWAGE TREATMENT IN HONG KONG

2.1 Past development

More than 2 million tonnes of domestic and industrial wastewater is generated each day in Hong Kong (EPD,97). The traditional methods for discharge of sewage with only preliminary treatment into the Victoria Harbor has lead to a steady decline in marine water quality. In response to this problem, the Government commissioned the Sewage Strategy Study in 1989 to device ways to protect the marine environment. The objectives of this study are to determine water quality objectives to protect the coastal waters of Hong Kong and then to establish a long term strategy for collection, treatment and disposal of sewage so as to meet these objectives. Meanwhile, the Drainage Services Department (DSD) was established in 1989 to provide an efficient approach to resolving the sewage and flooding problems in Hong Kong.

The first step in that study was the implementation of WQI which set the maximum level of pollutant in water or the minimum level of essential constituents of the water needed to sustain marine life (EPD,95). Besides, the development of 16 Sewerage Master Plans (SMP) was proposed to upgrade the sewerage, sewage treatment and storm drainage systems in the next 10 years. The central recommendation of the strategy study was the proposal of the Strategic Sewage Disposal Scheme (SSDS) which consisted of 4 stages (Section 2.3.). The whole strategy was reviewed and confirmed by Government between 1989 and 1993 and preliminary engineering studies were conducted. In 1993, the construction of the first stage of SSDS was commissioned to address the more significant discharges to the harbor (Slavnic et. al.).

Regarding sewage treatment facilities in Hong Kong, there are 7 major sewage treatment works operating in Hong Kong, which are located in Shatin, Tai Po, Shek Wui Hui, Yuen Long, Sai Kung, Stanley and Stonecutters Island, together with more than 60 smaller works and preliminary treatment facilities in the coastal areas and on islands to maintain the water quality of the receiving water-bodies .

2.2 Sewage Treatment Process

Sewage treatment processes are generally classified as preliminary, primary, secondary and tertiary treatment. Preliminary treatment removes large objects such as sand, grit and other heavy particles by screening, grit removal and flow equalization. After screening, the sewage is passed into primary sedimentation tanks to allow a longer time for most of the suspended solids to settle out by gravity. Secondary treatment is a biological process which converts the organics in wastewater into CO_2 and H_2O and new microbial cells that can be removed from the wastewater by secondary settling. Tertiary treatment is an advanced process which remove nitrogen, phosphorous and the remaining biological oxygen demand, as well as toxic contaminants in the sewage.

2.3 Strategic Sewage Disposal Scheme (SSDS)

2.3.1 Early Development (1989-1995)

There was 4 stages in the original scheme. Stage I involved with the collection and treatment of sewage generated around the harbor at the new sewage treatment works (STW) located at Stonecutters Island (SCI). Stage II concerned the construction of a long oceanic outfall into the deep ocean water south of Lamma Island for the disposal of treated wastewater. Stage III & IV would follow intercepting flow from the northern and south western areas of Hong Kong Island including the provision of collection and treatment facilities at Mount Davis, Aberdeen and Stanley (*Fig.2.1*). After extensive review by several consultants, the Government agreed that chemically assisted primary sedimentation process (CAPS) or chemically enhanced primary treatment (CEPT) should be adopted on SCI STW to produce an effluent that can be comparable to that achieved with biological treatment, which can also be readily disinfected (EPD,95). Besides, an interim outfall should be included for the discharge of effluent from SCI STW into the western approaches of the harbor. It is anticipated that the construction of Stage I will be completed by 1997. The estimated average dry weather flow of sewage from 1997 to 2021 of the SSDS (Pypun, 95) is shown in Table 2.1.

Table 2.1: Estimated sewage flow (m^3/sec) of SSDS

Year	1997	2001	2011	2021
Stage I	12.82	16.36	17.46	19.97
Stage III & IV	----	4.00	4.18	4.27
Total	12.82	20.36	21.64	24.24

2.3.2. Present Development

With the implementing of Stage I, preliminary treated wastewater from the 7 existing preliminary treatment works (PTW) are transferred to the SCI STW to undergo CAPS treatment. Delay completion of some of the collector tunnels mean that the full commissioning of the Stage I of the scheme will be delayed. (Lau et.al.,1998). Meanwhile, a 2-year environmental impact assessment (EIA) study on Stage II of the SSDS was carried out. Conclusively, 4 groups of options have been proposed as the environmentally acceptable treatment levels in Stage II (EPD, 98).

Table 2.2: The feasible and acceptable options for SSDS Stage II

Details & main criteria	Option 1	Option 2	Option 3	Option 4
Primary Treatment	CEPT	CEPT	CEPT	Primary
Biological Treatment	No	No	Yes	Yes
Nitrogen removal	No	No	No	Yes
Disinfection	Yes	Yes	Yes	Yes
Outfall	West Lamma/ East Lamma	SE Lamma	West Lamma/ East Lamma	West Lamma/ East Lamma
Capital costs (HK $ billion)	11-12	12-13	22-23	25-26
Land requirement	17 ha	17 ha	33 ha	39 ha

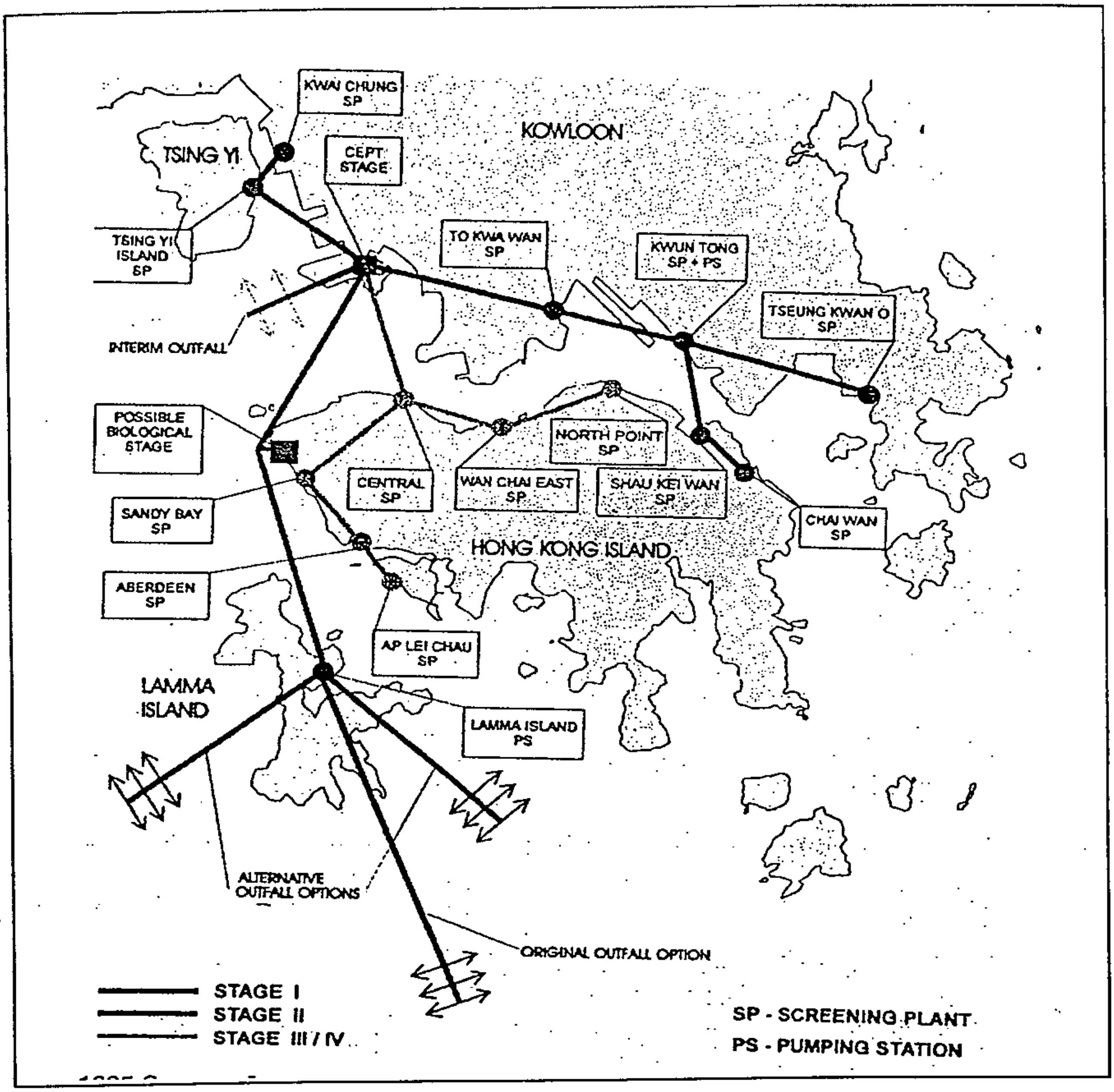

Fig. 2.1 : SSDS proposal

CHAPTER 3: CHEMICALLY ASSISTED PRIMARY SEDIMENTATION PROCESS (CAPS)

3.1. Coagulation & Flocculation

3.1.1. Definition & chemistry

Different definitions have been proposed for coagulation. Coagulation refers specifically to the destabilization of colloidal suspensions by salt (Adachi, 95). Hammer (96) stated that coagulation is the destabilization of suspended contaminants such that the particles contaminants such that the particles contact and agglomerate, forming flocs that drop out of solution by sedimentation. A simple idea stated by Huang (95) is that coagulation enables the finely-divided particles to form aggregates (floc) so that they can settle out within a reasonable period of time. Among the various mechanisms for colloid destabilization, four of them have been reviewed by most researchers, they are double layer compression, adsorption and charge neutralization, entrapment and interparticle bridging (Faust & Aly, 83).

3.1.2. Inorganic Coagulant

Alum was considered to be the pioneer of the coagulants (Faust & Aly, 83). Simple aluminum and iron salts such as alum, ferric chloride or ferric sulfate are some of the most commonly used inorganic coagulants. The actions of these metal salts depend on the chemical speciations of the stock solution, hydrolysis reactions, reactions with humics and other organic ligands and pH-solubility relationships (Edzwald, 81;Dentel et. al., 85). The improvement in the removal of different contaminants by the application of metal salts is well documented. For instance, the relative effectiveness of alum and ferric salts on the removal of heavy metals (Dentel, 91) is shown in Table 3.1..

Polyalumium chloride (PACl) is the most common form of prehydrolysed coagulant. It is produced by partial hydrolysis of aluminum chloride and is thought to consist of stable cationic polymers of aluminum. The advantages of PACl over simple metal salts are higher removal of particles, reduced need for neutralizing agents, active over a wide pH range and reduced sludge generation (Letterman et. al., 82; McKeen, 87; Heinzmenn,91; Jiang,93). The mechanism of coagulation by PACl is entrapment in which aluminum ion undergoes hydrolysis and precipitates as a gelatinous polymeric hydrated oxide.

Ferric chloride ($FeCl_3$) is another widely used coagulant with the advantages of the ability of formation of a stronger and heavier floc and lower cost than PACl (McKeen, 87; Cacres, 93). The mechanism of coagulation with $FeCl_3$ is that Fe^{3+} ion undergoes stepwide hydrolysis reaction in which metal hydroxide preceipitates will be formed.

Table 3.1. : Effectiveness of coagulation for the removal of selected inorganic contaminants

	Removal characteristics	
Contaminant	Coagulation with alum	Coagulation with ferric salts
Arsenic (III)	Poor	Fair
Arsenic (III)	Good	Excellent
Barium	Poor	Poor
Cadmium	Good	Excellent
Chromium (III)	Excellent	Excellent
Chromium (V)	Poor	Poor
Lead	Excellent	Excellent
Mercury (org.)	Fair-poor	Fair-poor
Mercury (inorg.)	Fair-poor	Fair-good

Lime is widely used in the past, but its use had declined nowadays because of the increased volume of sludge produced and the resulted high pH that will increase the toxicity of the effluent (Dentel,91; Huang,95). But lime is frequently used for pH control when acidic coagulants such as alum and ferric salts are employed (Dentel,91). The main mechanism of lime coagulation is often defined as coagulation-adsorption, during which the precipitating calcium carbonate and magnesium hydroxide, as well as Ca^{2+} ion interact with both organic and inorganic pollutants (Swiderska-Broz,91).

3.1.3. Organic coagulants

The use of synthetic organic polymers (polyelectrolyte/ flocculant/coagulant aid) in coagulation has been one of the most significant developments in wastewater treatment. The organic polymers are chains of individual monomer units, held together by covalent bonds. Since most colloids in wastewater possess negative charges, cationic polyelectrolytes are most effective in sewage treatment. And cationic polyacrylamides are often advocated as more effective than primary coagulants, polyamines, polyethylene-amines and polyamids. Basically, the action of polymers are charge neutralization, polymer contraction and displacement of adsorbed water.

3.2. Previous research on CAPS

Many researchers have investigated the effect of the different coagulants on the treatment of wastewater. A study carried out by the Drainage Services Department (94) in Hong Kong revealed that $FeCl_3$ was better than lime in terms of phosphorous, suspended solid, and biochemical oxygen demand removal. Lars et. al. (93) studied the effect of $Al_2(SO_4)_3$, PACl and a combination of lime and ferrous sulphate on the distribution of small particles in sewage wastewater. The result was that simple aluminum ions were the most efficient in reducing the particle concentration whereas the polyaluminum salt was the most effective in reducing turbidity and SS. A comparison of lime and alum on treatment of municipal wastewater was performed by Cacres (93) and it was shown that alum was slightly better than lime to remove COD, but lime performed better than alum in removing P & Mg. Jiang et. al. (93) suggested that performance of polyferric sulphate was superior than other coagulants including PAC and $FeCl_3$. Wu et. al. predicted that 100 ppm of ferric chloride and lime could result in 65% and 45% of total toxic metal (TTM) removal respectively. Table 3.2. compares some reported removal efficiency of the primary sedimentation and CAPS processes (Harleman,96).

Table 3.2.: Typical performance of primary sedimentation and CAPS processes

Parameter	% removal	
	Primary	CAPS
TSS	55	70-90
BOD	30	55-80
P	30	65-95
N	15	35-40
Oil & grease	50	70-80

CHAPTER 4: SLUDGE CHARACTERIZATION

4.1 Physical Properties

4.1.1. Solid concentration

Total solid (TS) is determined by drying a measured volume of sludge to a constant weight at 103°C -105°C. Whereas total volatile solids (TVS) is determined by igniting the dry solids at 550°C in a furnace. Both TS and TVS are widely used in sludge treatment and management practices as measures of dry matter and organic matter in sludges.

4.1.2. Thickening property - sludge volume index

SVI is the simplest parameter for characterizing thickening properties. It is the volume in milliliters occupied by a gram of solids following thirty minutes of sedimentation. Generally, a sludge having a SVI between 100 mg/l and 200 mg/l is considered to be well settled (Sammer et. al., 90). It was suggested by Richard (88) that the use of SVI could not lead to improved understanding of how the physical properties of sludges influence thickening.

4.1.3. Dewaterability - capillary suction time

CST is a common technique for expressing the dewaterability of sludge. It refers to the time the filtrate requires to travel a fixed distance in the filter paper. A large CST usually implies good sludge filterability. Some authors found out that CST was a good index for the product of solid concentration and average specific resistance. However, it could not be used to evaluate the bound water in the sludge (Chen et. al., 96).

4.1.4. Centrifugability

Centrifugability is defined as the aptitude of the sludge to be dewatered under the action of the centrifugal forces. It was suggested by Spinosa and Mininni (83) that centrifugability characterization of sludges was very difficult as it was practically impossible to reproduce in laboratory conditions actually existing in an industrial centrifuge.

4.2. Chemical Properties

4.2.1. Macronutrients

Although sludges contain relatively low levels of macro- and micro-nutrients, when applied to soil at recommended rates they can supply all the needed nitrogen (N), phosphorous(P), potassium(K) as well as calcium, magnesium and many of the essential micronutrients. The source of N in municipal wastewater comes from human excreta, ground garbage, and industrial wastes, particularly from food processing. Whereas 30 to 50% of the P in sludge is derived from sanitary wastes and the remaining 50 to 70% is from phosphate builders used in household detergents (Hammer, 86). Table 4.1 shows the typical concentrations of nutrients in different types of sewage sludge (CIWEM, 95).

Sewage sludge application rates on cropland are often based on N concentration and expected N availability to plants. It was demonstrated by some workers that growth of grass in sludge-amended soils was comparable to that by inorganic N application (Hall & Williams, 84). However, it was well known that ammonia in sludge would inhibit germination and root elongation of plants (Terry et. al., 78; Wong et. al., 83). When liquid sludge is applied to grassland and if the grass is to be cut for hay silage, supplementary K is required (Coker,85).

Table 4.1: Typical concentrations of crops nutrients and organic matter contents in various types of sewage sludge with (for comparison) values for farmyard manure and a chemical fertilizer

Types of sludge/ fertilizer	N	P	K	Organic matter
	(as % on dry solids)			(as % of total wet weight)
Activated (primary)	2.5	1	0.2	4.2
Surplus activated	5	0.6	<0.05	1.5
Digested (primary + secondary)	5	1.8	0.2	2.2
Dewatered sludge cake (primary + secondary)	3	1.1	0.1	18
Farmyard manure	1.7	0.2	1.3	30
Chemical manure	20	4.4	4.2	0

4.2.3. Organic matter

Microorganisms decompose sludges' organic matters and use some decomposition products for reproduction and, as a result, change the sludges' organic matters and release certain products for decomposition into the environment. The sludges organic matter can have a profound effect on the soil physical properties such as soil fertility, humus formation, bulk density, aggregation, porosity, and water retention.

4.2.4. Heavy metals

Heavy metals are commonly used in industry and are often present in industrial waste waters discharged into the public sewer. They are also derived from other sources, e.g.

foodstuffs, so that they can be present in sewage which is domestic in origin. It is well known that concentrations of heavy metals vary widely in sludges, as indicated in Table 4.2 (EPA, 84).

Table 4.2 : Typical metal contents in wastewater sludge

Metal	Range	Median
	(expressed as mg/kg of dry sludge)	
As	1.2-230	10
Cd	1-3410	10
Cr	10-99,000	500
Cu	84-17,000	800
Pb	13-26,000	500
Ni	2-5,300	80
Hg	0.6-56	6
Mo	0.1-214	4
Se	1.7-17.2	5
Zn	101-49,000	1700

4.3 Researches on Sludge Properties

A lot of works have been done on the characterization of different properties of various types of sludge. Alloway & Jackson (91) reported the coefficients of variation for metals in sludges from 8 U. S. cities to be: Cd, 27-160%; Zn, 26-58%, Cu, 18-167% and Pb, 9-56%. Regarding the forms of heavy metals, Davis (84) stated that Cd, Cu, Ni and Zn are more bioavailable in sludged soils than Pb, Hg and Cr. Legret et. al. (87) studied heavy metal in sludges and concluded that as treatment progressed, metals become less mobile and tended to associate with the solid phase. Sequential extraction was carried out by Petruzzeli et. al. (94) and it was shown that the total amount of extractable metals was generally lower in the sludge conditioned by CaO and $FeCl_3$. On the other hand, Strasser et. al. (95) found that the major part of metals in anaerobically-digested sewage sludge occured in the form of sulphides. In Hong Kong, Lowe (93) reported the metal concentration in the sewage sludge generated from different sewage treatment plants, as shown in Table 4.3. Pun et. al. (95) concluded that from the sludge samples collected between 1992 and 1994, the total concentrations of Cr (except at Yuen Long), Cu (except at Tai Po) and Ni were decreased. The major forms of Cu, Pb, Ni and Zn were found in the sulphide phase, organically-bound phase, adsorbed phase and carbonate phase, respectively. Besides, the physical properties of dewatered sludge for landfilling were studied by Koenig et. al. (96) and the results are presented in Table 4.4.

Table 4.3 : Typical metal concentrations in Hong Kong sewage sludge (mg/kg)

Sewage Treatment Plant	Cu	Zn	Ni	Cr	Pb	Cd	Ag
Sha Tin	2900	1500	630	630	180	3	35
Tai Po	3000	1300	80	120	300	2	14
Shek Wu Hui	700	5000	420	1150	90	1	18
Sai Kung	280	300	1200	360	120	6	8
Yuen Long	140	1700	100	270	50	1	7

Table 4.4 : Van shear strength, total solids, compression index (Cc) and compressibility factor (F) of different dewatered wastewater sludges of selected STPs in Hong Kong

Sample site	Van shear strength (kN/m^2)	Total solids (%)	Cc	F
Shek Wu Hui	3.59	18.67	2.38	0.39
Yune Long	7.53	17.93	2.1	0.40
Tai Po	5.51	18.62	2.00	0.21

CHAPTER 5: SLUDGE TREATMENT & DISPOSAL

5.1 Types of Sludge Stabilization Process

Sludge stabilization processes are key to the reliable performance of any wastewater treatment plant. The primary objectives are reduction of odors, pathogens, and putrescibility of the sludge. The means to eliminate the nuisance conditions through stabilization are (1) biological reduction of volatile content (2) chemical oxidation of volatile matters (3) addition of chemicals to sludge to render it unsuitable for survival of microorganisms and (4) application of heat to disinfect or sterilize the sludge (Metcalf & Eddy, 91). Commonly used sludge stabilization processes are anaerobic digestion, aerobic digestion, composting and lime stabilization.

5.1.1 Anaerobic digestion

Anaerobic digestion is among the oldest forms of biological wastewater treatment, and its history can be traced from the 1850s. The bacterial process, as summarized in Eq.1, consists of two successive processes that occur simultaneously in digesting sludge (Hammer, 96). The first stage involves the breaking down of organic compounds and converting them to organic acids with the release of gaseous by-products. In order for digestion to occur, second-stage gasification is needed to convert the organic acids to methane and carbon dioxide.

$$\text{Organic Matters} \xrightarrow[\text{Acid-forming bacteria}]{} \text{Organic Acids} \xrightarrow[\text{Methane-forming bacteria}]{} CH_4 \ \& \ CO_2$$

(Eq. 1)

5.1.2 Aerobic digestion

Aerobic digestion has been used primarily in plants of a size less than 5 Mgal/d, but in recent years the process has been employed in larger wastewater treatment plants (MOP 8, 88). Aerobic digestion is a sludge treatment process that reduces the microbial mass by forcing the microorganisms to use their own cellular mass as food under aerobic conditions.

5.1.3 Composting

In the period from 1883 to 1988 alone, the number of operating sludge-composting facilities in the United States has increased from 61 to 115 (Goldstein, 88). Composting is the biological decomposition of organic materials. Sludge has been composted properly is a sanitary, nuisance-free, humus-like material. Approximately 20 to 30% of the volatile solids are converted to carbon dioxide and water. As the organic material in sludge decomposes, the compost heats to temperatures in the pasteurization range (50 to 70°C), and destroys pathogenic organisms. A properly composted product is suitable for use as a soil conditioner or for final disposal.

5.1.4 Lime stabilization

According to the United States Environmental Protection Agency (EPA), over 250 municipal wastewater treatment plants in US use lime treatment to stabilize their sludge (Lue-Hing et. al., 92). The Federal Register defines a lime treatment process for pathogen control in Section 257, Appendix II, as 'sufficient lime is added to produce a pH of 12 after two hours of contact.' (Federal Register, 79). A minimum dose of 6% lime, plus the addition of 20 to 40% cement or lime kiln dust and maintenance of 50% solids sludge at pH above 12 for three days or dried to 65% total solids qualifies as a PFRP (Process to Further Reduce Pathogens) (Christensen, 87).

Many researches have been done on the characteristics of lime-stabilized sludge. Gossow & Spellier (80) revealed that the addition of lime at the primary settling stage resulted in a marked decrease in the concentration of ammonia nitrogen in the treated effluent and a reduction in the phosphorous content from 13 to only 5 mg/L. Whereas Tabasaran (80) found out that the exothermic reactions by the addition of quicklime would cause the temperature of the sludge to raise to about 70°C within 10 minutes. A study at Lebanon WWTP successfully demonstrated that lime stabilization of raw sludges reduced total coliform, fecal coliform, and fecal streptococci concentrations by more than 99.9% (Lue-Hing et.al., 92).

5.1.5 Chemical fixation of sludge (N-viro process)

CKD (cement kiln dust) and LKD (lime kiln dust) are by-products of the cement of lime manufacturing process. The chemical fixation process starts by mixing the dewatered sludge with CKD or LKD and quicklime in a pug-mill mixer. The material is then cured for about 12 hours and then dried to solids content of 50% in 3 to 7 days. The gel hardens to form thin, interlaced, densely packed silica fibrils that incorporate the aggregates and waste into a soil-like material called Chemsoil or N-Viro soil (Outwater, 94). Burnham et. al. (90) performed a series of experiments and showed that treatment of municipal wastewater sludge cakes with 35% CKD alone or a small amount of quicklime with 30% CKD would reduce the pathogenic microbial population below PFRP standard. Bennett (89) suggested that alkaline treatment of sludge with CKD and lime was beneficial, not only its capacity to stabilize the sludge to meet both PSRP and PFRP standards, but also in terms of heavy metal immobilization and minimization of metal solubility in treated sludge.

5.1.6 Other alternatives

Thermal treatment and incineration can also be used to stabilize the sludge before disposal. Table 5.1 (MOP 11, 90) lists the advantages and disadvantages of the different sludge stabilization processes.

Table 5.1: Comparison of sludge stabilization process

Process	Advantages	Disadvantages
Lime stabilization	Low capital cost Easy operation	Increases sludge volume Land application not suitable where soils are alkaline
Anaerobic digestion	Good VSS destruction Broad applicability	Requires skilled operators Foaming
Aerobic digestion	Low initial cost Simple operational control	Reduced pH & alkalinity Sludge is difficult to be dewatered by mechanical means
Composting	High quality Low initial cost	Requires bulking agent Requires forced air turning
Thermal treatment	More readily dewaterable sludge Effective sludge disinfection	Rupture cell walls of biological organisms releasing water & bound organic material
Incineration	Reduction in sludge volume for disposal Total pathogen destruction	Complex mechanical & control equipment Requires auxiliary fuel source

5.2. Sludge Disposal Practice

5.2.1. Hong Kong practice: present & future

It is envisaged that the sludge produced within the territory will be between 250,000 and 400,000 tonnes dry solid/year by the year 2000 (Oswell & Rootham, 91). This estimate of future sludge production are dominated by the very large amounts of chemically treated sludge produced at the major sewage treatment works on Stonecutters Island. Since there is no suitable agricultural land for disposal and to comply with the international trend to ban sea disposal, landfill remains as the most safe and practicable disposal outlet. Meanwhile, new technologies for the effective control of air emissions from the incineration of sludge are being considered by the government. It is claimed that if the whole of the sludge in Hong Kong were incinerated then in the year 2001, the sludge cake volume for landfill disposal would reduce from 2.5 million wet tonnes per year to approximately 50,000 dry tonnes of ash (Oswell & Rootham, 91). Table 5.2 shows the amount of sludge produced by the major STPs in Hong Kong and the treatment employed (Lau, 97).

5.2.2 International practice: current and future

From Table 5.3, it can be seen that most of the countries (10 out of 16) use landfill as their major route for sludge disposal (Osewell, 91). With the ban of sea disposal by the EU (European Union) by 31 December, 1998, it is envisaged that recycling to agricultural land and incineration will be the major disposal options in the future for European countries (Davis, 96). Besides, a new agreement requiring a phase-out of untreated sludge spreading on land will be fully implemented by 2002 (ENDS, 98).

Table 5.2 : Sludge generated in 6 STPs in Hong Kong

Plant Location	**Average amount of sludge produced (m^3/day)**	**Sludge treatment system**
Shatin	980	Thickening: flotation tanks Digestion: anaerobic Dewatering: centrifuge
Tai Po	679	Thickening: aqua belts & gravity Digestion: anaerobic Dewatering: filter presses & belt presses
Shek Wui Hui	326	Thickening: flotation tanks Digestion: anaerobic Dewatering: filter presses
Yuen Long	440	Thickening: gravity thickeners Digestion: anaerobic Dewatering: filter presses
Sai Kung	200	Thickening: decant basin Digestion: aerobic Dewatering: filter presses
Stanley	31	Thickening: not required(extended aeration) Digestion: not required (extended aeration) Dewatering: belt presses

Table 5.3: Current International Sludge Disposal Methods ('000 dry tonnes/year)

Country	Agriculture	Landfill	Incineration	Sea	Total
Belgium	8	**15**	6	0	29
West Germany	698	**1286**	196	0	2180
Greece	0	**15**	0	0	15
Ireland	7	4	0	12	23
Netherlands	**127**	55	6	11	199
Spain	**173**	28	0	79	280
UK	**455**	92	35	434	1016
Singapore	69	**103**	0	0	172
New Zealand	7	**31**	2	0	40
Japan	111	401	**781**	1	1294
Austria	50	**76**	74	0	200
USA	**2666**	1865	800	269	5600

5.3. Sludge Disposal Options

5.3.1. Agriculture

It is well known that sewage sludge contains a variety of constituents of importance, some of which are, potentially, of positive value while others are of negative value. The objective is to maximize the benefits of valuable constituents and minimize the impact of any undesirable constituents. Numerous researches have been done on both the phytoxic and beneficial effects of sludge on crops. Wong (83) found that the inferior growth of flowering Chinese cabbage harvested from sewage sludge amended soil was correlated with the edaphic properties of sludge amended soils. Rappaport et. al. (87) demonstrated that sludge application increased the Ni and Zn concentration while levels of Cd and Cu were unaffected by sludge application in the corn grain. Valdmaa (88) performed a 4-year experiment comparing sludge, manure and commercial fertilizer and revealed that sludge increased the yield as much as manure. Wong (95) showed that soil mixed with fly ash and sewage sludge could increase dry weight yields of *Apropyron elongatum* while reducing the uptake of Zn, Cu and Cd. Due to the presence of toxic elements in the sludge, regulations were set on concentration of Potential Toxic Elements (PTEs) for agricultural use in UK (Table 5.4, CIWEM, 95).

5.3.2. Landfill

Sewage sludge that has been dewatered and hence contains no free water can be satisfactory disposed in a sanitary landfill either alone or in a mixture with municipal solid waste. In the landfill, organic sludge would degrade in a manner analogous to garbage.

Table 5.4: Maximum Permissible Concentrations of PTEs in Soil (Sampled at 150 mm or 250 mm depth) after Applications of Sludge

PTE	Maximum permissible conc. of PTE in soil (mg/kg DS)			
	pH 5.0- 5.5	pH 5.5 - 6.0	pH 6.0 -7.0	pH > 5.0
Zn	200	250	300	
Cu	80	100	135	
Ni	50	60	75	
Cd				3
Pb				300
Hg				1
Cr				400

Consequently, organic sludge can be expected to contribute significantly to methane gas production. Leachate production would also increase, compared to municipal solid wastes (Eckenfeilder & Santhanam, 81). Blakey (89) found that codisposal of domestic waste and sewage sludge increased the rate of waste stabilization, effectively reduced the concentrations of organic and metals in leachate produced in both laboratory scale experiments and pilot scale field trials. Another large research program indicated that coal fly ashes were able to absorb heavy metals present in leachate from an municipal solid waste landfill and this phenomenon was enhanced by the presence of domestic sludges (Cossu et. al., 89). Whereas Beker & Berg (89) suggested that lower percentages of sludge disposed of together with other waste had no effect on environmental aspects of a landfill site, but higher percentage of sludge in combined disposal appeared to have a positive outcome on environmental aspects. Above all, there is increasing evidence that leachate quality may be improved by co-disposal (Farrell et. al., 87) and that methane production is enhanced (Blakey, 80). This is probably due to the buffering effect of sludge during the acid phase of anaerobic decomposition of the refuse allowing methanogenisis to occur many months earlier than without sludge. This effect will undoubtedly make sludge increasing attractive for co-disposal where commercial recovery of methane as an energy source is envisaged (Bradshaw, 92).

5.3.3. Incineration

Incineration provides a means of producing a sterile, odorless, inorganic residue, independently of the weather. It is known that sewage sludge has a calorific value which allows it to be burned without the need for support fuel (Lowe & Boutwood, 93). However, incineration does not provide complete disposal since about 30% of the solids remain as ash. Tay (87) reported that ash from sludge incineration could act as a partial replacement for cement in concrete.

5.3.4. Sea dumping

A study showed that sea disposal was, on average, by far the most economic option in terms of cost per tonnes of sludge solids disposed. Because of its size and mixing properties, the ocean may be, under properly engineered conditions, a convenient place to dispose various sludges (Eckenfedler & Santhanam, 81). During the late 1980s, there was great concern about the increasing environmental damage to marine life caused by pollutant in the sludge. And the EC (European Communities) finally announced that 'member states shall ensure that 31 December 1998 the disposal of sludge to surface water by dumping from ships, by discharge from pipelines or by other means is phased out .

CHAPTER 6: LABORATORY EXPERIMENTS

6.1. Materials

6.1.1 Raw sewage

The raw sewage samples were collected from 3 different sewage treatment plants (STPs) { Sha Tin (ST) STP, Tai Po (TP) STP, Stonecutters Island (SC) STP } after the initial screening process. Laboratory investigation was carried out immediately (within 24 hours) after the collection to minimize any change in the sewage characteristics.

6.1.2 Chemical coagulants

Polyaluminum chloride PACl (1000 ppm) stock solution was prepared by dissolving 1g of AR grade aluminum chloride ($AlCl_3$) in deionized (D. I.)water and subsequently adding 0.5 g of dry sodium bicarbonate ($NaHCO_3$). Polyferric sulfate (1000 ppm) solution was prepared in the same way by using AR grade ferric sulphate ($FeSO_4$). Stock $FeCl_3$ (1000 ppm) was prepared by dissolving 1g of AR grade hydrolysis ferric chloride ($FeCl_3 . 6H_2O$) in D. I.. And lime solution (1000 ppm) was made by dissolving 1g of AR grade calcium oxide (CaO) in D. I.

6.1.3. Polymer

The stock polymer solution was prepared by adding 0.5 g of a commercially available anionic polymer (supplied by Allied Colloids) to 3 ml methanol in order to thoroughly dissolve the product. 97 ml deionized water was then added and the mixture was vigorously shaken for 5 minutes and further stirred with a magnetic stirrer overnight. This procedure resulted in a 5000 ppm (0.5 %) stock polymer solution. The detailed molecular structure of the product was not revealed, but its general properties is shown in Table 6.1.1 (Allied Colloids) .

Table 6.1.1: General properties of anionic polymer (Magnafloc 1011)

Properties	
Physical form	White granular powder
Particle size	98% <1000u
Bulk density	0.7
pH of 1% at 25^0C	7.0

6.1.4 Sewage sludge

6.1.4.1 Sample collection

Seven different sewage sludge samples from various STPs were collected during the two years' study. They were : 1. Raw, liquid CAPS sludge of the pilot plant at Stonecutters Island ; 2. Primary, thickened sludge from Tai Po (TP) STP; 3. Primary, thickened sludge from Yuen Long (YL) STP; 4. Anaerobically digested, thickened sludge from TP STP; 5. Anaerobically digested, thickened sludge from YL STP; 6. Anaerobically digested, dewatered sludge from YL STP; 7. Raw, dewatered sludge from SC STP. Table 6.1.2 shows the types of sludge samples used in the different experiments.

Table 6.1.2: Sludge samples in various experiments

Experiment / Section	Sludge samples	Date of Sample Collection
6.3 Sludge Characterization	1, 2, 3, 4 & 5	December, 1996
6.4 Chemical Stabilization of Sludge	7	September, 1997
6.5 Plant Bioassay		
Series I	1	December, 1996
	4, 5	March, 1997
Series II	7	March, 1998
6.6 Column tests	6, 7	November, 1997

6.1.4.2 Sample treatment

For samples 1 to 5, the liquid sludges were analyzed for physical properties. Dewatered sludges were produced by centrifuging the liquid sludge at 10,000 rpm for 10 minutes. The supernatant was discarded and the remaining solid were analyzed for chemical properties. For samples 6 & 7, analysis was performed directly on the dewatered sludge samples.

Samples 1, 4 and 5 used in the plant bioassays were first centrifuged at 10,000 rpm for 10 minutes and then air-dried at an outdoor environment for 7 days. The dried sludges were cut into pieces by an electric blender and ground to pass through a 4-mm sieve.

The sludge characteristics are known to vary greatly according to wastewater composition which fluctuates from day to day operation. Also, the chemical constituents may undergo different reactions during the storage of sludge samples in the laboratory. Thus some basic analysis should be carried out on each sludge sample before starting each experiment.

6.1.5 Pulverized fuel ash (PFA)

PFA was collected from the Castle Peak Power Station of China Light & Power Co. Ltd.. PFA was air-dried at room temperature for 7 days and ground to pass through a 4-mm sieve. The typical composition of PFA is shown in Table 6.1.3.

Table 6.1.3: Chemical Composition of PFA

Constituent	Typical value
Silica (SiO_2)	48.04%
Alumina (Al_2O_3)	25.01%
Iron oxide (Fe_2O_3)	6.22%
Calcium oxide (CaO)	6.23%
Magnesium oxide (MgO)	2.28%
Sulphuric anhydride (SO_3)	0.31%
Loss on ignition (LOI)	11.14%

6.1.6 Soil

The soil sample used in Series I of plant bioassay was a sandy soil collected near Wu Kei Sha Beach whereas that of Series II was collected from the top soil of an site near a hillside. The soils samples were oven-dried at 105°C and ground to pass through 4-mm sieve before analysis.

6.2 Chemically Assisted Primary Sedimentation Process

6.2.1 Overall objectives

The relative effectiveness of different coagulants, including ferric chloride ($FeCl_3$), lime, polyferric sulphate (PFS) and polyaluminum chloride (PACl) on the sedimentation process was compared. Besides, the optimum dosage of $FeCl_3$ and an anionic polymer, Magnafloc 1011 on removal of suspended solids (SS) was studied. The above experiments were carried out by jar test. Finally, the properties of settled sludge generated by large scale test was analyzed.

6.2.2 Method

6.2.2.1 Jar test

The jar test experiments were performed using a series of 6 glass jars and the contents of the jars were mixed by a simultaneously stirring unit with a uniform power input. 1-L of the sewage (collected from SC and TP STPs after the initial screening process) was placed in each of the jars and increasing doses of coagulant solution was added to each jar as rapidly as possible. After the addition of coagulant, the wastewater was quickly stirred at 80 rpm for 2 minutes and then slowly stirred at 30 rpm for another 15 minutes. The sewage was then allowed to settle for 30 minutes and the supernatant was taken for the measurement of suspended solids (SS) concentration and/or turbidity (APHA ,Standard Method). In the case when the polymer was used, the sewage was first stirred at 80 rpm for 2 minutes after the addition of coagulants. Then, the polymer was added and the wastewater was further stirred for 2 minutes at 80 rpm and another 15 minutes at 30 rpm. After 30 minutes of settling, the supernatant was analyzed for SS and/or turbidity.

6.2.2.2 Large scale test

After the optimal dosages of coagulants and polymer for the removal of SS were determined, the efficiency of removing other contaminants was studied by a larger scale test. In this test, 10L of wastewater in a metal container was used instead of the 1-L beaker in the jar test. A motor-driven paddle was used for mixing the content. The experimental conditions was the same as the jar test. After 30 minutes of settling, the supernatant was carefully decanted for analysis. About 50 mL of liquid settled at the bottom of the container was collected as sludge.

6.2.2.3 Physical and chemical analysis of sewage and sludge

The total N, P and heavy metal contents of the influent and effluent after the treatment were analyzed by H_2SO_4-H_2O_2 digestion followed by the indophenol-blue method and the stannous chloride method, respectively (Allen et. al., 89). The following analysis of settled sludge were carried out: total solids (TS) (drying at 105°C), total volatile solids (TVS) (drying at 550°C), sludge volume index (SVI) (determined by measuring the volume occupied by sludge sample in a measuring cylinder following 30 minutes of settling). Capillary suction time (CST) was measured by passing a 20 mL sample through the CST device and recorded the time for the sludge to travel through the filter paper. Centrifugal settleability index (CSI) was measured by centrifuging 50mL of sludge at

3,500 rpm for 15 minutes; suspended solids concentrations were determined in both the initial sludge and in the resulting centrate (Sammer et. al., 90). The mathematical expressions for SVI and CSI are:

$$SVI\ (mL/g) = \frac{SV}{MLSS} \times 100\ mg/g$$

where SV: volume of settled solid in 500-mL graduated cylinder after 30 minutes settling

MLSS: mixed liquor supernatant solids concentration

$$CSI\ (\%) = \frac{Co - Cc}{Co} \times 100\%$$

where Co: initial sludge suspended solids concentration (mg/L)

Cc: supernatant suspended solids concentration (mg/L)

6.2.2.4 Determination of optimum dosage by removal efficiency (%)

The removal efficiency, which is defined as the percent of a parameter such as SS removed after the sedimentation process, is calculated as follows:

$$: \frac{SS\ \text{in raw sewage} - SS\ \text{in chemically-dosed sewage supernatant}}{SS\ \text{in raw sewage}} \times 100\%$$

6.3 Sludge characterization

6.3.1 Overall objectives

The purpose was to perform a detailed characterization on raw, digested and CAPS sludge collected from three STPs in Hong Kong. Also, an attempt was made to compare the different physical and chemical properties between chemically-treated sludge and the biologically-treated sludges.

6.3.2 Method

6.3.2.1 Physical analysis

Follows the methods described in section 6.2.2.3. (p.32)

6.3.2.2 Chemical analysis

The extractable nitrate, ammonia and phosphate were analyzed by D. I. extraction followed by UV-spectrophotmetric method, 6% KCl extraction followed by Indophenol-blue method and 2.5% HoAc extraction followed by stannous chloride method, respectively. Total N, P and K and heavy metals were analyzed by the method described in section 6.2.2.3.

The different phases of heavy metals in the sludge were determined by sequentially extracting the samples with 1M KNO_3, 0.5M KF, 0.1M $Na_4P_2O_7$, 0.1M EDTA and 6M HNO_3. After shaking with each extractant for 16 hours, the solution was centrifuged at 4,000 rpm for 10 minutes and then filtered. The remaining residue was washed twice with

D. I. before extraction with other extractants (Pun et. al., 95). The heavy metal contents (Cd, Cr, Cu, Ni, Pb and Zn) were analyzed using an Atomic Absorption Spectrophotometer (AAS). Triplicate samples were performed for each measurement. The forms that are extracted by KNO_3, KF, $Na_4P_2O_7$, EDTA and HNO_3 are, respectively, exchangeable, adsorbed, organically-bound, carbonate-bound and sulphide-bound phase.

6.4 Chemical Stabilization of Sludge

6.4.1 Overall objectives

The purpose was to investigate the effect of stabilization of CAPS sludge with PFA and CaO on the heavy metal and bacterial contents as well as other chemical properties. It is expected that sludge treated in this way will have better characteristics, particularly with respect to its disposal, than mechanically dewatered raw sludge.

6.4.2 Method

6.4.2.1 Preparation of stabilized samples

Stabilized samples were prepared by manually mixing the sludge, PFA and anhydrous calcium oxide (CaO, AR grade) until a homogenous mass was obtained. The mixed samples were then placed in containers without lids for curing inside the laboratory. The mixed proportions of the samples prepared for the investigation are shown in Table 6.4.1.

Table 6.4.1 : Mixing proportions of the different mixutres

Sample	Proportion (wet weight basis)		
	Sludge	PFA	CaO
A	6	3.5	0.5
B	6	3.8	0.2
C	7	2.5	0.5
D	7	2.8	0.2
E	6.5	3.0	0.5
F	6.5	3.3	0.2
G	6.5	3.5	0
H	7	3.0	0
I	7.5	2.5	0
J	10	0	0

6.4.2.2 Physical analysis

After 48 hours, the dry solid contents of the mixed samples were determined according to the Standard Methods (APHA). pH was measured by pH electrode using solid: deionized water at 1:5 (w:v). Two of the mixtures (which achieved both elevated pH level and solid content) and the raw sludge were chosen for further experimental study. A number of analysis were carried out on the 3 samples (one sample was with PFA and CaO , the other one with PFA only and finally, the raw sample) . Total coliform counts were performed in accordance with the Standard Methods' (APHA) most probable number method. The coliform count was determined at 48 h after treatment.

6.4.2.3 Chemical analysis

The USEPA TCLP method was used to assess the leaching of heavy metals from the raw and stabilized sludges. The sludge samples and PFA were extracted with an amount of extraction fluid (dilute acetic acids at pH 2.8) equal to 20 times the weight of the samples in a rotary extractor device for 18 hours. The mixture after extraction was then filtered and the pH of the filtrate was adjusted to below 2, and analyzed for metals (Cu, Zn, Ni, Cd) by an AAS. Multiple extraction, in which fresh portions of the extraction fluid was used to extract the leached samples, was carried out to assess the change of metal leaching upon subsequent extractions. A total of five extractions were carried out.

The different phases of heavy metals, extractable nitrate, ammonia and phosphate in the sludge samples were determined by methods decribed in Section 6.3.2.2. Total N, P, K and heavy metals were measured following the methods in Section 6.2.3.2.

6.5 Plant Bioassay

6.5.1 Overall objectives

The whole experiment was divided into 2 series. In Series I, 3 different sewage sludge samples were stabilized with PFA and CaO, and the stabilized samples were mixed with a sandy soil at different proportions. The inhibitory effect of the various stabilized sludge amended soil mixtures on the early development of two edible crops were studied. Besides, the effect of stabilized sludge-amended soil mixtures on the long term growth of a grass were studied. In Series II, the first part was to investigate the effect of various application rates on grass growth whereas the second part evaluate the effect of different mixing proportions of PFA/CaO on planting grass. Also, an attempt was made to compare the different effects of PFA stabilized CAPS sludge and PFA plus CaO stabilized on plant growth.

6.5.2 Method

6.5.2.1 Preparation of stabilized samples

Series I: The stabilized samples were prepared by manually mixing the sludge, PFA and CaO until a homogenous mass was obtained. The mixing ratio for sludge, PFA and CaO was 6: 3.5: 0.5 on a wet weight to weight basis, following the method developed by Poon & Boost (96). The mixed samples were then placed in an outdoor covered environment for 4 weeks. The stabilized sludge mixtures were then thoroughly mixed with the soil manually at proportions equivalent to 2.5, 5, 10 and 20% (v/v) of the final amended soil content.

Series II: In the first part, 2 stabilized samples, one with PFA and CaO (sludge: PFA: CaO = 6.0:3.5:0.5)and another with PFA only (sludge: PFA = 6.5:3.5) were prepared on a wet weight to weight basis. The mixed samples were cured for 4 weeks and then thoroughly mixed with the hillside soil manually at the rates equivalent to 2.5, 5, 10 and 20% (v/v). The notations for the 8 mixutres prepared are shown in Table 6.5.1. In the second part, 8 stabilized samples with different proportions of sludge, PFA and CaO were prepared . The samples were cured for 4 weeks and then mixed with the soil manually at a rate equivalent to 10% (v/v). The components of the different stabilized sludge amended soil mixtures are listed in Table 6.5.2.

Table 6.5.1 : Application dosage of stabilized sludge samples in Part I experiment

Stabilized sludge	Code	Stabilized sludge: soil
SPC	SPC 2.5	0.25:9.75
(Sludge+PFA+ CaO)	SPC 5	0.5:9.5
	SPC 10	1.0:9.0
	SPC 20	2.0:8.0
SP	SP 2.5	0.25:9.75
(Sludge + PFA)	SP 5	0.5:9.5
	SP 10	1.0:9.0
	SP 20	2.0:8.0

Table 6.5.2 Mixing proportions of stabilized samples in Part II experiment

Code	Sludge:PFA:CaO	Code	Sludge:PFA
SPC 50	5.0: 4.5: 0.5	SP 50	5.0: 5.0
SPC 60	6.0: 3.6: 0.4	SP 60	6.0: 4.0
SPC 70	7.0: 2.7: 0.3	SP 70	7.0: 3.0
SPC 80	8.0: 1.8: 0.2	SP 80	8.0: 2.0

6.5.2.2 Chemical analysis of samples and amended soil mixtures

Samples of PFA, soil, raw sludges, stabilized sludges and different sludge amended soil mixtures were ground to pass through a 2-mm sieve before chemical analysis. pH, extractable nitrate, ammonia and phosphate, extractable and total Cu, Zn, Pb, Ni, Cd and Cr, total N, P and K were measured by the methods described in Section 6.2.2.3. Extractable B was extracted by HoAc and determined by the Azomethine-H method (Page et. al., 82).

6.5.2.3 Short-term plant growth experiment

Two edible crops, Chinese radish (*Raphanus sativus*) and barley (*Hordeum vulgare*) were used as the test plants. Seeds were first pregerminated in petri dishes lined with moistened filter papers in the laboratory for 48 hours. Only those with a root tip length 2cm length were chosen for the experiment. 100g of each amended soil mixture was placed in 8 Oz foam cups. The foam cups were perforated with 8 holes of diameter 3mm to avoid waterlogging. The sandy soil alone was used as the control. 10 germinated seeds were transplanted into each cup and the cup was watered to its field capacity with deionized water. All the cups were placed in random order in the laboratory with a temperature of 20± 3°C and relative humidity of 68-75% for 7 days. The plants were watered daily with deionized water to eliminate any trace of heavy metal in tap water. At the end of the growth period, the plants were carefully removed from the soil and the number of seedlings, the root and shoot length were recorded.

6.5.2.4 Long term plant growth experiment

Series I: The test plant used was a tall wheat grass (*Apropyron elongatum*). Approximately 1 kg of the amended soil mixtures were placed in stainless steel boxes of 12" x 6" x2" (length: width : depth). The boxes were perforated with holes to avoid waterlogging. Duplicate set-ups were used for each dosage treatment. The sandy soil alone was used as the control. 300 seeds of the grass were sown on the surface of the soil mixtures for each treatment. The soil was then watered to its field capacity with water. All the containers were placed at an outdoor environment with a temperature of 25 - 32°C and relative humidity of 78 - 96% for 6 weeks. The plants were watered daily and carefully removed from the soil after 6 weeks.

Series II: The amended soil mixtures were placed into pots of 11-cm in diameter. 150 seeds of tall wheat grass were sown into each pot. There were duplicate set- up for each treatment. The hillside soil alone was used as the control. The soil was then watered to its field capacity with water. All the pots were placed at outdoor environment with a temperature of 26 - 30°C and relative humidity of 68 - 85 % for 6 weeks. The plants were watered daily and carefully removed from the soil after 6 weeks.

6.5.2.5 Chemical analysis of grass materials

At harvesting, the plants were washed with tap water to remove any attached particles and then rinsed twice with deionized water. The shoot and root were separated and oven-dried at 70°C for 72 hours. The dry weight yields of root and shoot were recorded. The plant tissues were cut into pieces and grinded by an electric cutter and then ground through a

2mm sieve for chemical analysis. Total N, P and K and total Cu, Zn, Pb, Ni, Cd, Cr and B were determined by the methods described earlier. All the measurements were done in triplicates.

6.6. Lysimeter tests

6.6.1 Approach

To simulate sludge landfilling as it is commonly practiced, the experimental design included laboratory-scale lysimeters (column) filled with sludges and/or shredded paper. Conceptually, each lysimeter acted as an independent landfill, operated under anaerobic conditions. The objectives of this experiment were to monitor and evaluate leachate and gas release from sludge landfilling, operated under the following conditions:

1. Landfills receiving anaerobically digested sludge versus those receiving CAPS sludge
2. Landfills receiving ash/lime stabilized sludge versus those receiving raw sludge
3. Landfills receiving sludge only versus those receiving municipal solid waste (paper) and sludge

6.6.2 Materials

The characteristics of the samples incorporated into the 7 columns were:

Column 1: Dewatered, raw CAPS sludge from SC STP

Column 2: Dewatered, digested sludge from TP STP

Column 3: PFA & lime stabilized CAPS sludge (sludge: PFA: lime = 6.0:3.5:0.5, w/w)

Column 4: PFA & lime stabilized digested sludge from TP STP

Column 5: PFA stabilized CAPS sludge (sludge:PFA = 6.5: 3.5, w/w) plus paper

Column 6: PFA & lime stabilized CAPS sludge plus paper

Column 7: Paper plus raw CAPS sludge (paper: sludge = 1:20, w/w)

For the stabilized samples, PFA, lime and sludge were manually mixed until a homogenous mass was obtained. The mixtures was then placed in an open environment in the laboratory for 4 weeks for curing. Waste white printing papers were collected from the general office of the Department of CSE and cut into small pieces with size less than 5mm^2 by a paper-shredding machine.

6.6.3 Methodology

6.6.3.1. Column design

The 7 identical laboratory-scale columns, as shown in Fig 6.6.1 & Photo 3, were designed with the principle of providing durable, acid resistant and gas-tight containers for simulating the waste decomposition processes occurred in landfills. The columns were made by 10 mm thickness of PVC sheets and stainless screws, and all the joints were sealed by silicon sealant to avoid any gas or leachate leakage. Each column had two chambers separated by a PVC solid-liquid separator. The upper chamber contained waste samples whereas the lower one stored leachate emanated from the wastes. The columns were supported by a specially built steel stand for easy sampling of leachate.

Gas generated during the decomposition process automatically flowed into the sample bags via a gas valve on the top of each lysimeter (Photo 4). There was another opening used as water inlet for irrigating purposes. Leachate was drained through the water-outlet at the bottom of the column.

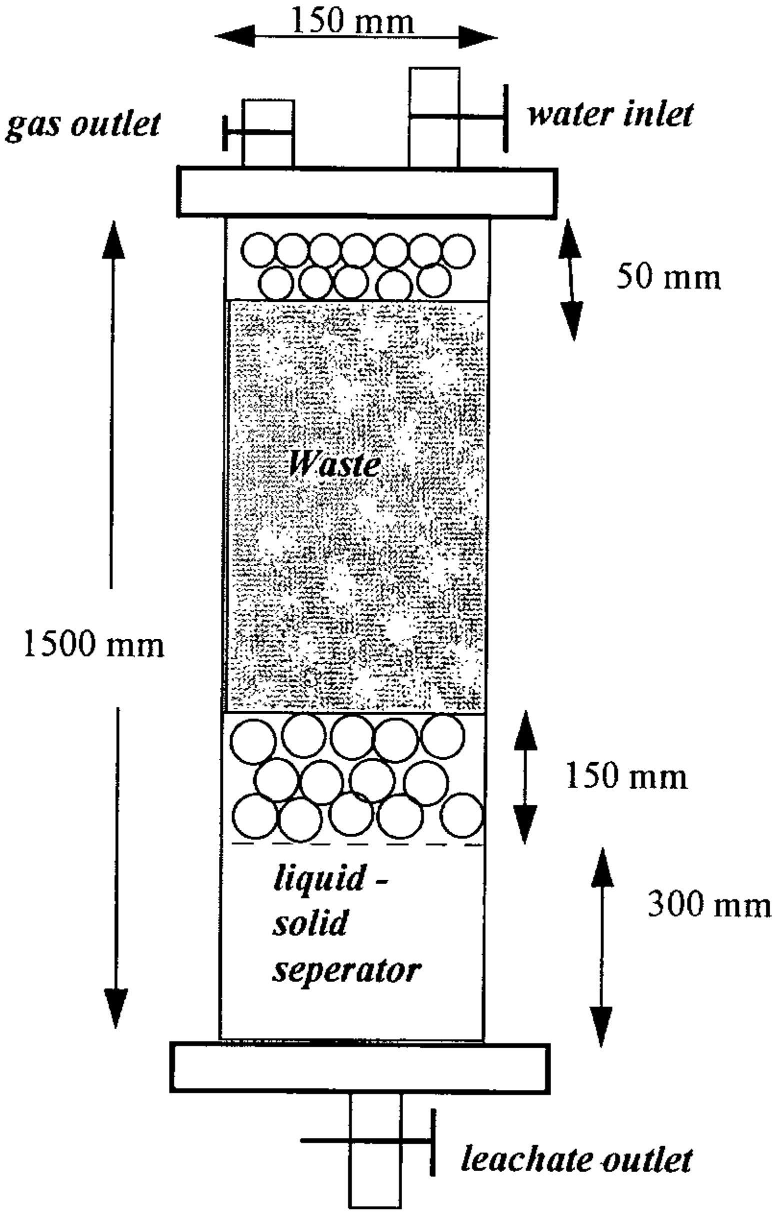

Fig. 6.6.1 : Experimental Column

6.6.3.2. Column loading

Before filling the column with waste samples, pebbles which had passed through a 2-cm sieve were packed to a height of 150 cm above the solid-liquid separator. This was to ensure the even drainage of leachate. The pebbles were carefully rinsed with D. I. water for two times to discard any silt and dirt which might affect the quality of leachate. Then, well-mixed sludge and waste samples were slowly loaded into the columns with hand compaction by a PVC object in between to avoid liquid short circulating. In case for co-disposal of two waste samples, the column was filled with alternating layers of waste to 1:1 volume to volume basis (say sludge first, followed by paper, and then sludge, and so on). Finally, another patch of pebbles (screened by a 1-cm sieve) were packed on top of the waste for better distribution of inlet water.

6.6.3.3 Column irrigation

The columns were irrigated at a rate approximately equivalent to the average local rainfall rate of 2000 mm/ year. This simulated the "worst case" situation since processes such as runoff, evaporation and evapo-transpiration would render actual landfill infiltration rates less than rainfall rates. The daily liquid additions required to achieve an equivalent irrigation of 2000 mm/year is:

$\{ [\pi (15/2)^2] \times 200 \} /365 = 97$ cm^3/day (Binnie, 86)

A standard volume of 100 cm^3/day of D.I. water was therefore used to irrigate the columns. Starting from week 6, to promote the decomposition rate, few drops of concentrated H_2SO_4 was added to D.I. to adjust the pH to between 5.6-6.0 before irrigation. This simulated the slight acidity of the rain falling into Hong Kong environment.

6.6.3.4 Leachate collection and analysis

In the first month after filling the columns, leachate was collected from the column outlets into plastic containers for analysis every week. From week 5 onwards, analysis was done every two weeks. The following parameters were measured: pH, total organic carbon (TOC) and total inorganic carbon (TIC) (measured by Astor 2001TOC analyzer), total Cu, Ni, Pb, Zn ,K (H_2O_2-H_2SO_4 digestion followed by AAS) and total N (H_2O_2-H_2SO_4 digestion followed by indophenol-blue method). In order to minimize any changes in leachate quality, pH, TOC and TIC were done immediately after sample collection. Acid digestion was carried out within 3 days.

6.6.3.5 Gas analysis

The gas production by the columns was very slow. After 35 weeks of running of the column, the composition of the gas produced was measured by a landfill gas analyzer (LFG-20, manufactured by Analytical Development Company Ltd.).

CHAPTER 7: RESULTS & DISCUSSION

7.1. Chemically Assisted Primary Sedimentation Process

7.1.1. The effectiveness of polyaluminum chloride (PACl), ferric chloride ($FeCl_3$), lime and polyferric sulphate (PFS) on suspended solids (SS) and turbidity removal

As a preliminary screening, 4 inorganic coagulants were added to the raw sewage collected from Sha Tin (ST) STP individually. The dosages used were 20, 50, 100 ,250 and 500 ppm. From *Fig. 7.1.1*, the dosages of $FeCl_3$ and PACl for achieving the highest percentage of SS removal were 250 ppm while that for PFS was 100 ppm, respectively. For lime, the highest SS removal has not been reached yet. In terms of relative efficiency, PACl seemed to perform the best among the coagulants because a dosage of 100 ppm could achieve more than 80% SS removal. After the optimal dosage, any further increase would cause a drop in SS removal efficiency for all the coagulants (except lime). This is the so-called overdosing phenomenon. As regards turbidity (*Fig. 7.2.2*) , $FeCl_3$ produced the worst performance whereas PACl performed the best at low dosages (50 ppm). The trend for the various coagulants were more or less similar to that of SS removal efficiency. Another interesting phenomenon was that PACl could give good performance over a wider dosage range than the other coagulants. This implies that coagulation with PACl is far less sensitive to variations in raw sewage composition than the traditional coagulants which need to function in a very narrow dosage range in order to get good results. It was well documented that the advantages of PACl over simple salts were higher removal of particles, reduced need for neutralizing agents, active over a wide pH range and reduced sludge generation (Letterman, 82; McKeen, 87; Heinzmenn, 91; Jiang, 93).

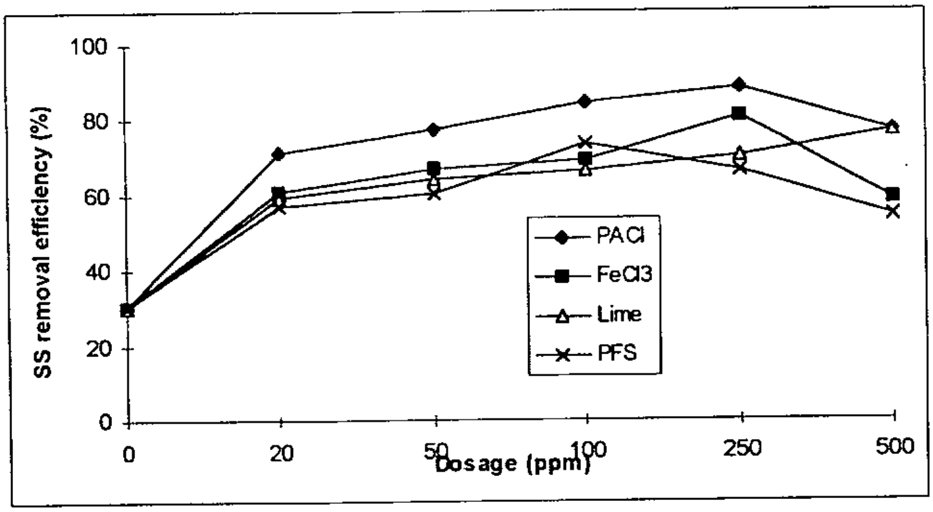

Fig. 7.1.1: SS removal efficiency by PACl, $FeCl_3$, lime and PFS (influent from ST STP, SS conc.: 290 ppm)

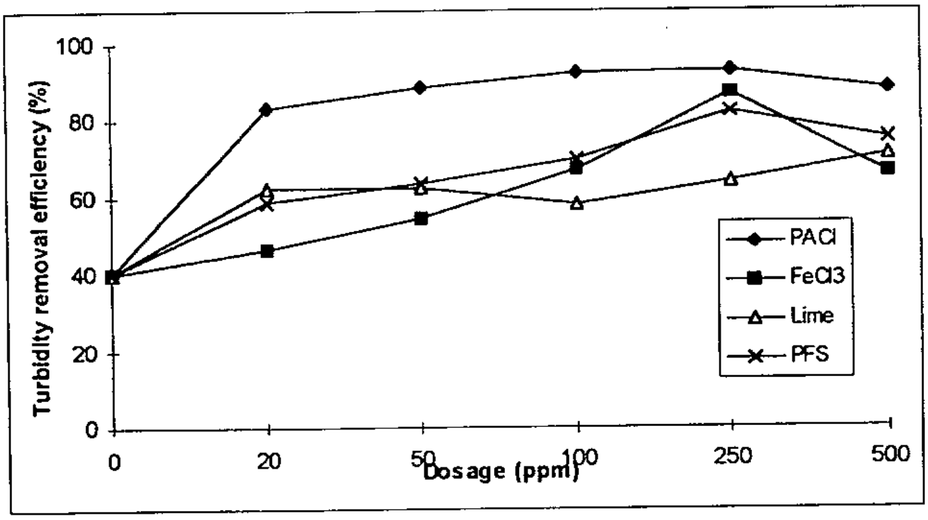

Fig. 7.1.2: Turbidity removal efficiency by PACl, $FeCl_3$, lime and PFS (influent from ST STP, turbidity: 250 NTU)

Gillberg et. al. (90) compared the performance of aluminum sulphate, PACl and $FeCl_3$ on removal of turbidity, COD and SS and found out that PACl was most effective. This is consistent with my findings. The superior performance of PACl might be due to its abundant cationic aluminum polymer sites for the coagulation process. When comparing the performance of $FeCl_3$ and lime, the Drainage Services Department (94) reported that $FeCl_3$ was better in terms of TSS, COD, BOD and E-coli removal.

7.1.2 The effect of SS concentration of influent raw sewage on SS removal

It was found that the coagulation efficiency of the same coagulant changed with the variation of wastewater samples. The number of wastewater particles was believed to be one of the most important factors governing the coagulation process. It could be seen from Fig. 7.1.3 that the efficiency of $FeCl_3$ to remove SS varied with the original SS concentration of raw sewage. When using 20 ppm of $FeCl_3$, the SS removal efficiency increased with the increase in SS concentration of raw sewage. Besides, the efficiency of using 20 ppm of $FeCl_3$ in the sewage containing 371.5 ppm SS was even better than that using 60 ppm $FeCl_3$ in the sewage containing 210.5 ppm SS. Thus, it could be concluded that SS removal efficiency of $FeCl_3$ was dependent on the concentration of SS of the influent sewage. It is reasonable as the coagulation process relies mainly on the collision frequency between the coagulant and wastewater particles. Dempsey (88) described the physical removal of contaminant particles from water by the following equation: $dN/dt = -\alpha kN^2$ where N was the number of particles, α was the fraction of successful collision and k was the mixed rate constant. As a result, when the influent SS is high, more wastewater particles will be available for reactions with the coagulant particles.

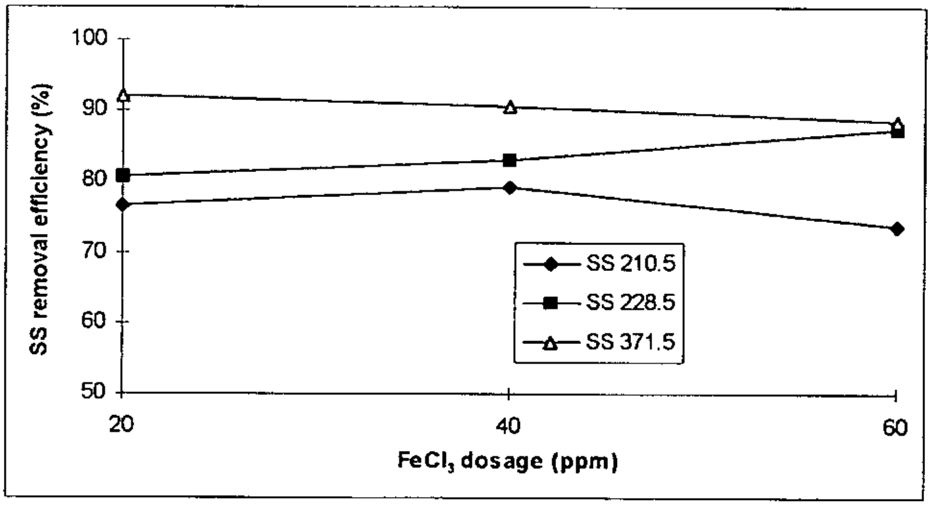

Fig. 7.1.3: SS removal efficiency by $FeCl_3$ in sewage with different SS concentration (influent from ST STP)

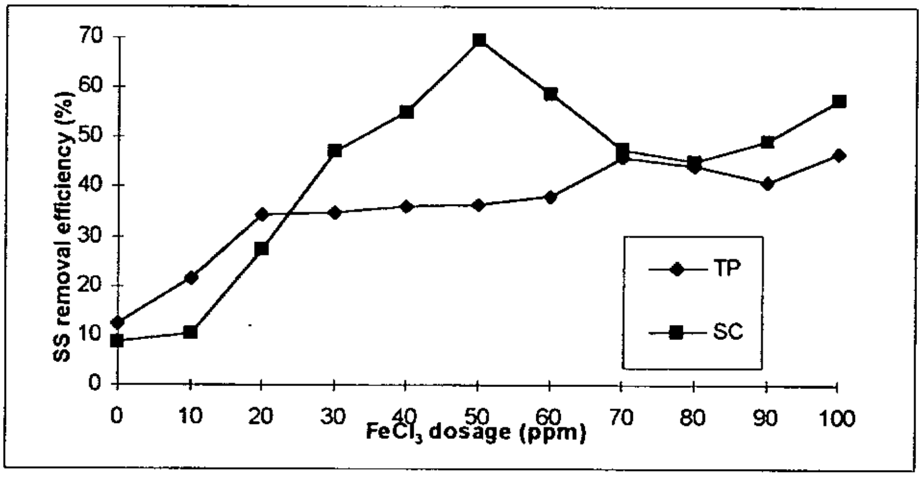

Fig. 7.1.4: SS removal efficiency by $FeCl_3$ in TP and SC sewage (influent SS of TP : 289 ppm, SC: 450 ppm)

7.1.3 The optimum dosage of $FeCl_3$ and Magnafloc 1011 in SS removal

The performance of the coagulants and polymers were studied by another series of jar tests to determine their optimum application dosage. From Fig. 7.1.4, it can be seen that for both sewage samples, under the experimental conditions the increase in dosage of $FeCl_3$ up to 100 ppm alone could only achieve a SS removal efficiency to up to 50 %. One of the possible reasons to account for the low SS removal was that pH was not controlled. Another explanation was that a higher dosage or a longer settling time might be needed for its full action. Besides, the inconsistent SS removal efficiency reported in Figs. 7.1.3 & 7.14. from ST and SC STPs indicated that apart from influent SS concentration, other wastewater characteristics such as the presence of different organic compounds and humics might affect the process.

Coagulation with ferric salts involves three steps (Dentel, 91): (i). destabilisation begins after the operational solubility limit of iron hydroxide has been exceeded, (ii). iron hydroxide species are then deposited onto the colloidal surfaces; (iii). under typical conditions, the iron hydroxide is positively charged, while the original colloidal material or particles are negatively charged. The deposition process thus can lead to charge neutralisation or charge reversal at certain doses. Besides, it was found that the SS removal efficiency with SC sewage was generally higher than that of TP sewage. This was probably due to the fact that the coagulation process was dependent on the original concentration of SS of the influent sewage.

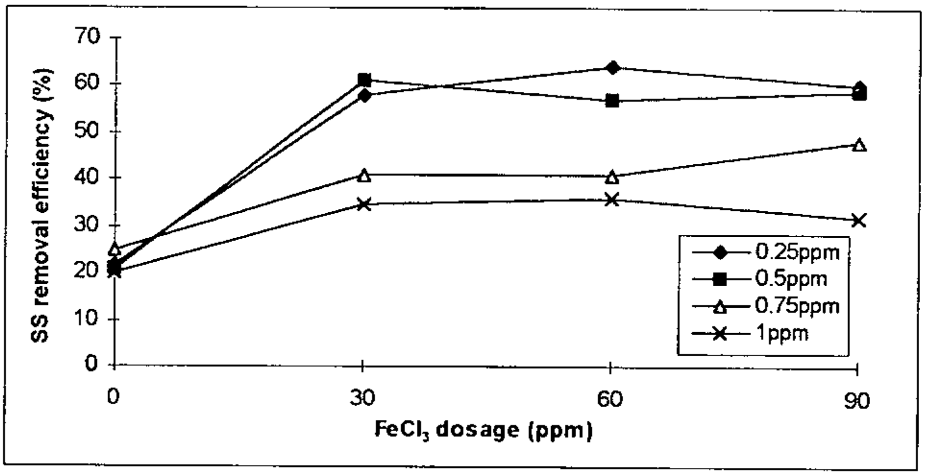

Fig. 7.1.5: SS removal efficiency by $FeCl_3$ & Magnafloc 1011 in TP sewage

The effect of adding the polymer (Magnafloc 1011) together with $FeCl_3$ on SS removal are shown in *Fig. 7.1.5* and *Fig. 7.1.6*. When the polymer was added as a primary coagulant (no $FeCl_3$ was added), there was no significant difference in SS removal efficiency when different concentrations of polymer were added. When the polymer was added as a secondary coagulant (i.e. after $FeCl_3$ coagulation), dosages as low as 0.25 and 0.5 ppm of polymer could achieve more than 60% SS removal. Further increase in the dosage did not improve but decrease the removal efficiency. Again, this can be attributed to overdosing. One of the most likely actions of this anionic polymer was that it bridged the ferric ions and by the formation of insoluble polyacrylate salts which led to enhanced destabilisation (Dentel, 91) . The results showed that for nearly all polymer dosages, $FeCl_3$ dosage higher than 30 ppm caused no significant change in SS removal efficiency. Thus, 30 ppm of $FeCl_3$ was chosen for the subsequent experiment. Though jar test can be used to determine the optimum dosage of coagulants, it is noted that the dose required in the pilot or the full-scale plants are usually 10 -25% less than those found in the jar test

(Singh, 85). Above all, when $FeCl_3$ costs approximately $ 5,000 per metric ton dry weight and polymer costs nearly $ 26,000 per metric ton, it is more economical to use a lower dosage in actual plant operation (Kukregja, 98). This explain why in the actual operation of CAPS plant on SC, 10 ppm of $FeCl_3$ and 0.1 ppm of anionic polymer were used. Besides, other parameters such as sewage flow rate, fluid residence tiems, loading rates as well as coagulant feeding rate in the actual STP can also account for the difference between the dosing of coagulants in jar tests and sewage teatment plant operation.

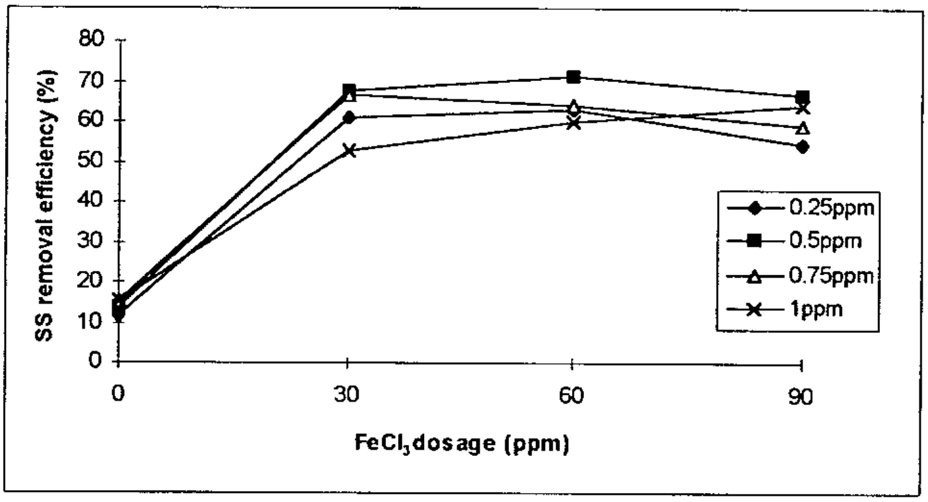

Fig. 7.1.6: SS removal efficiency by $FeCl_3$ & Magnafloc 1011 in SC sewage

Table 7.1.1: Results of SS, N & P removal by $FeCl_3$ and polymer

Coagulant used	Removal Efficiency (%)					
	SS		N		P	
	TP	*SC*	TP	*SC*	TP	*SC*
Control	25.26	*30.99*	12.30	*24.40*	12.30	*26.00*
$FeCl_3$ 30 ppm	53.77	*60.87*	55.85	*65.50*	36.60	53.50
$FeCl_3$ 30 ppm + Polymer 0.25 ppm	77.03	*73.87*	**84.09**	*77.40*	31.40	***59.50***
$FeCl_3$ 30 ppm + Polymer 0.5 ppm	**82.19**	*86.94*	77.88	*67.00*	**44.70**	*46.90*
Polymer 0.5 ppm	26.14	*28.97*	31.10	*25.70*	12.10	*19.10*

7.1.5 The characteristics of settled sludge generated by CAPS in the large scale test

Different combinations of coagulants and polymer will produce various types of floc which settle to form the sludge after the sedimentation process. In the large scale test, the settled sludge collected was physically and chemically characterized. From Table 7.1.1., it can be seen the addition of $FeCl_3$ resulted in a better removal efficiency of N & P than the unassisted sedimentation process (control). The results reveal that 30 ppm of $FeCl_3$ with 0.5 ppm of polymer could remove about 80% of SS, 70% of total N and 40% of total P. The higher SS removal efficiency achieved in the large scale test than the jar test was probably due to the larger sewage volume with more uniform wastewater characteristics. It might also be probably that the spatial variation of velocity gradients within the two type of containers were different. In fact, it was reported by other researchers that the flocculation results would not be identical on different containers (Dentel, 91). In terms of phosphorous removal, it has been stated that chemical precipitation using aluminium and iron coagulants is effective (Girovich, 96). For its removal the primary action may be the reaction of the orthophosphate with the metal cation. The possible reaction converting phosphorous from wastewater into the forms found in CAPS sludge is $FeCl_3$ + PO_4^{3-} = $FePO_4$ + 3 Cl^-. Polyphosphates and other organic phosphorous compounds may also be removed by being entrapped, or adsorbed in the floc particles (Hammer, 86). The results also show that at the optimal dosage, the removal of N was very prominent. One possible explanation is that together with the removal of SS, the amine group of the organic polymer tends to form stable complexes with the organic-N compound of wastewater. For comparison, the typical removal efficiency of N and P by some biological processes (IWEM, 94) are summarized in Table 7.1.2.

Table 7.1.2: Typical P and N removal efficiency for different biological treatment processes

Nutrient	Biological Process	% removal
P	Biological filters	10-15
	Activated-sludge	20-40
N	Single-stage denitrification	70
	Multi-stage Bardenpho	80

The characteristics of the settled sludge produced by the addition of $FeCl_3$ with polymer was further characterized. From Table 7.1.3, it can be seen that the solid content of sludge increased after the addition of coagulants. This was due to the better SS removal efficiency by chemical coagulation. The government policy, however, states that the solid content of sludge for disposing in landfill must be above 30% by weight. Thus, further dewatering and conditioning must be carried out on the liquid sludge to fulfill disposal requirements.

CST is a common technique for expressing the dewaterability of sludge. A large CST value implies poor sludge filterability (Chen, 96). The results showed that the addition of coagulants greatly improved the filterability of the settled sludge. It was because when coagulants were added, wastewater particles began to coagulate which caused the coagulated sludge in suspension and increased the rate of water flow. Thus, CST value should drop with the increase in coagulation efficiency. In other words, CST was dependent on the solid concentration of the settled sludge. This was consistent with my findings that the higher the solid content, the lower the CST value in the sludge. SVI is another simple parameter for characterizing sludge thickening properties. It was stated that a sludge with a SVI of less than 100 mL/g was considered a well settling sludge, whereas one with a SVI greater than 100 was often troublesome (Vesilind, 87). In fact, a poorly-settled sludge may cause serious bulking problems in the final settling tanks. It was revealed that the chemical dosed sludge was not well settled. This could be attributed to the polymer which increased the settling velocity of the wastewater particles by bridging.

Table 7.1.3: Characteristics of settled sludge with different coagulant dosages

Coagulant used	Solid Content (%)	CST (s)	SVI (mL/g)	CSI (%)	Cu (mg/L)	Zn (mg/L)	Ni (mg/L)
Control	1.87	120	67.9	87.03	1.85	2.20	0.35
$FeCl_3$ 10 ppm + polymer 0.1 ppm	2.28	49.5	108.9	50.67	4.60	3.85	1.05
$FeCl_3$ 30 ppm + polymer 0.5ppm	2.64	37.3	123.5	42.83	4.95	4.15	1.25

Regarding CSI, a small CSI value corresponds to good sludge dewaterability (Sammer, 90) . The result of the present study shows that the sludge produced by the chemically assisted sedimentation process had better dewaterability than that of unassisted sedimentation process. Concerning heavy metals content, their concentrations were also higher in the chemically modified sludge than in the control sludge. From the above result, it could be seen that the addition of coagulants in the sedimentation process would generally improve the physical characteristics of the sludge produced. However, there was no significant differences in properties between the two types of sludge which received different chemical dosages. This can explain why a lower chemical dosage is chosen in the actual operation of the plant when cost is taken into consideration.

7.2 Sludge Characterization

7.2.1 Physical properties

TS and TVS are widely used in sludge treatment and management practices as measures of dry matters and organic matters in sludges. From Fig. 7.2.1, it can be shown that more than 60% of the solids was in the volatile fraction in all the sludge samples (except digested YL). This implies that a large proportion of the solids is of organic nature. According to a review of sewage sludge treatment in Hong Kong (Aggarwal et. al., 91), the primary sludge solid concentrations in TP STP and YL STP were about 4% and 2.3%, respectively, whereas that obtained in this experiment were 2.4% for TP and 1.3% for YL. The solid concentrations for the anaerobic digested sludge in 1991 were found to be 2.4 and 2.2% for TP STP and YL STP, respectively, and the corresponding concentrations in this study were 0.9 and 0.6%, respectively.

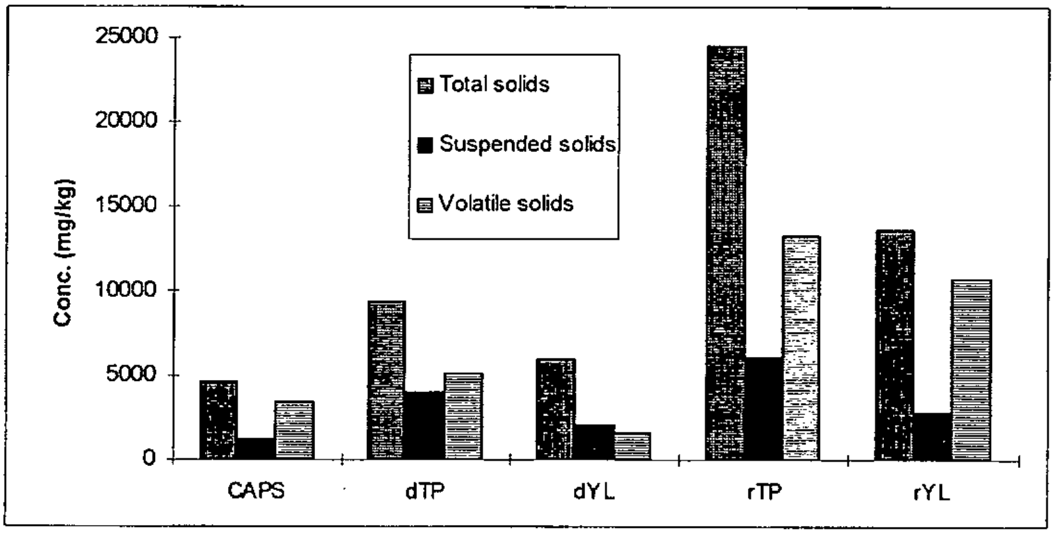

Fig. 7.2.1: Concentrations of total solids (TS), suspended solids (SS) and volatile solids (TVS) in sludge samples (CAPS: sludge from Stonecutters Island pilot plant; dTP: digested sludge from Tai Po STP ; dYL: digested sludge from Yuen Long STP; rTP: raw sludge from TP; rYL: raw sludge from YL) (conc. express in mg/kg sludge on dry weight basis)

CST is a common technique for expressing the dewaterability of sludge. A large CST value implies poor sludge filterability (Chen et. al., 96). The result of Table 7.2.1 shows that CAPS sludge was better than all other sludges in terms of filterability. CST is also useful in screening alternative sludge conditioning agents. With respect to this, it can be seen that the use of ferric chloride as a coagulant in CAPS would produce sludge with good dewaterability.

SVI is another simple parameter for characterizing sludge thickening properties. Vesilind (87) concluded that in activated sludge plants a sludge with an SVI less than 100 ml/g is considered a well settling sludge, whereas one with an SVI greater than 100 is often troublesome. CAPS sludge and digested sludge from YL could meet this criteria. Regarding CSI, a small CSI value corresponds to good sludge dewaterability. In this aspect, CAPS sludge had better dewaterability than the other sludge samples.

Table 7.2.1 The dewaterability properties in sludge samples

	CAPS	rTP	rYL	dTP	dYL
CST (s)	18.9	43.1	48.6	28.1	24.3
CSI (%)	22.72	92.03	79.00	88.00	62.48
SVI (ml/g)	67.56	162.03	339.70	139.37	76.96

(data shown are the mean value of triplicates)

7.2.2 Chemical properties

7.2.2.1 Extractable N & P

The concentrations of extractable nitrate in CAPS sludge was higher than the other sludges (excepted digested TP), as shown in *Fig. 7.2.2*. Besides, CAPS contained a significant higher amount of extractable ammonia and phosphate than the other sludges (except digested YL). This might be due to the different source of wastewater entering the 3 treatment plants but another possible reason was that the chemically assisted process was effective in removing soluble N & P compounds. It was stated that only chemical precipitation using aluminum and iron coagulants or lime was effective in phosphorus removal (Girovich, 96). The reaction converting phosphorous from wastewater into the forms found in CAPS sludge is $FeCl_3 + PO_4^{3-} = FePO_4 + 3Cl^-$. When comparing the raw sludges with the digested sludges, it could be seen that digested TP and YL sludges had higher amounts of extractable NO_3^- and NH_4^+ than their raw counterparts. It is reasonable because during anaerobic digestion, decomposition of nitrogenous organic matter will occur to form ammonical compounds which become dissolved in the liquid phase.

7.2.2.2 Total N, P and K

From *Fig. 7.2.3*, the concentrations of total N and P in CAPS sludge were higher than the other sludge samples (except digested YL). CAPS sludge also contained a significant higher amount of K than others. Sewage sludge usually contains small amount of K (0.02 to 2.5 % dry basis) (Girovich, 96). Thus, when sludge was applied purely as a fertilizer, additional potassium would always need to be added (Sterritt & Lester, 88).

The rich nutrient content of CAPS sludge seemed to make it applicable in agricultural utilization. However, the elevated K concentration would contribute to high conductivity in the treated soil. And this was known to inhibit root growth due to the excessive uptake of salts. Thus, although CAPS sludge compared favorably with artificial fertilizers and other sludge samples, extra care should be needed to counter the salting effect.

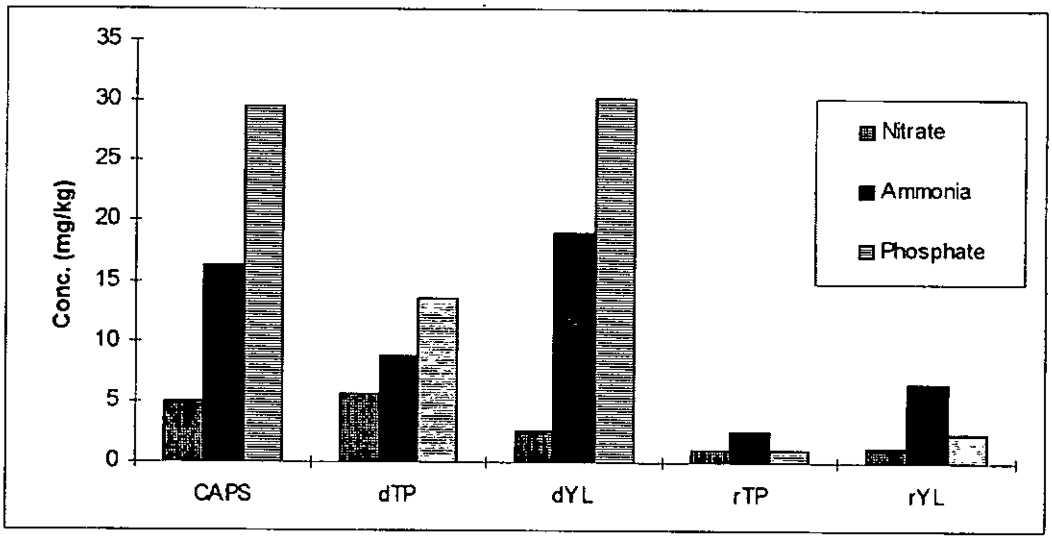

Fig. 7.2.2: Concentrations of extractable nitrate, ammonia and phosphate in sludge samples

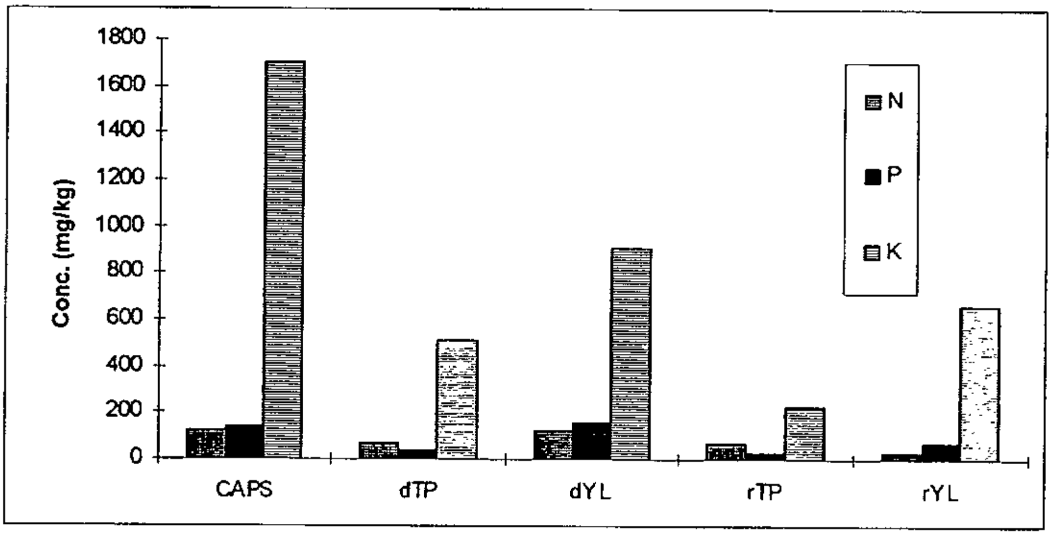

Fig. 7.2.3 : Concentrations of total N, P and K in sludge samples

Besides, it was found that digested sludges contained more nutrients than their raw counterparts. It is reasonable for digested sludges to contain large amount of P which is generally removed from the secondary treatment process. Also, dewatering has a concentration effect on the insoluble compounds. This also explains why raw liquid sludge is seldom used in agricultural purpose.

7.2.2.3 Metal speciations

Most of the Cu in the sludges was in the sulfide phase (except CAPS) while it was least distributed in the adsorbed phase (*Fig. 7.2.4*). Most of the Ni was found in the exchangeable phase in CAPS and YL sludges while the least was in the carbonate phase (*Fig. 7.2.5*). For Cd, the organically bounded phase contained the largest amount (except dYL) while the carbonate phase contained the least amount (except dTP) in all the sludge samples (*Fig. 7.2.6*).

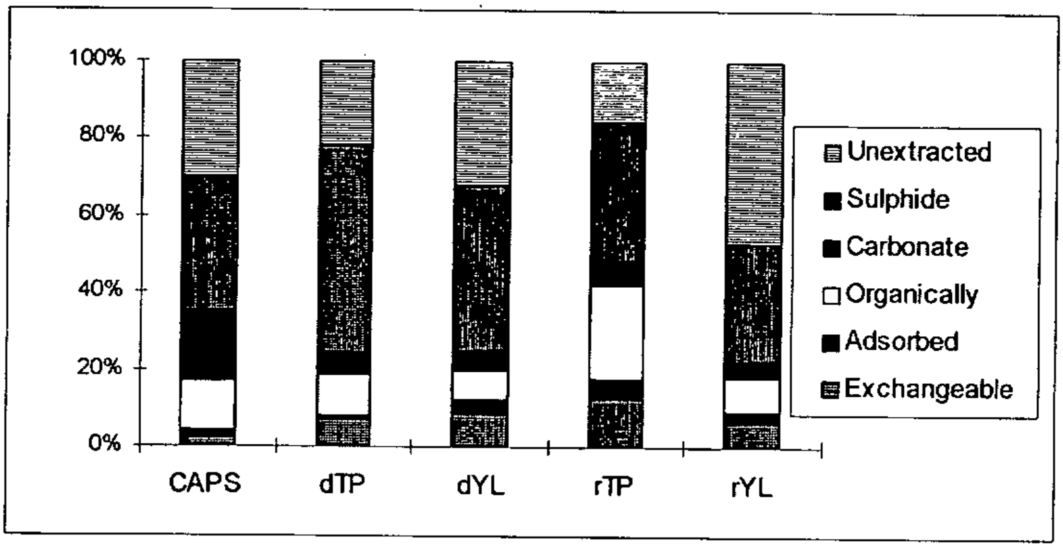

Fig. 7.2.4: Distribution of different phases of Cu in sludge samples

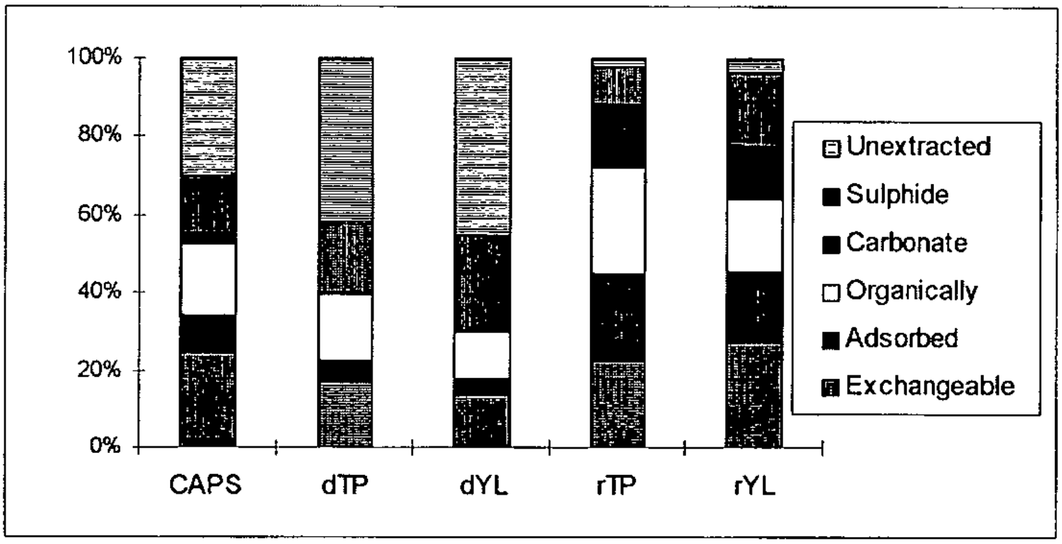

Fig. 7.2.5: Distribution of different phases of Ni in sludge samples

For Pb, it was dominant in the organically bounded phase and exchangeable phase in the digested sludges and the raw sludges, respectively (*Fig. 7.2.7*). As for the case of Cr, it was equally distributed in different phases in the sludge samples (*Fig. 7.2. 8*). Most of the Zn was in the carbonate phase in YL sludges (*Fig. 7.2. 9*). The least amount of Zn was in the exchangeable phase in all sludge samples (except dYL).

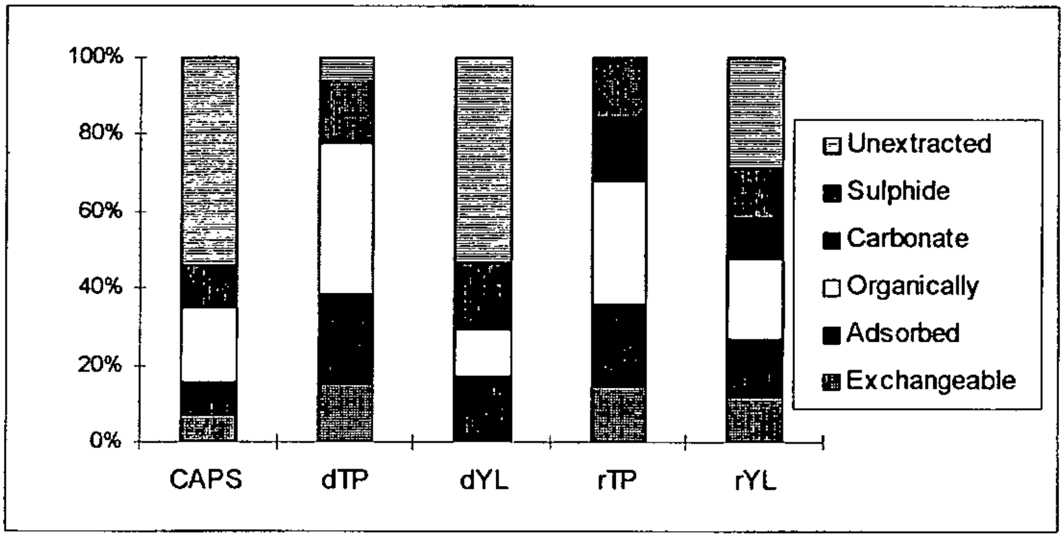

Fig. 7.2.6: Distribution of different phases of Cd in sludge samples

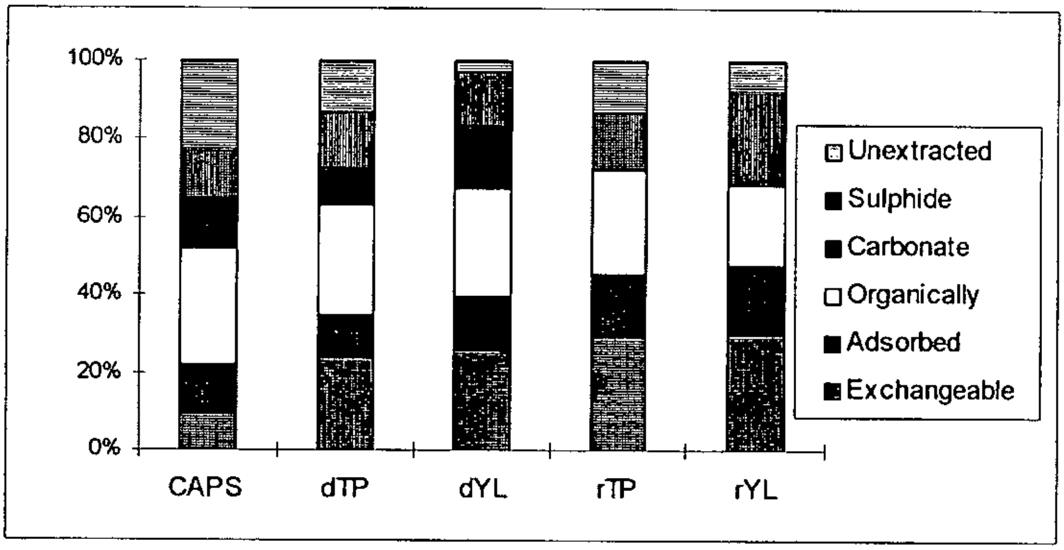

Fig. 7.2.7: Distribution of different phases of Pb in sludge samples

A study on four digested sludges in Hong Kong by Pun et. al. (95) concluded that the major forms of Cu, Pb, Ni and Zn were in the sulfide phase, organically-bound phase, adsorbed phase and carbonate phase, respectively. The dominant phases of Cu and Pb were comparable to that obtained in this experiment. Sterritt & Lester (88) stated that the major forms of Cd and Pb in sludges were carbonates, whereas 56% of Zn was in organic forms, Cu and Ni existed mainly as sulphides and exchangeable forms, respectively. Thus, it can be concluded that the forms of different phases of heavy metals in sludges vary greatly according to the characteristics of wastewater treated and the sludge treatment employed. From my results, when comparing raw and digested sludges, there was a shift from the more available form (exchangeable) to the less available(organically) form of Pb. This was consistent with the finding that during sewage sludge treatment, the metals become less and less easy to mobilize and tended to associate in the reducible and residual phases (Legret, 93). Comparing the CAPS sludge with other sludge samples, higher percentages of the metals (Cd, Pb, Cr and Zn) were associated with the organically-bounded phase. One of the possible explanations was due to the high chelating effects of Fe (III) ions that tended to form stable organic complexes.

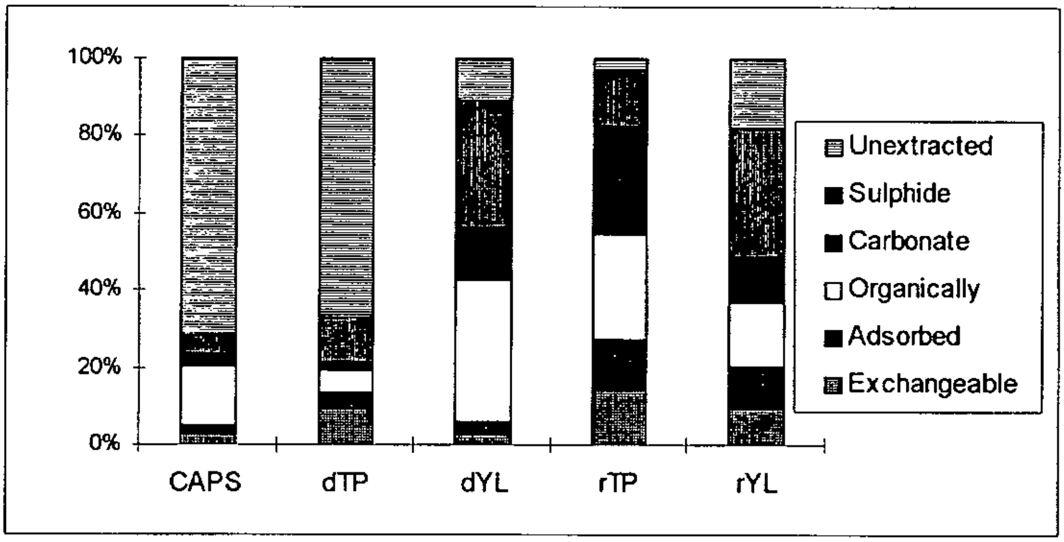

Fig. 7.2.8: Distribution of different phases of Cr in sludge samples

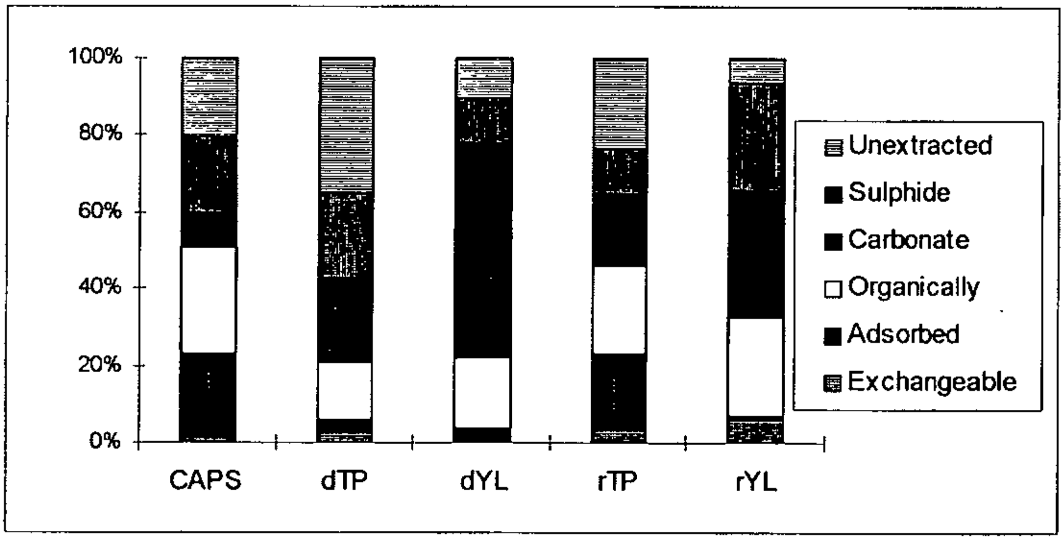

Fig. 7.2.9: Distribution of different phases of Zn in sludge samples

7.2.2. 4 Total heavy metal content

From *Fig. 7.2.10* and *Fig. 7.2.11* , the concentrations of total Cu, Ni, Cd, Pb and Cr in CAPS sludge were significantly higher than all the other sludges. The Stonecutters Primary treatment works is designed as the Stage I SSDS which dealt with the 'worst first' pollution problem (EPD, 95). The source of sewage includes a large proportion of industrial effluent generated in western Kowloon. The primary treatment process is enhanced by the addition of ferric chloride to reduce bacteria and heavy metal levels. These are probably the reasons to account for the high metal contents in CAPS sludge. On the other hand, the industrial wastes from electroplating factories in YL area contribute to the significant amount of Zn in YL sludges but all heavy metal concentrations are within the range reported in typical wastewater sludge (EPA, 94).

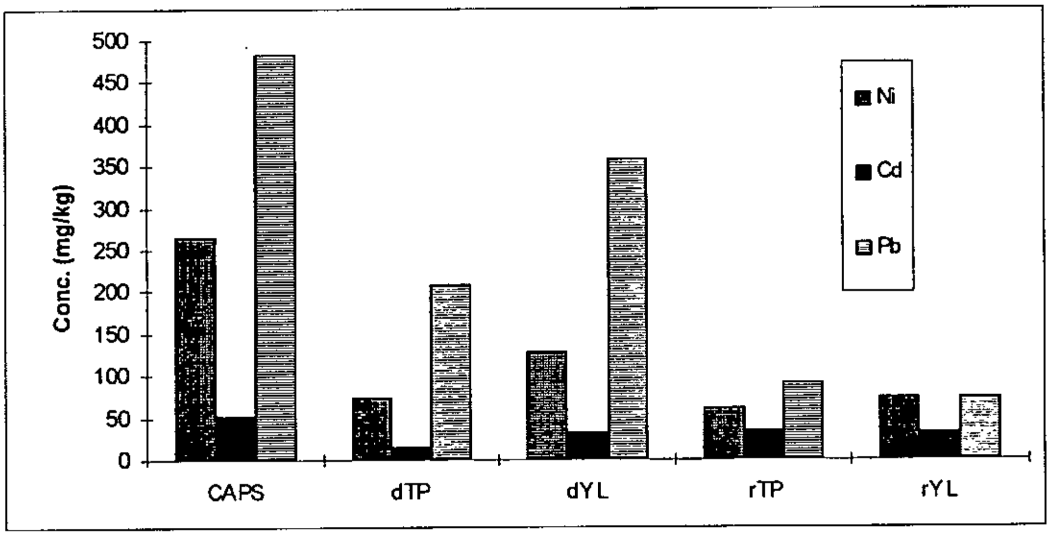

Fig. 7.2.10 : Concentrations of total Ni, Cd and Pb in sludge samples

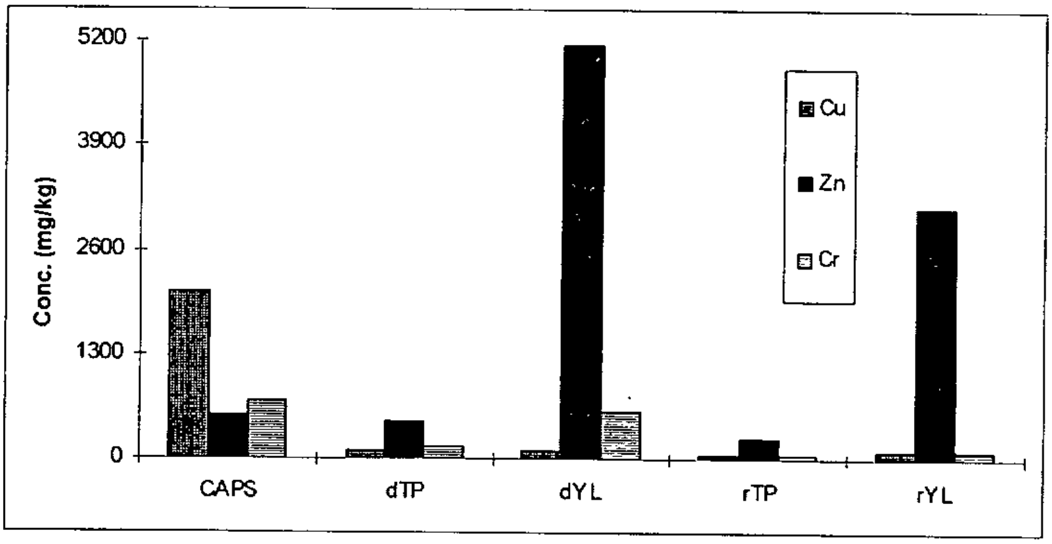

Fig. 7.2.11 : Concentrations of total Cu, Zn and Cr in sludge samples

Table 7.2.2 shows the comparison between DoE (maximum permissible concentration of potentially toxic element in soil after application of sludge, expressed as mg/kg dry solid , adopted from UK Code of Practice) and the metal concentration of the sludge samples (CIWEM, 90). It could be seen that all the metal contents in CAPS sludge exceeded the DoE level. On the other hand, digested TP sludge samples also had metal concentrations (except Cu) greater than that of DoE. When comparing raw and digested sludge samples, the raw sludge was more suitable for land application due to the lower metal concentrations. Among the 6 metals, Zn and Cd were of the greatest concern . This was consistent with the other findings in that the rapid expansion of industries such as electroplating and electronic-related establishments in Hong Kong gave rise to elevated concentrations of heavy metals such as Zn, Cr and Cd (Pun et. al., 95; Cheung, Y. H. et. al., 95).

Table 7.2.2 Comparison of DoE value (mg/kg) and heavy metal concentration in sludge samples

Metal	DoE	CAPS	rTP	rYL	dYL	dTP
Zn	250	Y	Y	Y	Y	Y
Cu	100	Y	N	N	Y	N
Ni	60	Y	N	Y	Y	Y
Cd	3	Y	Y	Y	Y	Y
Pb	300	Y	N	N	N	Y
Cr	400	Y	N	N	N	Y

Key: Y: concentration greater than DoE ; N: concentration smaller than DoE

7.2.2.5 Summary

CAPS sludge was better than the other 4 sludge samples in terms of filterability, settleability and dewaterability. CAPS sludge contained a significant higher amount of extractable compounds than other sludges (except digested YL). The concentrations of total N and P in CAPS were higher than the TP sludge samples. The concentrations of total Cu, Pb, Ni, Cd, Cr and K in CAPS sludge were also higher than the other sludges. Most of the metals (Cu, Pb, Cr and Zn) in CAPS sludge were associated with the organically-bounded phase. It is concluded that there are significantly differences in both physical and chemical properties between the chemically modified sludge and biological treated sludges. CAPS sludge should be considered as superior than the biological sludges in terms of dewatering properties and nutrient contents. The elevated heavy metals and ammonia concentrations in CAPS sludge, on the other hand, will complicate the handling and disposal of the large quantities of sludges produced by Stonecutters Island STP in the coming years. Thus, the biological and ecological effects of CAPS sludge on the environment have to be further investigated in order to assess its possible contamination problem when it is disposed of at landfills or agriculturally utilized.

7.3 Chemical Stabilization of Sludge

7.3.1 pH and solid content

Table 7.3.1: pH and solid content of different mixutres

Sample	Proportion (wet weight basis)			pH	Solid content
	Sludge	PFA	CaO		(%)
A	6	3.5	0.5	11.93	97
B	6	3.8	0.2	11.45	98
C	7	2.5	0.5	12.13	89
D	7	2.8	0.2	11.21	86
E	6.5	3.0	0.5	12.03	87
F	6.5	3.3	0.2	11.16	91
G	6.5	3.5	0	10.05	91
H	7	3.0	0	9.32	84
I	7.5	2.5	0	9.60	82
J	10	0	0	7.43	42

From the table, the pH of the sewage sludge (sample J) was nearly neutral. On the other hand, PFA used in this study contained sufficient alkaline materials to increase the pH of its slurry to about 12 but it has a low alkaline content. This could be shown by the small increase in pH values in the sludges mixed with PFA only (sample G to I). Thus, PFA alone could not produce a highly alkaline environment for the stabilization of sludge in term of the pH criterion (≥ 12). When lime was added, all the mixture becomes highly alkaline, with samples C and E showing pH values higher than 12. This showed that lime itself had a high alkaline content.

To facilitate easy handling and reduce the transportation cost, the solid content of sludge must be high. The results revealed that the addition of PFA and lime into the sludge cake greatly increased the solid contents. The increase in solid content was mainly due to the water sorption capacities of PFA and lime and the exothermic reaction between anhydrous CaO and water which resulted in elevated temperatures to dry off the water. According to the Federal Register , the requirement for solids content of PFRP from USEPA must be at least 50% by weight. The experimental results demonstrated that the samples reached solid contents to above 80% after mixing with the stablizing agents.

7.3.2 Total Coliform Count

The raw sludge and mixtures E and G were selected for further analysis because of their relatively higher pH value. The MPN coliform count for the raw sludge, samples E and G were >18000, 0 and 21, respectively. Using total coliform as an indicator, the results showed clearly that the addition of PFA alone would reduce the number of pathogenic bacteria in sewage sludge. Above all, the mixing of sludge with PFA and lime could completely eliminate all the coliform. The main explanation was that the elevated pH of this mixture could sustain an alkaline environment for a longer period which pasteurized the bacteria. According to the USEPA's PSRP, the addition of PFA and lime can be regarded as a PSRP since there was a '2 log' reduction of faecal coiforms after stabilization. The pasteurization action by PFA and lime is believed to be due to a combination of the stresses of alkali pH, accelerated drying and high temperatures.

7.3.3 Total heavy metals and nutrient

Fig. 7.3.1 and *Fig. 7.3.2* show the total concentrations of heavy metals and nutrients in the samples. The concentration of Zn was the highest in the sludge samples. It could be seen the concentrations of the total heavy metals and nutrients dropped after the sludges were amended with fly ash and CaO. This change in trace metal contents could be attributed to the dilution effect. There was no significant differences in total metal and nutrient concentrations between the sludge samples mixed with PFA and that mixed with PFA plus lime.

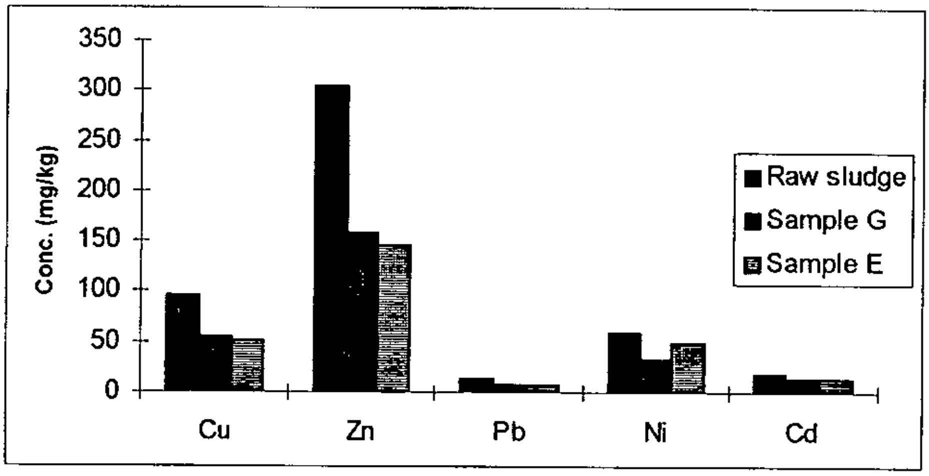

Fig. 7.3.1 : Concentrations of total Cu, Zn, Pb,Ni and Cd in sludge samples

(Sample G: sludge:PFA=6.5:3.5; Sample E: sludge:PFA:CaO =6.5:3.0:0.5)

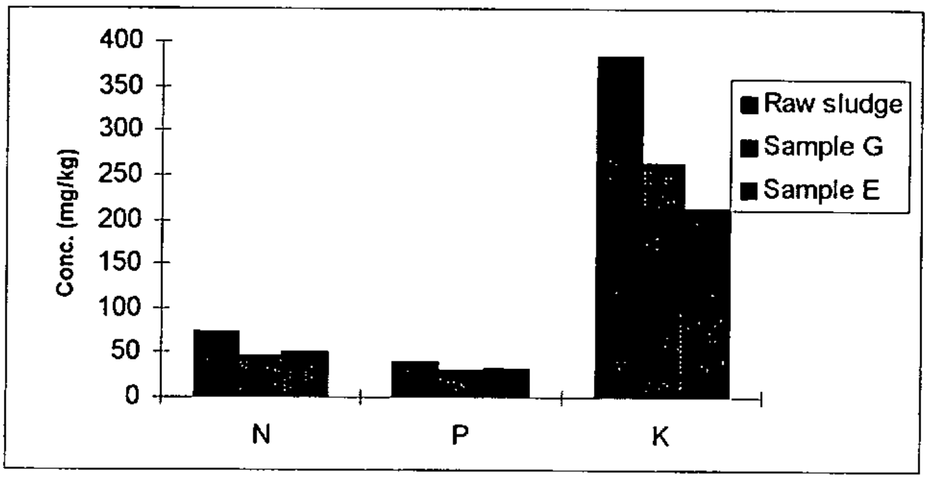

Fig. 7.3.2 : Concentrations of total N, P and K in sludge samples

7.3.4 Multiple Extraction by TCLP

From *Fig.7.3.3*, it could be seen that the leaching in the raw sludge increased when the number of extraction increased. For the stabilized samples, the leaching increased as time proceeded and then dropped after the third extraction. Also, the total percentage of Cu leaching decreased after stabilization (Table 7.3.2). The possible reason to account for this was either precipitation which converted heavy metals in liqud phase to solid phase and/or sorption which bound heavy metals onto solid particles (Wang, 98). The leaching of heavy metals from PFA was much smaller than the raw sludges and the stabilized sludge samples, but the trend was similar.

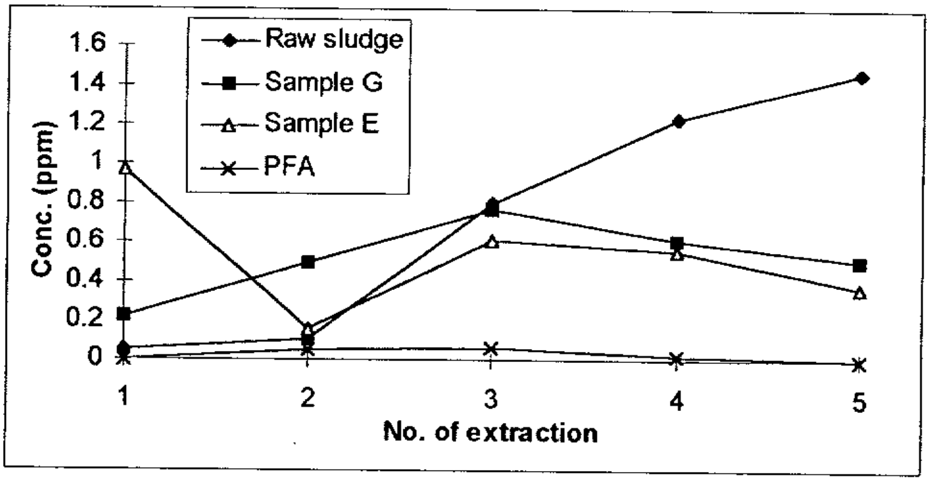

Fig. 7.3.3 : Cu analysis of multiple extraction

Fig. 7.3.4 shows that for the stabilized samples, the leachate Zn concentration decreased as the number of extractions increased. Above all, the total leaching percentages was raised from 70 to above 90% after stabilization (Table 7.3.2). This revealed that PFA/lime stabilization could not reduce Zn leaching in the sludge.

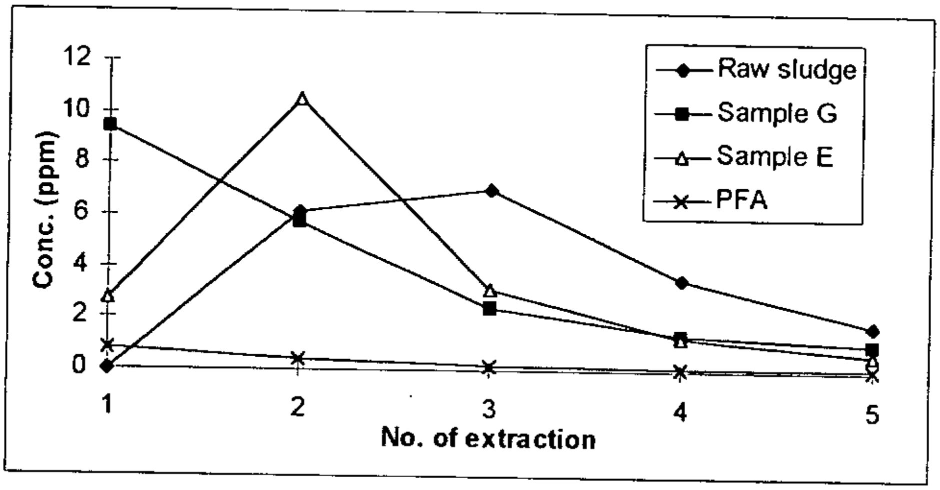

Fig. 7.3.4 : Zn analysis of multiple extraction

It was clear that Ni leaching was reduced as the number of extraction increased (*Fig. 7.3.5*). The total percentage of Ni leached also dropped after stabilization. The possible reason was the same as Cu. It might also be due to the fact that most metals generally exhibited minimum solubility in high pH. The pH values of the extracts of the stabilized samples (though not reported here) were still high (~ 9.5-10), thus decreased the leachability of most heavy metals.

The Cd concentrations in all the TCLP extracts were far below the regulated level of 1ppm (*Fig. 7.3.6)*) . The leaching was decreased after the samples were extracted for more than 3 times. There was no significant difference between the total leaching percentages of the 3 samples. The relatively low leaching percentages showed that Cd in raw sludge had a good ability to withstand leaching (Table 7.3.2). It was possibly due to the formation of stable organic-Cd complexes in the sludge and the solubility of which was not sensitive to change of pH.

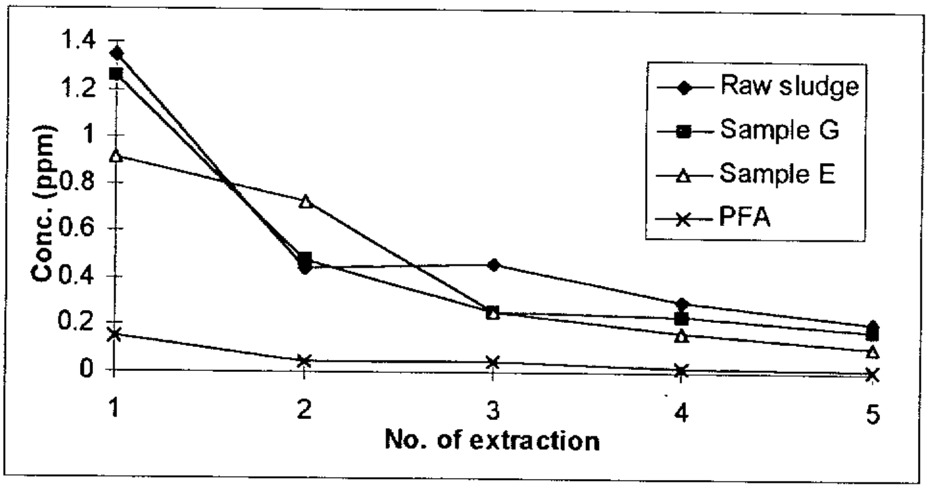

Fig. 7.3.5 : Ni analysis of multiple extraction

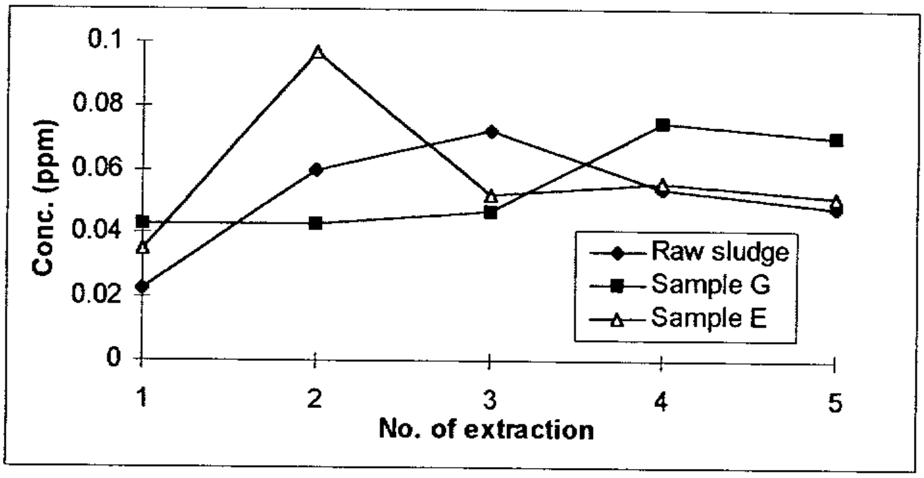

Fig. 7.3.6 : Cd analysis of multiple extraction

Table 7.3.2: Total percentage of leaching after multiple extraction

Sample	Cu	Zn	Ni	Cd
Raw sludge	45.59	69.41	57.99	16.09
G	33.96	92.27	53.97	14.85
E	37.91	96.11	33.77	15.71
PFA	24.92	84.31	79.80	-----

The knowledge of the elemental leaching behavior of sludge is important for devisng environmentally and agronomically sound management practices. It is widely accepted that total metal content is important in characterizing sewage sludge, but not sufficient in predicting sludge effect on plant growth or on ground water quality (Van der Sloot, 96). Generally speaking, my results illustrated that the 4 metals showed various leaching response to the effect of stabilization. It is mainly because the distribution ratio of total metal content between the sludge and the water phase depends upon the various chemical properties of the metal and of the physicochemical properties of the sludge. The latter, in turn, depends on such conditions as pH, presence and concentration of complexing or precipitating agents. Another important result obtained from the experiment was that though the leachate of PFA contained relatively little amount of metals, the overall percentages of metal leaching were (especially Zn and Ni) very high. This is consistent with the conclusion that trace metals, though present as relatively small fraction in PFA, are of great concern, due to their cumulative build up, long life, and high toxicity to plants and animal through air, water, and soil intake (Fytianos, et. al., 98) .

7..3. 5 Metal Speciations

In the raw sludge, most of the Cu was organically bound while the least amount was in the adsorbed phase (*Fig.7.3.7*). This could be explained by the known affinity of Cu for organic ligands (McLaren, 73; Emmerich, 82). The major portion of Cu was in the exchangeable phase in the two stabilized sludge samples. For PFA, the most dominant portion was the carbonate phase. This means that for Cu, there was a shift from the organically-bound form to the exchangeable form after sludge stabilization. In other words, lime and PFA treatment caused Cu in sludge to become unstable. Hsiau & Lo (98) also obtained the same results and concluded the instability was due to the weaker affinity of Cu for organics, which irreversibly dissolved with Cu at very high pH during stabilization. In this aspect, Cu speciation seemed not to be coherent to its TCLP leachability. However, the amount of Cu in the unextracted form was larger in the stabilized samples than in the raw sludge sample. This could be linked to the reduction in TCLP leaching, as for those forms which could be extracted, there was a shift from the more stable to the less stable forms.

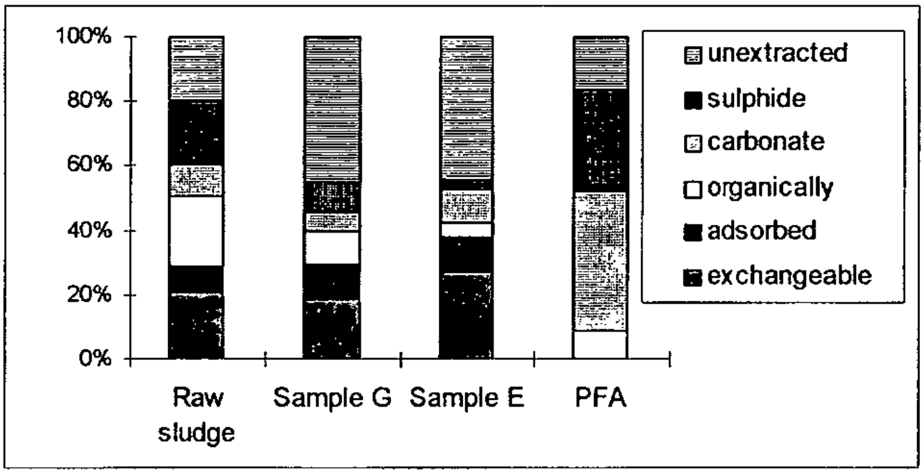

Fig. 7.3.7 : Distribution of different phases of Cu

For Zn, most of it was in the organically bound phase in the raw sludge (*Fig 7.3.8*). When the sludge was mixed with the alkaline stabilization materials, the major portion of Zn was in the carbonate phase. The carbonate phase accounts for 20% among the extracted forms in PFA. The exchangeable phase of Zn made up the least amount in all of the sludge samples. Thus, Zn was changed from the organically-bound form to carbonate-bound form after stabilization. This meant that among the extractable forms, Zn further shifted to the less available phase after stabilization. This can be attributed to the enhanced formation of organic matter-metal complexes at alkaline pH (Leita & Nobili, 91).

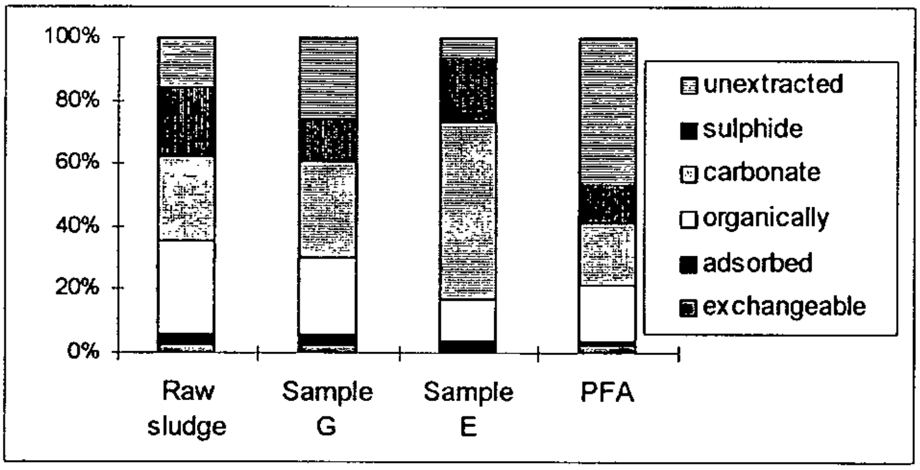

Fig. 7.3.8 : Distribution of different phases of Zn

In all the sludge samples, the most dominant form of Cd was the exchangeable phase while the least distributed was the sulphide phase (*Fig.7.3.9*). The results show that stabilization had no effect on the speciation of Cd.

Most of the Ni was in the exchangeable phase in the raw sludge and the sludge mixed with PFA (*Fig.7. 3. 10*). Whereas the sulphide phase made up the largest amount in sludge mixed with PFA plus lime. The dominant phase of Ni in PFA was carbonate. The least Ni was found in the adorbed phase and organically-bound phase in the raw sludge and the stabilized sludges, respectively.

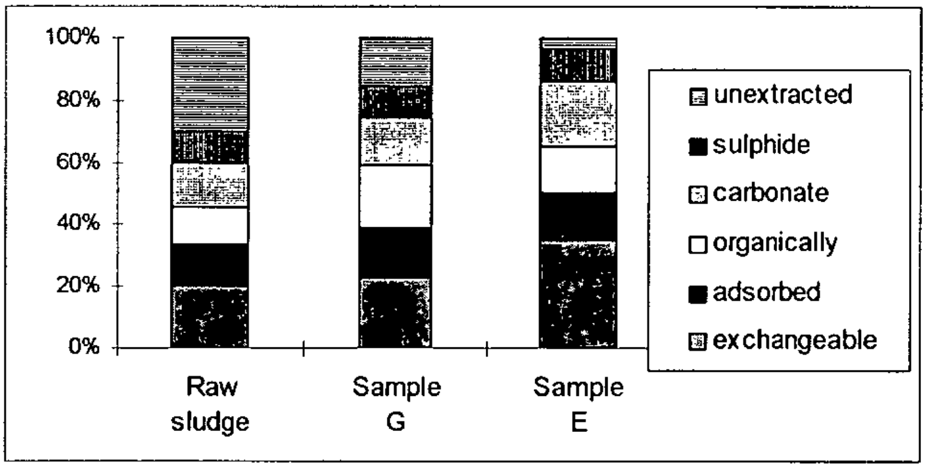

Fig. 7.3.9 : Distribution of different phases of Cd

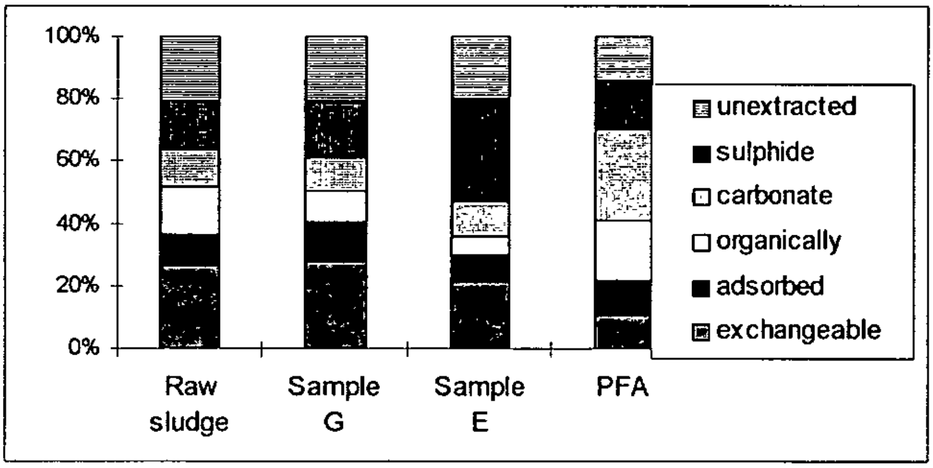

Fig. 7.3.10 : Distribution of different phases of Ni

Generally, the results of the speciation tests show that stabilization of sewage sludge by PFA and lime induced changes to the forms of the metals. In fact, it is believed that the forms of different heavy metals in sludges may vary greatly according to the characteristics of wastewater treated and the sludge treatment employed (Sterritt & Lester, 88; Pun et. al., 95). Another study showed that the distribution of heavy metals was stongly influenced by certain solid phases in sludge, although it was difficult to identify properly the different chemical forms of heavy metals (Flyhammar, 98). The speciation of heavy metals affects the availability of metals for plant uptake and the potential of groundwater contamination following the application of sludge to land (Lake, 84).

7.3. 6 Extractable N & P

The concentrations of extractable nitrate, phosphate and ammonia of the sludge decreased after stabilization with PFA and CaO addition are shown in *Fig. 7.3.11* . This might be due to both the dilution effect of adding PFA to the sludge and the change of pH. The typical pH values of sewage sludges was between 6 and 8, which allow the ammonia to remain bound in the material. When the pH is raised by the addition of PFA and lime, gaseous ammonia will be released (Weissinger & Girvich, 94). Similar results were obtained by Wong (95) and it was suggested that NH_3 was released and vaporised into air when the sludge was mixed with PFA because of pH effect. Besides, the numerous chemical reactions that occurred during stabilization might lead to chemodenitrification (i.e. the conversion of nitrate into gaseous forms, nitrous oxide or nitrogen) which resulted in a decrease in NO_3^- concentration in stabilized sludges (Loehr, 79). Whereas the change in phosphate content could be attributed to the pH effect. When the pH is raised to above 8, precipitation of insoluble calcium phosphates becomes dominant and thus the amount of extractable phosphate will decrease (Loehr, 79). On the whole, the experimental results show that the addition of PFA and lime caused a larger drop in the extractable compound concentrations than the addition of PFA alone. This was due to the higher pH value of PFA/lime stabilized sludge.

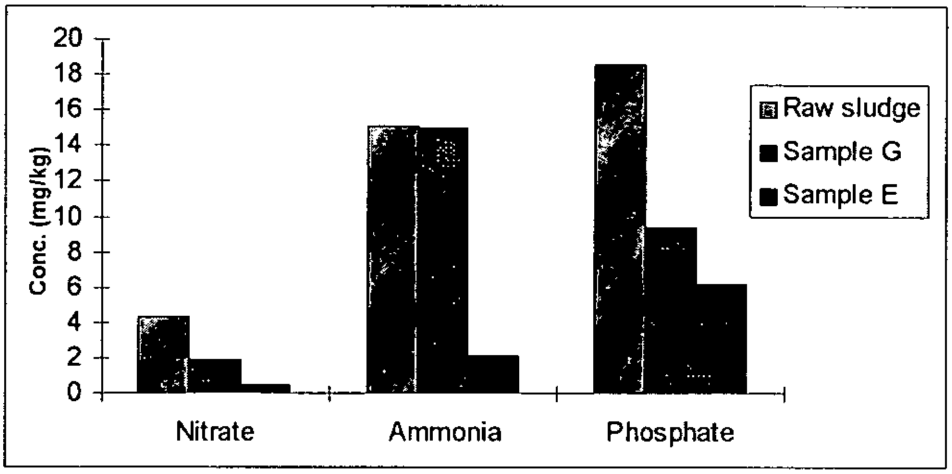

Fig. *7.3.11* : Concentrations of extractable nitrate, ammonia and phosphate in sludge samples

7.3.7. Comparison of the stabilization effect of PFA and PFA plus lime addition

The addition of PFA and lime produced a mixture with higher pH value than the addition of PFA alone. Also, ash together with lime could successfully eliminate all the coliform present in the sludge. In terms of heavy metal leaching, the trend of Cu and Zn leaching between the two stabilized samples were more or less the same. For Ni and Cd, there was variations in leachate concentration for both samples as extraction progressed. Also, there was not much difference in the total percentage of heavy metal leached except that Ni leaching was greater in the PFA stabilized sludge than the PFA plus lime stabilized one. This suggested that the stabilising effect of PFA alone mostly affected the leaching behaviour of Cu, Zn and Cd in stabilized sludge whereas lime contributed little effect.

The change in phases of Cu and Cd after PFA stabilization and PFA plus lime stabilization was very similar. For Zn and Ni, PFA and lime could induce a shift of metal forms in the sludge whereas PFA induced only a small change. The higher pH value of PFA plus lime stabilized sludge also accounted for its lower extractable N and P concentrations than PFA stabilized sludge. The total Cu, Zn, Pb and K concentrations in the PFA and lime stabilized sludge was lower than that in the PFA stabilzed one, whereas the amount of N and P showed opposite trends.

7.3.8 Summary

The results show that PFA and lime could stabilize the sewage sludge by reducing metal leachability (Cu & Ni), pasturing the pathogens and increasing the solid content. Most of the organically-bound Cu and Zn shifted to the exchangeable form and the carbonate phase, respectively after alkaline treatment. The change in chemical form of the metals were mainly due to pH effect. The drop in concentrations in extractable N and P compounds could also be attributed to pH effect. Besides, the concentration of total heavy metals and nutrients decreased after stabilization because of dilution effects. All in all, it was found that the use of PFA together with lime is able to render the stabilized sewage sludge meeting the USEPA's criteria for Process to Further Reduce Pathogens (PFRP) in addition to producing a final product with improved handling characteristics than the raw sludge.

7.4. Plant bioassay

7.4.1. Series I

7.4.1.1. Physicochemical properties of constitute materials

Table 7.4.1 lists the relevant measured chemical properties of the PFA and the sandy soil. Both the PFA and soil were rich in extractable phosphate and total N, P & K. It also contained trace amount of heavy metals (Zn, Pb and Cu) but the concentrations were below the toxicity limits (Chapman, 96; Soltanpour, 91). For PFA, it contained a significant amount of B. The concentrations of all the metals were also higher than that in the soil. It had more nutrients (N & P) than the soil as well.

Table 7.4.1 : Physicochemical properties of fly ash and soil

		PFA	Soil
Extractable NO_3^-		7.28 (0.946)	15.51 (3.649)
Extractable PO_4^{3-}		123.04 (13.09)	126.75 (1.519)
Extractable NH_4^+		6.43 (0.905)	5.03 (0.979)
Extractable	Cr	4.24 (0.149)	2.61 (0.231)
	Cd	2.50 (0.105)	2.61 (0.231)
	Cu	0.75 (0.250)	2.52 (0.115)
	Zn	3.52 (0.725)	3.54 (0.245)
	Pb	2.41 (0.260)	6.32 (0.757)
	Ni	5.41 (0.341)	4.29 (0.127)
	B	204.2 (13.32)	1.86 (0.284)
Total	Cr	5.06 (0.261)	3.33 (0)
	Cd	9.54 (0.549)	3.89 (0.964)
	Cu	24.29 (6.016)	6.55 (0.191)
	Zn	93.53 (9.047)	52.78 (5.090)
	Pb	8.33 (0)	11.11 (0.964)
	Ni	8.46 (1.821)	6.11 (0.964)
	B	849.07 (31.451)	8.88 (1.705)
Total	N	209.92 (23.014)	155 (0)
	P	89.47 (11.488)	122.21 (12.497)
	K	2313.27 (475.633)	1411.11 (195.313)

N.B. Values in parentheses are standard deviation of means of triplicates
Data are expressed in dry weight basis (mg/kg)

From Table 7.4.2, the pH of the soil was slightly acidic as it was collected near a beach area. The pH of the original raw sludge was around neutral but was raised to above 10 after stabilization. This was due to the liming effect of fly ash and CaO. Hodgson et. al. (82) suggested that the initial increase in soil pH after ash addition was caused by the release of Ca, Na, Mg and OH ions from fly ash. This would be beneficial to plant as bioavailability of metals to plants from sludged soils decreased as pH was increased either by liming or applying calcareous sludges (Alloway & Jackson, 91). Though it was widely accepted that a soil pH of 6.5 was more desirable for most agricultural purposes (Sterritt & Lester, 88).

Table 7.4.2: pH of fly ash, soil, sewage sludge and stabilized sludge

	PFA	Soil	rTP	sTP	rSC	sSC	rYL	sYL
pH	11.53 (0.261)	5.74 (0.447)	6.90 (0.144)	10.43 (0.426)	6.88 (0.021)	11.19 (0.053)	7.44 (0.064)	10.87 (0.074)

N.B. Values in parentheses are standard deviation of means of triplicates
rTP: raw sludge from Tai Po sTP: stabilized TP sludge
rSC: raw sludge from Stonecutters Island sSC: stabilized SC sludge
rYL:raw sludge from Yuen Long sYL: stabilized YL sludge

7.4.1.2. Effect of addition of stabilized TP sludge on soil properties

From Table 7.4. 3, the pH of the amended soil samples were raised with the increase in the percentage of the stabilized TP sludge addition. Soils generally have pH values within the range of 4-8.5 with the extreme range of 2-10.5. Brady (74) stated that the normal soil pH is 5-7 in humid regions, pH 7-9 in arid regions. The optimum soil pH for most arable crops is 6.5 on mineral soils and 5.5 on peaty soils. The results of the present study indicate that the acidic sandy soil was neutralized by the application of the stabilized TP sludge. However, the amended soil samples that had received >10% TP stabilized sewage sludge had pH values greater than 8, which is considered to be too alkaline for plant growth (Charman & Murphy, 91). Applying the stabilized TP sewage sludge to the soil increased the extractable PO_4-P and NO_3-N contents of the soil. But the NH_4-N content decreased with the increase in stabilized sludge application rate. Similar results were obtained by Wong (95) and it was suggested that NH_3 was released and vaporized into air when mixing the stabilized sludge with the soil. There was an increase in extractable heavy metal concentrations in the amended soil when the dosage of TP stabilized sludges increased (except for Cr). Similarly, the total heavy metal contents in the amended soil generally increased with the increase in TP stabilized sludge application rate. There was an increase up to 3 fold in Cd, Cu and Zn contents from applying 2.5% to 20% of the stabilized sludge . Also, there was an increase in nutrient concentrations when the sludge application dosage increased.

7.4.1.3. Effect of addition of stabilized YL sludge on soil properties

There was a slight increase in soil pH when the application dosage increased. Even a dosage as high as 20% could provide a suitable environment for growing plants. The effect on the NH_4^+, NO_3^- and PO_4^{3-} content in the amended soil was also the same as the other two stabilized sludge samples. However, the change was not very obvious , mainly attributed to the small increase in pH value. The total heavy metal and nutrient concentration increased with the increase in dosage. For the extractable metals, except Cd and Pb, they showed a linear relationship with the application rates.

Table 7.4. 3. Physicochemical properties of stabilized sludge amended soil.

	pH	NO_3^-	PO_4^{3-}	NH_4^+	Extractable Cr	Cd	Cu	Zn	Pb	Ni	B
TP											
2.5%	6.49a	13.95a	96.96b	27.88	2.10cd	0.65a	0.22a	6.57	2.83	2.59b	2.61
	(0.084)	(1.768)	(5.612)	(1.104)	(0.108)	(0.139)	(0.015)	(1.685)	(0.470)	(0.396)	(0.309)
5%	7.47	10.79a	85.30b	28.58ef	1.33	0.93c	0.23 a	5.88d	4.04a	3.04	8.07b
	(0.015)	(1.836)	(4.606)	(8.087)	(0.168)	(0.167)	(0.006)	(1.841)	(0.618)	(0.362)	(0.678)
10%	8.73	17.42a	122.30a	10.25	1.33	0.99a	0.29	10.07	4.78	3.54	7.05
	(0.340)	(7.702)	(21.10)	(1.974)	(0.015)	(0.017)	(0.015)	(0.030)	(0.311)	(0.169)	(0.501)
20%	10.44	13.92a	129.54	4.34	1.43e	1.71a	0.51	8.91c	4.58	3.66	6.29
	(0.170)	(3.961)	(2.267)	(0.224)	(0.159)	(0.212)	(0.017)	(1.935)	(0.444)	(0.456)	(1.180)
SC											
2.5%	6.66	17.70 a	67.59	4.03b	1.17	1.65a	3.95	15.74	4.93	14.30	3.36
	(0.206)	(5.732)	(3.859)	(1.757)	(0.676)	(0.111)	(2.195)	(4.587)	(0.345)	(0.401)	0.350)
5%	6.50d	12.38a	65.55	4.58abc	1.86	1.62a	10.52a	19.95bd	5.98	25.02	1.78c
	(0.108)	(2.556)	(19.451)	(0.975)	(0.517)	(0.156)	(4.801)	(2.811)	(0.863)	(0.767)	(0.275)
10%	8.20	17.19	85.24	4.30cd	2.54bc	1.71a	153.64	59.54	6.59a	32.43	6.52
	(0.189)	(3.833)	(1.463)	0.219)	(0.440)	(0.535)	(22.636)	(1.882)	(0.820)	(2.536)	(1.283)
20%	9.52	19.27	81.99	3.63 ad	2.69ab	2.13a	139.59	51.41	8.73	33.62a	8.39
	(0.396)	(7.822)	(1.482)	(0.305)	(0.352)	(0.215)	(10.872)	(2.262)	(0.878)	(2.916)	(1.397)
YL											
2.5%	6.67b	7.56	129.54	35.31	0.80	2.41a	0.24	37.8ac	6.02	3.957	3.44c
	(0.135)	(1.357)	(2.267)	(1.845)	(0.142)	(0.088)	(0.008)	(3.196)	(0.775)	(0.326)	(0.140)
5%	6.52cd	15.78 a	156.38a	27.36 f	0.61e	1.27a	0.24	43.11b	6.44	3.67	8.40b
	(0.036)	(3.067)	(38.981)	(0.211)	(0.150)	(0.070)	(0.01)	(28.335)	(0.695)	(0.454)	(0.352)
10%	6.55bc	17.32 a	156.43	27.22 e	1.19d	1.44 a	0.32	60.38a	5.73	4.02b	12.75a
	(0.154)	(3.058)	(28.518)	(0.947)	(0.040)	(0.006)	(0.141)	(18.610)	(0.881)	(0.286)	(2.639)
20%	7.35a	17.19a	154.54	28.35	1.68	1.51 a	0.74	184.52	5.35	4.77	15.37a
	(0.057)	(6.176)	(35.107)	(1.916)	(0.400)	(0.145)	(0.231)	(4.587)	(0.286)	(0.335)	(2.091)

Table 7.4 .3 (Con'd): Physicochemical properties of stabilized sludge amended soil

					Total					
	Cr	Cd	Cu	Zn	Pb	Ni	N	P	K	B
TP										
2.5%	3.29	2.52c	4.30	22.10a	15.99c	5.87	137.84b	111.28d	1484.85g	14.99d
	(0.380)	(1.139)	(1.227)	(3.670)	(2.725)	(0.960)	(31.737)	(12.705)	(271.058)	(3.910)
5%	5.26c	4.47	4.76	16.86b	21.11a	6.28	166.03	148.34	1897.03g	24.48
	(0.759)	(0.936)	(0.358)	(3.048)	(2.540)	(2.101)	(15.130)	(11.165)	(538.222)	(1.065)
10%	4.89b	5.41b	9.30	26.53b	19.58b	7.37	342.94	158.59	1796.70f	27.39c
	(0.714)	(0.974)	(0.618)	(3.207)	(1.672)	(1.566)	(27.725)	(11.582)	(154.416)	(1.881)
20%	5.32c	6.47c	13.62b	65.24	17.96c	6.61	356.17	175.34b	2304.32ef	37.03
	(0.413)	(1.384)	(1.195)	(6.713)	(1.397)	(2.315)	(51.912)	(14.018)	(263.629)	(2.368)
SC										
2.5%	16.13	10.49a	136.86a	25.38	22.5	15.54	156.23	184.69a	3016.78e	24.01
	(4.590)	(1.304)	(11.028)	(2.800)	(0.971)	(3.557)	(46.527)	(8.942)	(207.489)	(0.431)
5%	21.66a	13.55	142.57b	25.85a	33.68	21.63	258.20	165.00	2760.28de	35.10
	(2.933)	(5.544)	(9.426)	(4.575)	(2.354)	(5.197)	(73.443)	(14.629)	(206.371)	(0.693)
10%	23.56	16.47a	243.45a	24.56	23.42	42.05a	278.71	212.81	3144.59	44.09a
	(5.616)	(1.381)	(11.509)	(2.936)	(3.721)	(4.091)	(17.071)	(20.418)	(369.96)	(3.062)
20%	24.29b	13.10b	297.05	24.68	24.86	43.79a	362.20a	150.88a	4445.32ac	45.48a
	(2.483)	(2.823)	(33.420)	(6.592)	(1.732)	(3.396)	(26.703)	(11.768)	(378.097)	(0.657)
YL										
2.5%	37.5	5.92	2.67c	110.60	26.82	6.33	226.89	108.13d	4032.30a	14.82d
	(1.627)	(1.554)	(0.954)	(1.952)	(4.793)	(1.504)	(10.015)	(11.690)	(281.123)	(2.273)
5%	34.83	6.14	2.81	126.69a	28.36b	5.63b	245.37a	136.16c	3375.44d	23.34c
	(6.855)	(1.766)	(0.653)	(2.217)	(1.827)	(1.303)	(3.866)	(12.470)	(384.619)	(2.682)
10%	41.86	8.54	6.06	164.38	28.46	8.09	272.39	166.74c	3744.54bc	37.37b
	(10.658)	(2.761)	(1.970)	(23.452)	(6.328)	(1.728)	(28.888)	(15.868)	(79.197)	(3.057)
20%	44.54a	8.82	6.24c	285.86	36.14a	9.57b	284.94b	154.48	4348.13b	34.86b
	(5.791)	(0.915)	(1.021)	(12.879)	(1.583)	(1.194)	(10.253)	(11.012)	(337.22)	(3.300)

N.B. Values in parentheses are standard deviation of means of triplicates
Data are expressed in dry weight basis
Values followed by the same letter within the same row do not differ significantly at the 5% level according the Student-Newmen-Kewdi test

7.4.1.4. Effect of addition of stabilized SC sludge on soil properties

Similarly, the addition of stabilized SC sludge raised the pH of the soil according to the dosage applied. The pH of the soil that had received 10% and 20% stabilized SC sludge also did not favor plant growth. The trend for the change in PO_4-P, NO_3-N and NH_4-N contents of the soil after SC sludge addition were the same for that of TP sludge addition. However, there were obvious differences between the NH_4-N concentrations of the two kinds of stabilized sludge amended soil. The NH_4 concentration of the stabilized TP sludge ranged from 28 to 4 mg/kg whereas that for the SC stabilized sludges was about 4 mg/kg . The concentrations of both the extractable and total heavy metals in the soil increased when the application rate of stabilized sludge increased. It is noticeable that there was a dramatic increase in extractable Cu concentration in the amended soil when the dosage of sludge was increased from 2.5% to 10%. For the nutrient contents, the N and K contents in the soil increased when stabilized sludge was added.

7.4.1.5 Effect of stabilized TP on short-term plant growth

From *Fig. 7.4. 1*, the crops grown in TP stabilized sludge-amended soil had lower germination rates than the control. The application rate that achieved maximum emergence seedling for radish and barley were 20 and 5%, respectively. Root and shoot retardation was observed for both crops in all the treatments, as revealed in *Fig. 7.4.2* & *Fig.7.4.3*. Besides, the degree of retardation increased with the increasing application rates. This implied that the crop growth was sensitive to the toxic contaminants in the TP stabilized sludge amended soil.

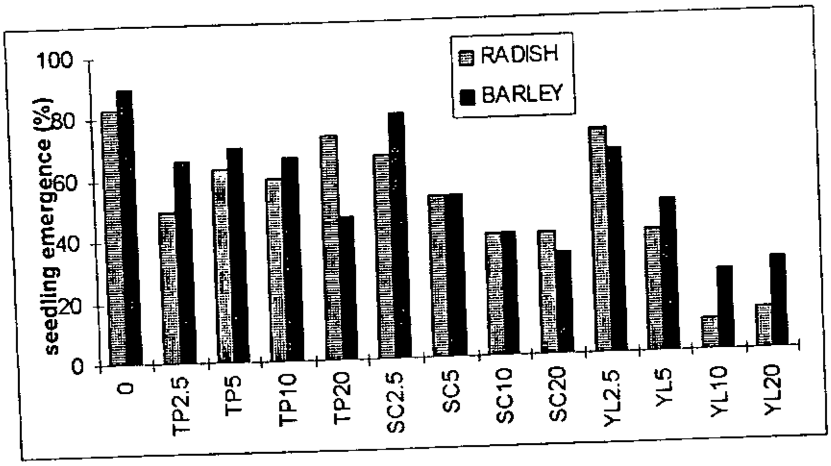

Fig. 7.4. 1: Seedling emergence of Chinese Radish and barley harvested from soils treated with various concentrations of stabilized sludge

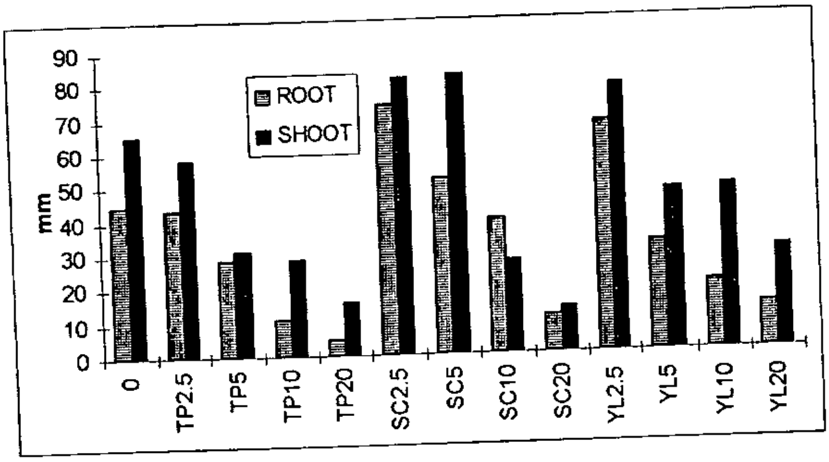

Fig. 7.4. 2: Root and shoot length of Chinese Radish harvested from soils treated with various concentrations of stabilized sludge

7.4.1.6 Effect of stabilized SC on short-term plant growth

Seedling emergence of radish and barely in natural soil (control) were higher than that of the amended soil. The highest seedling emergence was observed in 2.5% replacement for both crops. And the germination rate dropped with the increase in application dosage. The root and shoot growth of radish seedlings decreased when the application rate increased, though the plants in 2.5 & 5% amended soil had better root and shoot growth than the control. For barley, the extent of root and shoot inhibition increased with the stabilized sludge addition. The above results showed that a low dosage was suitable for the early development of the two seedlings.

7.4.1.7 Effect of stabilized YL sludge on short-term plant growth

The effect of applying stabilized YL sludge on seedling emergence was the same as that of stabilized SC sludge. And soil receiving 2.5% treatment harvested the most number of seedlings. Radish receiving 2.5% treatment showed better root and shoot growth than that of the natural soil. And the extent of shoot and root inhibition increased with the application rate. For barley, all the treatments had root and shoot retardation comparable to the control. Among the various treatments, 5% stabilized sludge achieved the optimum root and shoot growth.

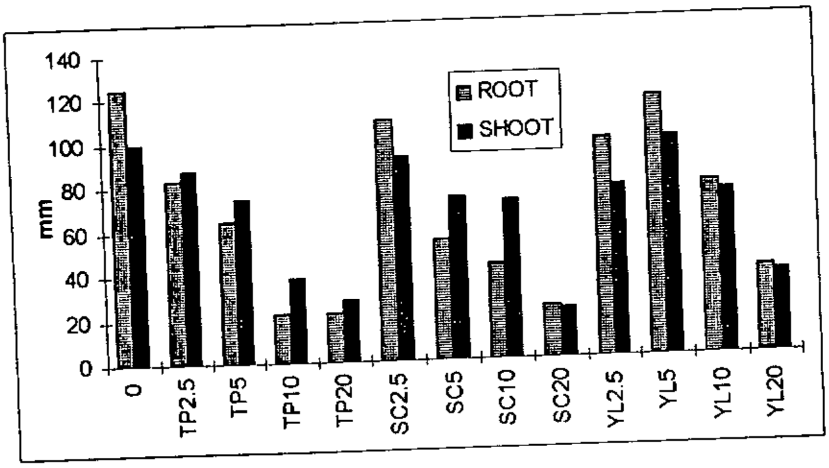

Fig. 7.4. 3: Root and shoot length of barley harvested from soils treated with various concentrations of stabilized sludge

7.4.1.8 Summary of the short-term plant experiment

All the stabilized sludge had an inhibitory effect on the germination rate of the two seedlings. The poor seedling emergence may be due to the poor physical properties and high metal and ammonia contents of sewage sludge. Besides, it was found that fly ash incorporation in soil might delay germination of crops, most likely because of increased impedance offered by the soil/ash matrix to germinating seeds (Kalra et. al., 97). In terms of total percentage of seedling emergence from the stabilized sludge amended soil followed the order of TP>SC>YL. The dosage that obtained the maximum germination rate from SC and YL was 2.5% whereas for TP was 5%. The dosages that achieved the maximum root and shoot elongation was 2.5% for all the sludge samples. Thus, the growth of plants harvested from YL stabilized sludge was the best whereas that from TP was the worst.

Seed germination , root and shoot elongation has long been used as a rapid and reliable technique to investigate the toxic effects of animal manure or sewage sludge (Cheung & Wong, 83; Cheung et. al., 89; Tam & Tiquia, 94). And different crops are known to have different responses towards the toxicity in the sludge samples. Chinese radish is a root plant whereas barley is a cereal plant. It is generally agreed that cereal does not accumulate significant amounts of toxic elements in its seed because of its high food reserve; so it is not sensitive to toxic contaminants of sludges (Sterritt & Lester, 81; Wong & Chu, 87). This is not consistent with the results of the present study as the inhibitory effect on the two plants was more or less the same. And this was probably due to the use of sandy soil. Also, it was hard to decide whether the chemically treated sludge or the biologically treated sludge favored the early development of the two edible crops . Nevertheless, it can be concluded that a lower dosage have to be used to avoid any inhibitory effect on the plants. Of course, this short-term study can only be used as a preliminary evaluation of the growth of edible crops in sludge-amended soil. The exact accumulation of heavy metals in the edible parts of the plant have to be further investigated by long-term pot trials.

7.4.1.9 Effect of stabilized TP sludge on grass growth

Fig. 7.4. 10 shows the seedling emergence of the grass. Seedling emergence of TP stabilized sludge at dosages <20% were higher than that of the control but germination rate decreased as the sludge application rate increased. This decline can be attributed to the elevated metal contents and high pH levels. The dry weight of the shoot of the crops were measured after harvesting and the results are shown in *Fig. 7.4.10*. The shoot yield resulted from stabilized TP soil were significantly higher than that of the natural soil. The optimum application rate that achieved the highest yield were 5%. A higher dosage resulted in a decline in yield. Again, this might be due to the larger amount of toxic substances present in 10 & 20% stabilized sludge amended soil.

7.4.1.10 Effect of stabilized SC sludge on grass growth

All the soil treatment with SC stabilized sludge had lower seedling emergence than the control (*Fig. 7.4. 4*). There was no significant difference between the percentage of germinated seedlings grown in 2.5, 5 and 10% amended soil. This indicated that stabilized SC sludge could not improve soil conditions for seedling emergence. The most possible explanation is that SC stabilized sludge amended soil contained a significant amount of heavy metals that was harmful to the plant. From *Fig. 7.4. 5*, the total shoot yield harvested from SC amended soil at dosages <20% were higher than that of the natural soil. The optimum application rate that achieved the highest yield for SC amended soil was 2.5%. Similarly, there was no significant differences in dry weight yield of plant between various dosages of SC amended soil.

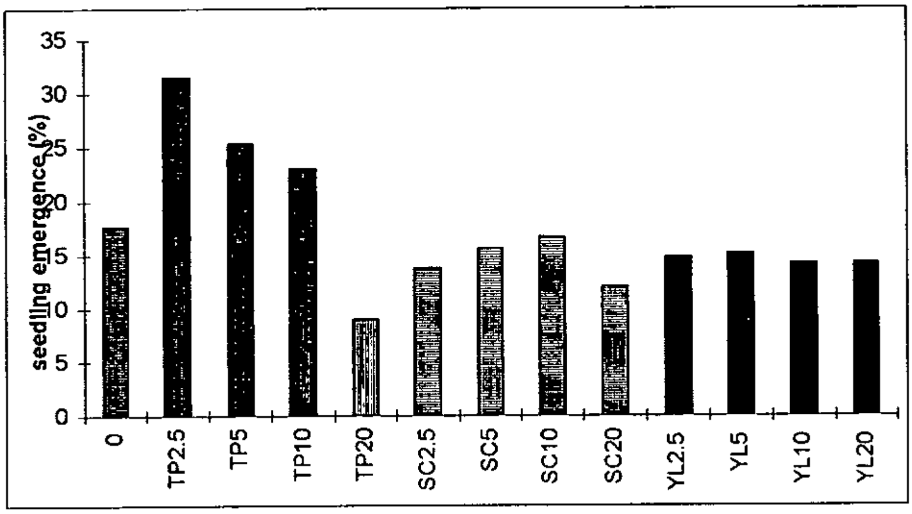

Fig. 7.4. 4: Seedling emergence of tall wheat grass harvested from soils treated with various concentrations of stabilized sludge

7.4.1.11 Effect of stabilized YL sludge on grass growth

Seedling emergence in the natural soil was higher than that in YL stabilized sludge amended soil. However, there was no significant difference in the germination rate between the different application dosages. Shoot dry weight yield of all the grass, on the other hand, was higher than that of the control. This again indicated that YL stabilized sludge amended soil exhibited a certain degree of fertilizer capacity. And again, not much difference is observed between the yield produced from different treatments.

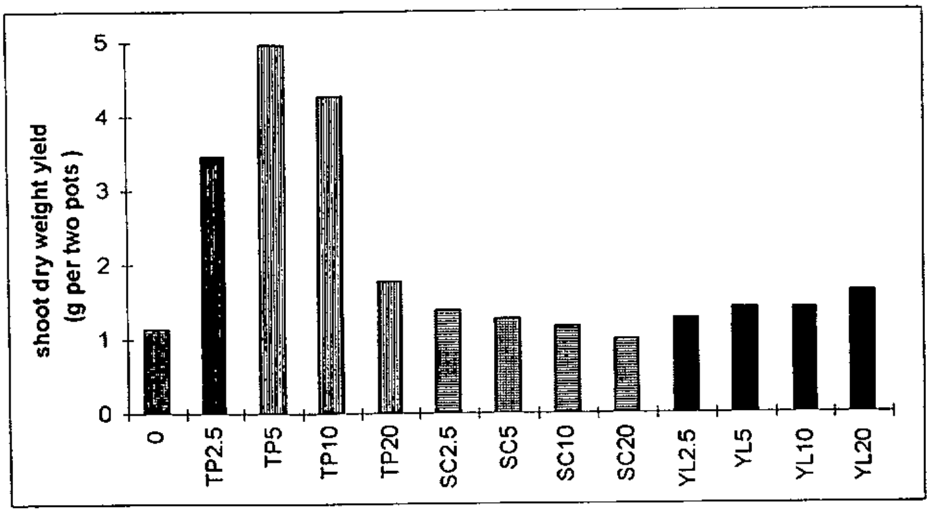

Fig. 7.4. 5: Shoot dry weight yield of tall wheat grass harvested from soils treated with various concentrations of stabilized sludge

7.4.1.12 A comparison of stabilized TP, SC and YL sludge on grass growth

The yield of grass grown in TP stabilized sludge was significantly higher than that grown in SC and YL stabilized sludge. This is due to the higher metal contents and salt (because of the large amount of K) concentrations in the SC stabilized sludge. For YL stabilized sludge, the elevated Zn and K contents might exert certain inhibitory effect on grass growth. There are some other reasons to explain the various phytoxic effects of the two sludge samples. For instance, it had been found that the Fe hydroxides content of soils was an important parameter in affecting metal uptake by some plants. And Fe hydroxides were known to be important adsorbents of metals in soils which in turn increased the bioavailability of metals to plants (Alloway & Jackson, 91). Thus, it could be expected that the chemically ($FeCl_3$) treated SC sludge exerted a different action from the biologically treated TP sludges. Nevertheless, the results of the present study showed that the stabilized sewage sludge had certain fertilizing effects for plant growth.

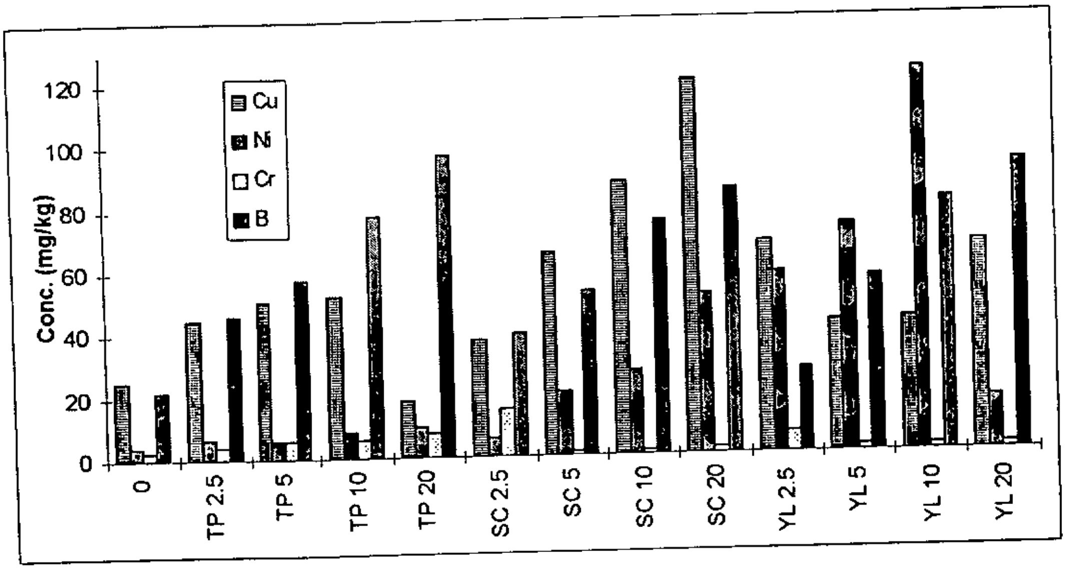

Fig. 7.4. 6: Concentrations of total Cu, Ni, Cr and B in shoot tissue of tall wheat grass

7.4.1.13 Elemental uptake of crop grown in TP amended soil

The relevant chemical contents of the shoot of the grass are shown in *Figs. 7.4.6 - 7.4.8*. The heavy metal and nutrient contents (except P) of the grass grown on TP stabilized amended soils were higher than that grown in natural soil. Shoot B content increased with the application rate probably as a result of the enriched B content of fly ash, together with the high pH after soil amendment making B more available for plant uptake. But all the shoot B contents were far below the toxicity level of 200 mg/kg (Elseewi, et. al., 80). The shoot concentrations of Cr and K also increased with the application dosage. For Zn, there was no significant differences between the various application rates. The shoot tissue Pb and Cd concentrations were below the detection limit of 0.02 ppm. *Figs. 7.4. 9-7.4. 10* illustrate the chemical contents in the root tissues. Applying TP stabilized sludge to the soil reduced the Zn, Cr and P but increased Cu, Cd, N and K in the root tissues of the grass. The uptake of Pb and Ni by the root was very low for all the treatments.

7.4.1.14 Elemental uptake of crop grown in SC amended soil

It can be seen from *Figs. 7.4. 6- 7.4. 8* that SC stabilized sludge amended soil decreased Cr content but increased the other chemical contents in the shoot of the grass as compared to the control. It is noticable that the N content in the shoot and Cr content in the root were greatly increased with addition of stabilized sludge. Besides, all the elemental concentrations (except Cr) increased with the increase in application dosage. This showed that the uptake of heavy metals and nutrients in SC stabilized sludge was dependent on the application rate.

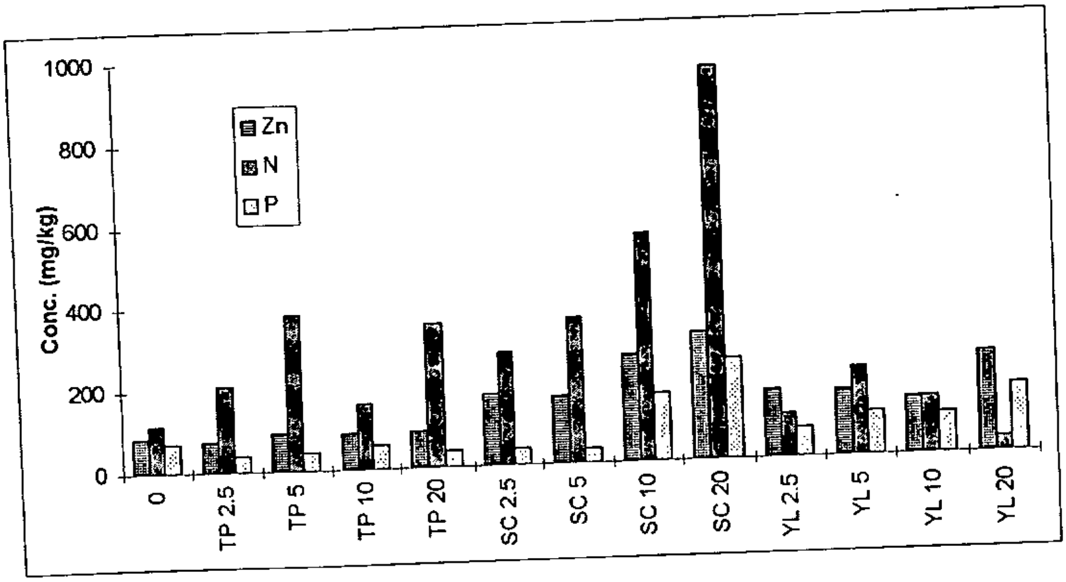

Fig. 7.4. 7: Concentrations of total Zn, N and P in shoot tissue of tall wheat grass

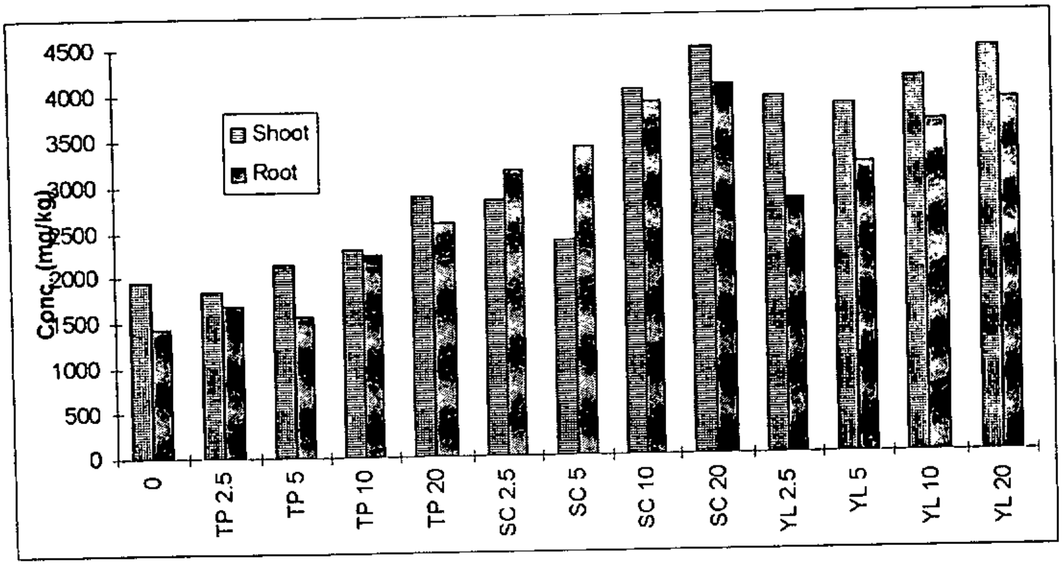

Fig. 7.4. 8: Concentrations of K in shoot and root tissue of tall wheat grass

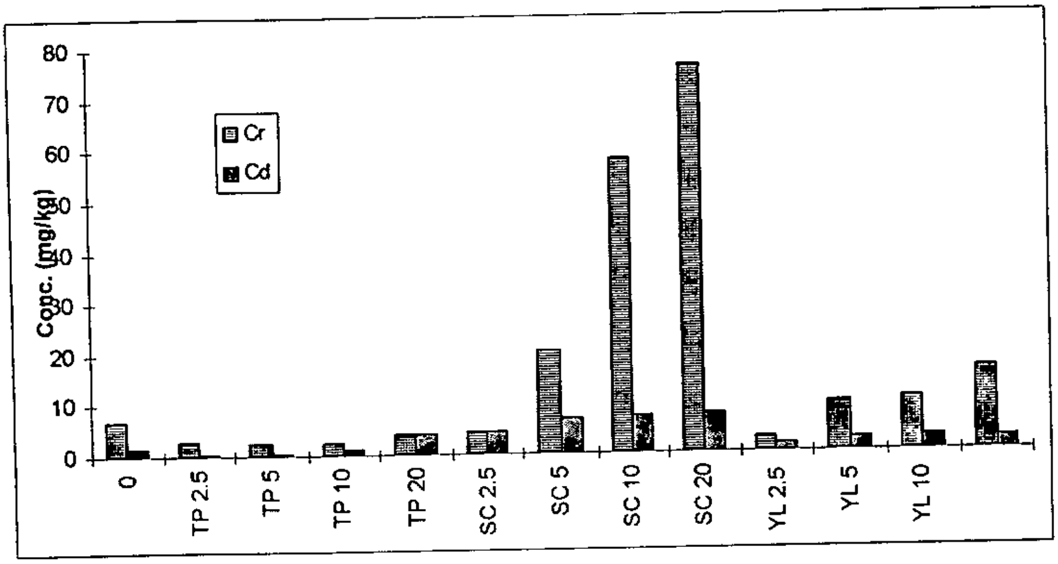

Fig. 7.4. 9: Concentrations of total Cr and Cd in root tissue of tall wheat grass

7.4.1.15. Elemental uptake of crop grown in YL amended soil

All the shoot heavy metals and nutrient contents in the grass grown in the natural soil were lower than that of the YL amended soil. The amount of B also increased with the application rate. And it can be shown that there is little correlation between elemental uptake in the shoot and the dosage applied. Applying YL stabilized sludge increase root

Cu, Zn and K contents in the grass. The concentrations of Cu, Zn and K increased when the dosage increased.

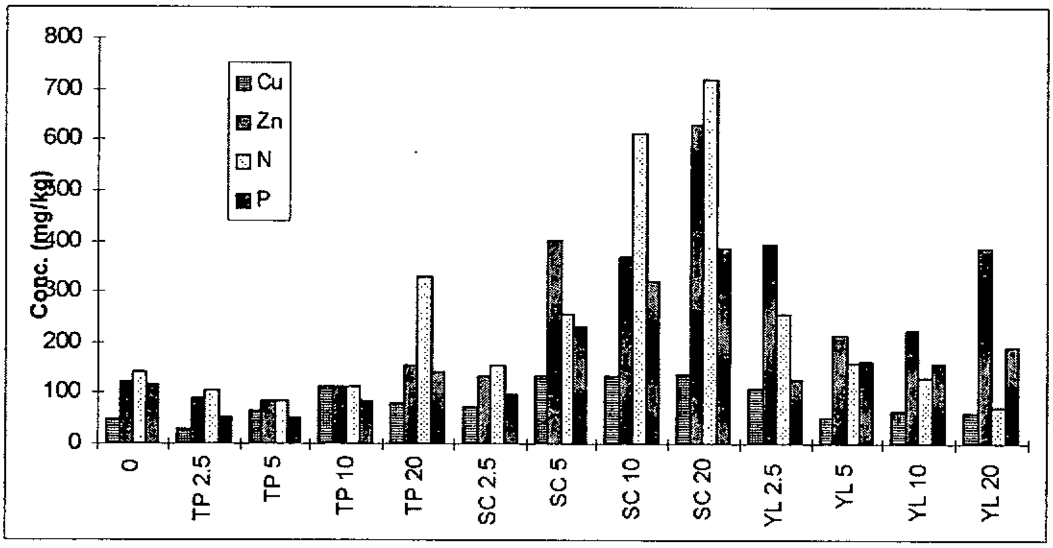

Fig. 7.4. 10: Concentrations of total Cu, Zn, N and P in root tissue of tall wheat grass

7.4.1.16. Correlation between metal concentrations in soil and crops

It is generally agreed that the uptake of heavy metals by plants depends mainly on the extractable metal concentrations in soil but not on the total metal contents. From Table 7.4.4 , there are good correlation (r>0.8) between the total B, Cd and Cr concentrations in the TP stabilized sludge amended soil and their contents in the plant tissues. The metal concentrations in the grass harvested from TP stabilized sludge amended soil were inversely related with the concentrations of extractable Cu, Ni, Cd and Cr in the soil . These inverse relationships probably reflected dilution of the metal concentrations due to the yield (i.e. mass of tissues) increase because of N and K applications (Tam & Tiquia, 94). But the P and total and extractable Zn content of the plant harvested from TP amended soil were not related to their corresponding concentrations in the soil. The total and extractable Cu, B ,Ni as well as N contents in SC stabilized sludge amended soil were all correlated well (r>0.8) with their corresponding contents in the plant tissues. However, negative values of r were found between plant tissue metal contents and total Zn, total and extractable Cr contents in the SC amended soil. Similar to that of the TP stabilized sludge amended soil, there was no relationship between P content in the plant and the corresponding content in SC sludge amended soil.

Table 7.4.4.: Correlation of heavy metal and nutrient content in amended soil and plant tissues

	TP		SC		YL	
Cu	Total	Extractable	Total	Extractable	Total	Extractable
Shoot	0.483	-0.509	0.966	0.847	-0.419	-0.576
Root	0.588	-0.286	0.817	0.666	0.383	-0.273
Zn	Total	Extractable	Total	Extractable	Total	Extractable
Shoot	-0.188	0.167	-0.668	0.864	0.845	0.842
Root	0.794	0.330	-0.540	0.737	0.626	0.577
Ni	Total	Extractable	Total	Extractable	Total	Extractable
Shoot	0.268	-0.079	0.883	0.843	0.776	0.406
Root	0.008	0.581	0.932	0.862	0.663	0.11
Cd	Total	Extractable	Total	Extractable	Total	Extractable
Root	0.882	-0.535	0.718	0.307	0.544	-0.685
Cr	Total	Extractable	Total	Extractable	Total	Extractable
Shoot	0.831	-0.630	-0.181	-0.514	0.012	-0.216
B	Total	Extractable	Total	Extractable	Total	Extractable
Shoot	0.952	0.694	0.961	0.870	0.940	0.927
N	Total		Total		Total	
Shoot	0.131		0.841		0.567	
Root	0.599		0.819		0.026	
P	Total		Total		Total	
Shoot	0.036		0.059		0.582	
Root	0.272		0.151		0.295	
K	Total		Total		Total	
Shoot	0.716		0.641		0.952	
Root	0.519		0.528		0.874	

For YL stabilized sludge, there was good correlation ($r>0.8$) between B and K contents in the plant and that in the amended soil. Cu, Cr and Cd content in the plant tissue had inversely relationships with their corresponding extractable concentrations in the amended soil.

7.4.1.17 Summary of Series I planting experiment

The germination of Chinese Radish and barley grown in sludge amended soil was inhibited by the 3 sludge samples. The extend of root and shoot retardation of the two plants increased with the increase in application dosage of the stabilized sludge. The short-term study suggested that the planting of edible crops in stabilized sludge amended soil was not recommended regardless of the type of sludge. For the grass, its germination rate in SC and YL stabilized sludge amended soil were lower than the control. And the percentage of seedling emergence was in the order of TP> YL> SC. In terms plant growth, all the grass receiving stabilized sludge amendments (except SC 20%) had higher biomass than that of the control soil. The order of productivity followed the same order as that of seedling emergence. The grass potting trial revealed that the chemically treated sludge exerted more toxic effect than the biologically treated sludge. This was mainly due to the higher elemental uptake by the grass receiving SC stabilized sludge amendments.

7.4.2. Series II

7.4.2.1 Chemical constituents of stabilized sludge mixtures

Table 7.4.5: Chemical constituents of stabilized sludge mixtures

	pH	Cu	Zn	Ni	Pb	N	K
Sand	6.59	0.85	61.95	16.65	1.65	0	1643
	(0.021)	(0.007)	(13.789)	(0.495)	(0.495)		(154.15)
S	7.57	76.83	256.12	40.91	6.77	33.21	897.04
	(0.321)	(3.606)	(26.532)	(8.26)	(0.976)	(6.576)	(23.684)
SP	9.67	24.5	160.4	21.5	0.8	14.1	1244
	(0.007)	(3.540)	(1.697)	(0.849)	(0.05)	(2.121)	(41.61)
SPC	10.12	25.5	134.55	21.75	1.6	22.55	1255
	(0.017)	(0.707)	(3.041)	(3.606)	(0.05)	(1.344)	(186.68)
S50P	9.44	22	95.25	16.2	5.65	11.8	1665
	(0.007)	(2.828)	(6.859)	(0.424)	(0.014)	(0.424)	(79.20)
S60P	9.58	26.5	122.5	18.1	4.15	12.2	1450.5
	(0.007)	(0.707)	(3.677)	(0.99)	(0.084)	(0.424)	(108.19)
S70P	9.80	22.5	112.1	18.5	2.95	17.4	1320.5
	(0.021)	(3.54)	(0.283)	(0.707)	(0.071)	(1.273)	(57.28)
S80P	9.90	36	154.85	16.6	2.3	25.55	1526.5
	(0.020)	(0)	(12.232)	(0.707)	(0.050)	(0.212)	(6.36)
S50PC	9.52	30.5	161.5	21.85	1.95	21.15	1630
	(0)	(0.702)	(9.90)	(1.768)	(0.028)	(1.626)	(46.67)
S60PC	9.75	26	128.5	20.9	2.6	20.4	1293
	(0.007)	(0)	(5.657)	(1.273)	(0.014)	(1.131)	(48.08)
S70PC	9.92	24	150.15	23.25	1.15	25.75	1522.5
	(0.007)	(0)	(7.283)	(4.031)	(0.028)	(3.748)	(14.85)
S80PC	9.88	20.85	157	19.85	1.70	29	1727.5
	(0.021)	(0.707)	(14.142)	(2.758)	(0.057)	(1.000)	(34.65)

N.B. Values in parentheses are standard deviation of means of triplicates
Data are expressed in dry weight basis
S: raw sewage sludge , SP: sludge:PFA = 6.5:3.5, SPC: sludge: PFA: lime = 6:3.5:0.5,
S50P: sludge:PFA= 50:50, S60P: sludge:PFA = 60:40, S70P: sludge:PFA = 70:30,
S80P: sludge:PFA = 80:20, S50PC: sludge:PFA:lime = 50:45:5, S60PC: sludge:PFA:lime = 60:36:4,
S70PC: sludge:PFA:lime = 70:27:3, S80PC = 80:18:2

From Table 7.4.5, the pH of the natural soil and the SC sludge was nearly neutral. With the addition of PFA and lime, the pH of all the stabilized mixtures were raised. Lime had a higher buffering capacity than PFA, as revealed by the higher pH value in SPC mixture than SP one. The change in the mixing ratio of sludge, PFA and CaO induced little change in pH value among the different samples. For Cu, Ni and K, no significant difference in content was observed between in SP and SPC mixtures. For the mixtures stabilized with PFA alone, all the chemical contents increased (except Pb) when the amount of sludge added decreased. For the mixtures with both PFA and CaO, the concentrations of Cu, Zn, Ni and Pb increased when the application rate of sludge increased. The opposite trend was observed for N and K.

7.4.2.2 Effect of addition of stabilized sludge on soil properties

From *Fig. 7.4. 11*, the pH of amended soil increased with the application dosage increased (refers to PC 25 -20 & P 2.5 -20). Whereas there was no definite trend in pH values for different sewage sludge/fly ash and lime mixture ratios (refers to SPC 50-80 & SP 50 - 80). *Figs. 7.4. 12 - 7.4. 27* shows the heavy metal contents in the stabilized sludge-amended soil mixtures. For Cu, Pb and K their concentrations were not dependent on the dosage of the stabilized sludge. The concentrations of Zn, Ni and N in the soil mixtures increased when the application rate of stabilized sludge increased. For Cu and Pb, no significant difference was observed with different mixing ratios of sludge, PFA and CaO . For the PFA stabilized sludge, the Zn and N contents decreased when the proportion of sludge increased. The opposite trend was observed for K and Ni. For the PFA and CaO stabilized sludges, there was an inverse relationship between the K, Ni and N contents and proportion of sludge added

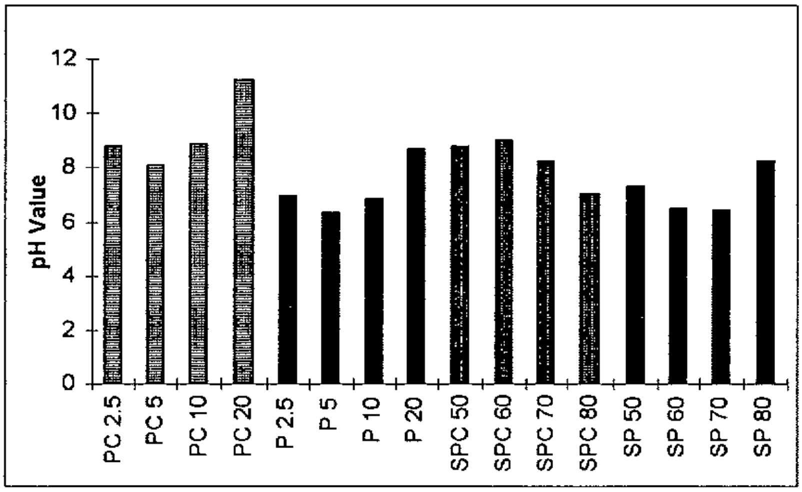

Fig. 7.4. 11: pH value of stabilized sludge amended soil mixtures

(**PC2.5:** SPC:soil = 0.25:9.75, **PC5:** SPC:soil = 0.5:9.5, **PC10:** SPC:soil= 1:9, **PC20**: SPC:soil=2:8, **P2.5**: SP:soil=0.25:9.75, **P5:**SP:soil=0.5:9.5, **P10:** SP:soil=1:0, **P20:** SP:soil=2:8, **SPC50:** S50PC:soil=1:9, **SPC60:** S60PC:soil=1:9, **SPC70:** S70PC:soil=1:9, **SPC80:** S80PC:soil=1:9, **SP50:** S50P:soil=1:9, **SP60:** S60P:soil=1:9, **SP70:** S70P:soil=1:9, **SP80:** S80P:soil=1:9)

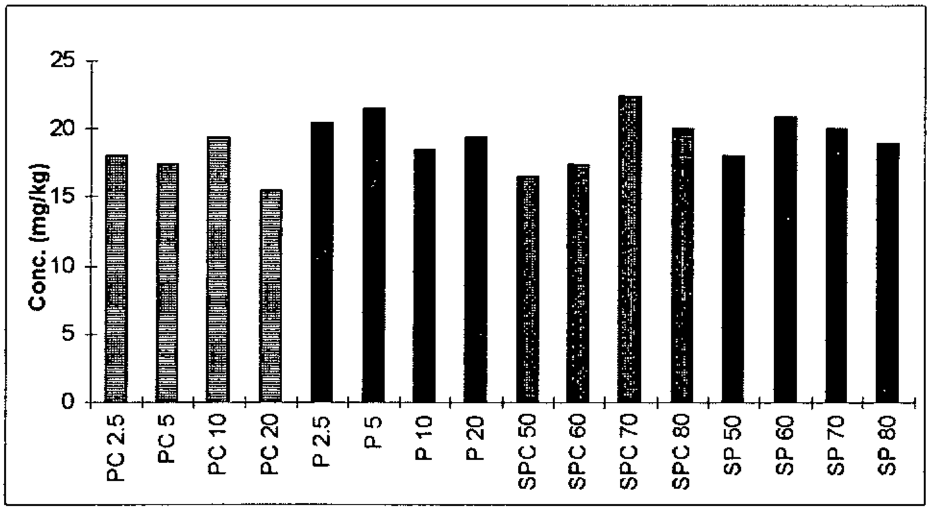

Fig. 7.4. 12: Concentration of Cu in stabilized sludge amended soil mixtures

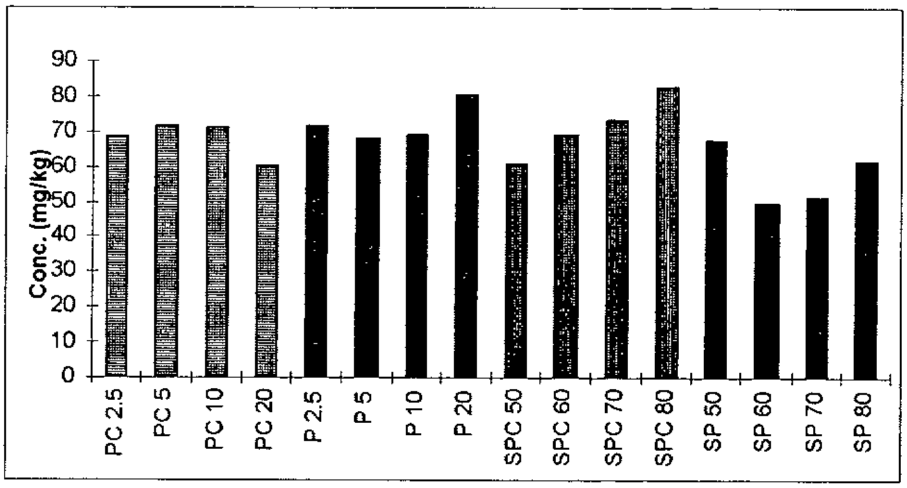

Fig. 7.4. 13: Concentration of Zn in stabilized sludge amended soil mixtures

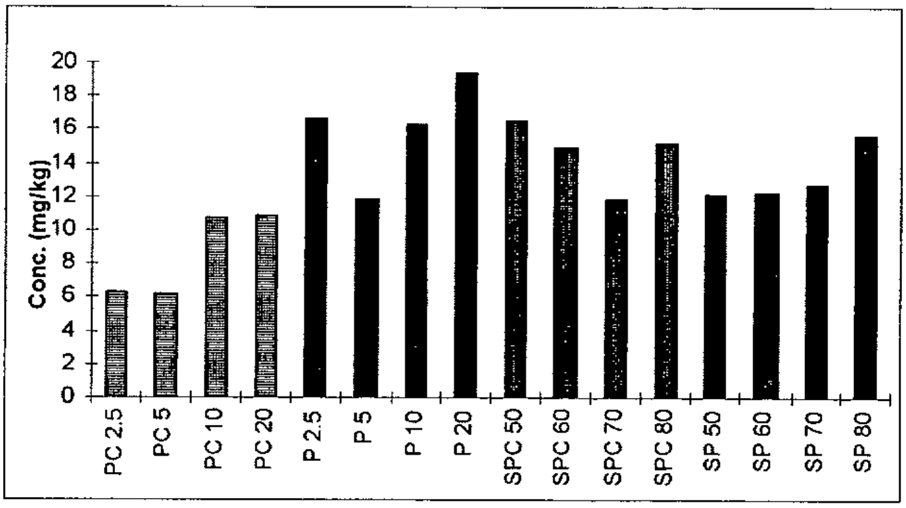

Fig. 7.4. 14: Concentration of Ni in stabilized sludge amended soil mixtures

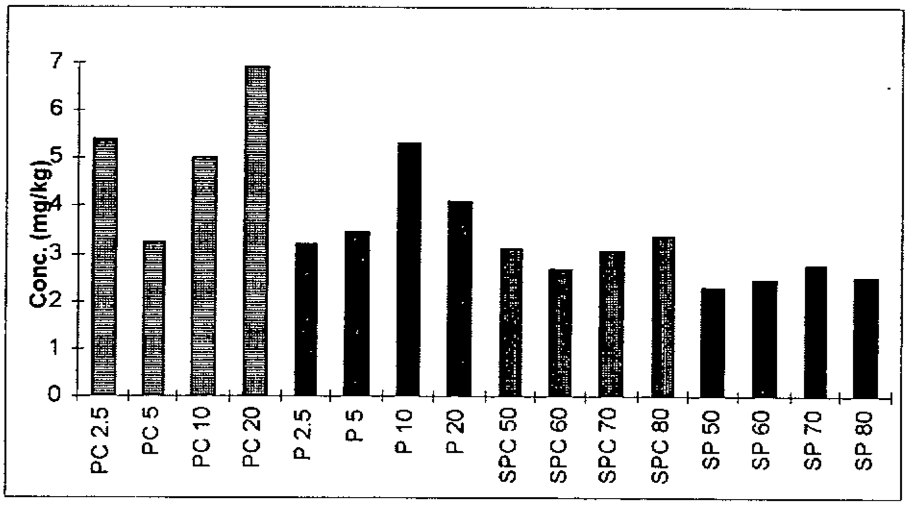

Fig. 7.4. 15: Concentration of Pb in stabilized sludge amended soil mixtures

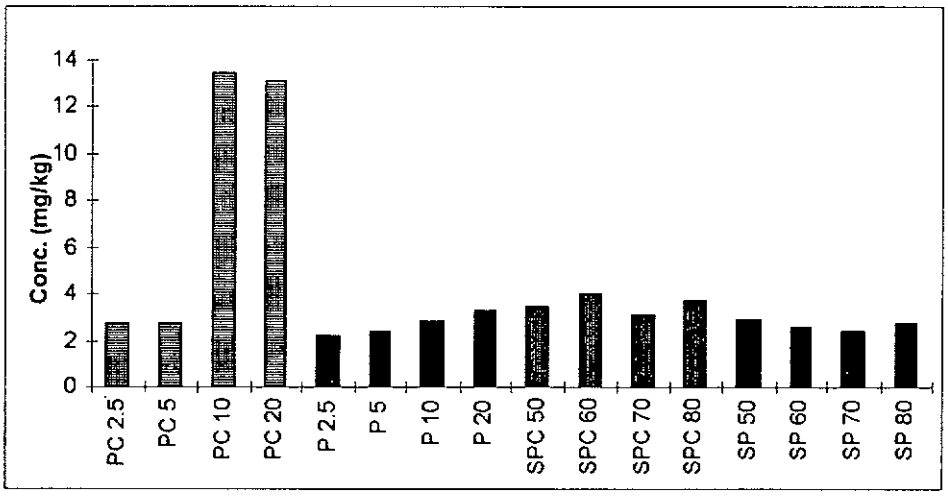

Fig 7.4. 16: Concentration of N in stabilized sludge amended soil mixtures

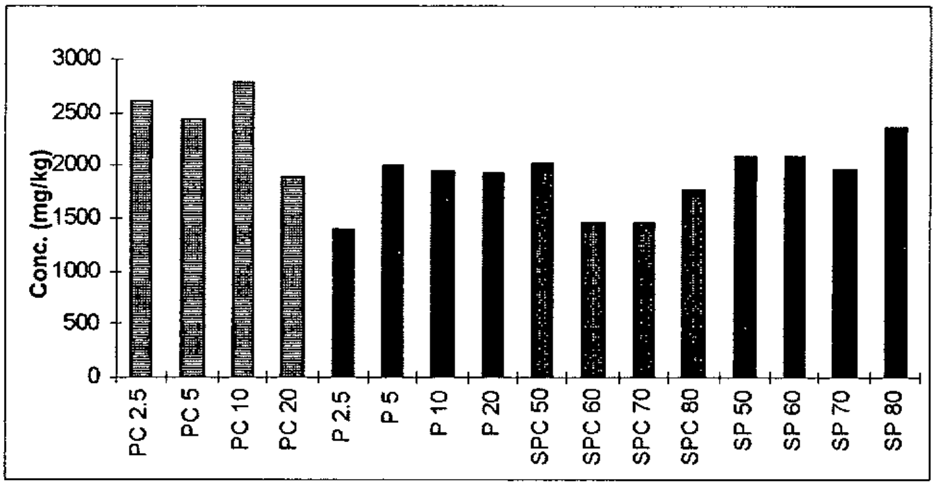

Fig. 7.4. 17: Concentration of K in stabilized sludge amended soil mixtures

7.4.2.3 Effect of different application rates of stabilized sludge on grass growth

From *Fig. 7.4. 18*, the germination rate of all the treated soils were higher than that of the control. This improvement could be explained by the improvement in soil property due to the incorporation of stabilized sludge. And the seedling emergence increased when the application rate increased. When comparing the two kinds of stabilized sludge mixtures, the one with PFA and CaO had a higher germination rate than the one with PFA alone.

This is due to the higher pH value in SPC amended soil mixtures which decreased toxic metal solubility. From *Fig. 7.4. 19*, the yield of the grass harvested from the amended soil was also higher than that from the natural soil This yield increase could be attributed to correction of nutrient deficiencies, neutralizing soil acidity, or a combination of pH adjustment and nutrient supplement (Hammermeister et. al., 98). And the yield produced by different treatments had a positive relationship with the dosage applied. The above results show that a dosage of as high as 20% can be safely applied where no inhibitory effect had been observed in the grass.

7.4.2.4 Effect of different sludge to PFA and lime ratios in stabilized samples on grass growth

The grass harvested from all the treatments had better germination rates than that from the natural soil. When the sludge / PFA and lime ratio increased, the percentage of seedling emergence decreased. This might be due to the cooresponding higher metal contents in the higher mixing proportions. The sludge stabilized with PFA and lime harvested more germinated seedlings than that by PFA alone (*Fig. 7.4. 18*). Likewise, the yield produced by sludge amendments were better than the control soil. And the yield declined when the sludge/PFA and lime ratio increased (*Fig. 7.4. 19*). One possible reason to account for this was when sludge/fly ash mixture ratio increased, the accumulation of toxic metals in plants increased (Sajwan et. al., 95). On the other hand, the PFA and lime stabilized sludge amended soil produced higher yield than the PFA stabilized one.

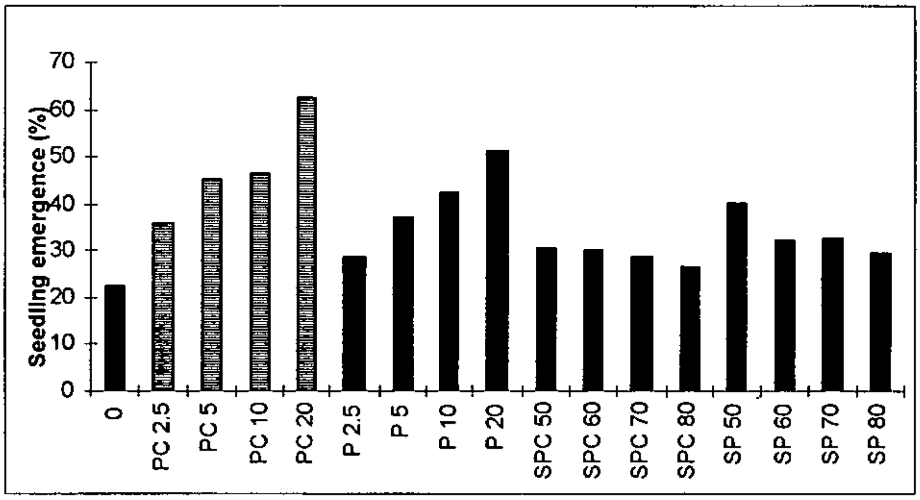

Fig. 7.4.18: Seedling emergence (%) of grass harvested from soil amended with stabilized sludge mixtures

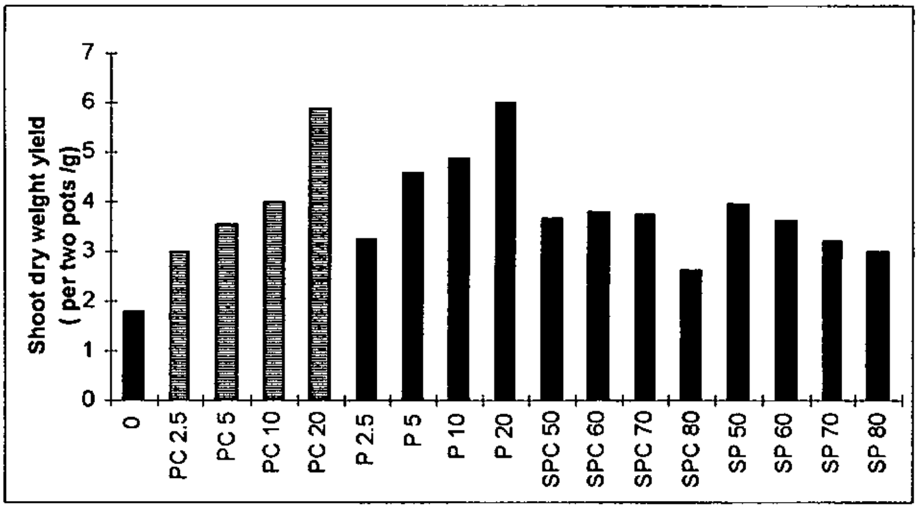

Fig. 7.4. 19: Shoot dry weight yield of grass harvested from soil amended with stabilized sludge mixtures

7.4.2.5 Effect of different application rates on elemental uptake of metals and nutrients by plant

From *Fig. 7.4. 20*, adding stabilized sludge mixtures to the soil increased the shoot Cu content. There was no significant relationship between shoot Cu uptake and the application dosage. For the root, the uptake increased when the application rate increased. Applying stabilized sludge to the soil reduced the Zn content in shoot of the grass, as revealed by *Fig. 7.4. 21*. Above all, their concentrations decreased with the application dosage. On the other hand, the shoot Pb content in the grass was increased and root Pb content decreased after amended with PFA and lime stabilized sludge (*Fig. 7.4. 22*). Its shoot content decreased with the increasing application of PFA stabilized sludge. The opposite trend was observed for root. For Ni uptake, its shoot content was increased after stabilization. Also, there were no significant trend observed in the plant harvested from different treatments (*Fig. 7.4. 23*). The root N content of the grass receiving stabilized sludge amendment were all higher than that of the control (*Fig. 7.4. 24*). Both the shoot and root N contents of the grass harvested from SPC treatments had positive direct relationship with the dosage applied. *Fig. 7.4. 25* shows that applying stabilized sludge increased the shoot K content in the grass. Also, K concentration in grass receiving SP treatment increased when the application rate increased. All in all, no obvious conclusion could be drawn on the difference in elemental uptake between SPC and SP treatments.

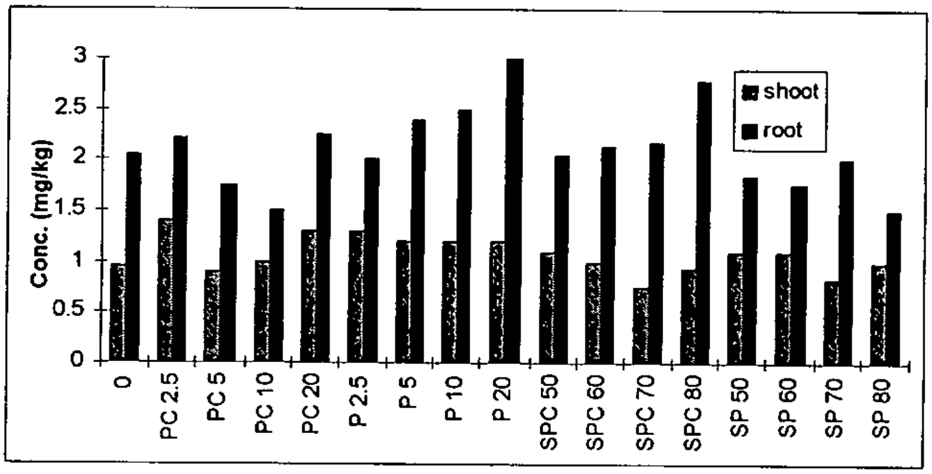

Fig. 7.4. 20: Concentrations of Cu in grass harvested from amended soil

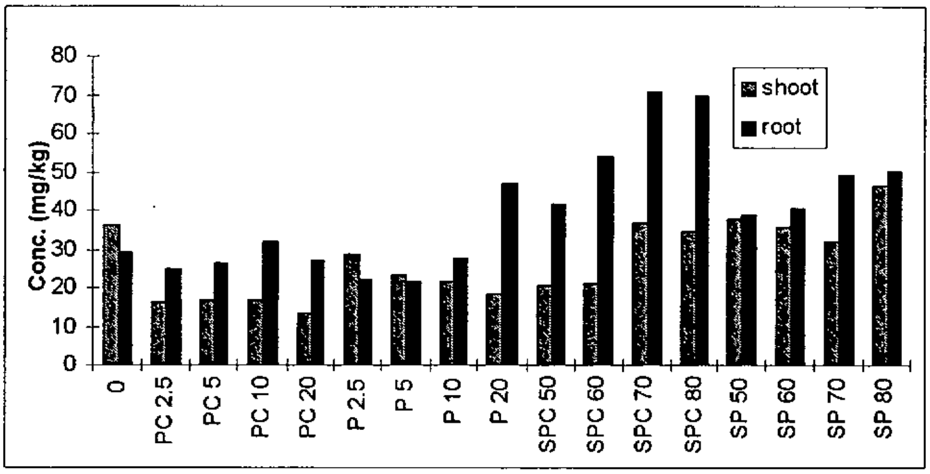

Fig. *7.4. 21*: Concentrations of Zn in grass harvested from amended soil

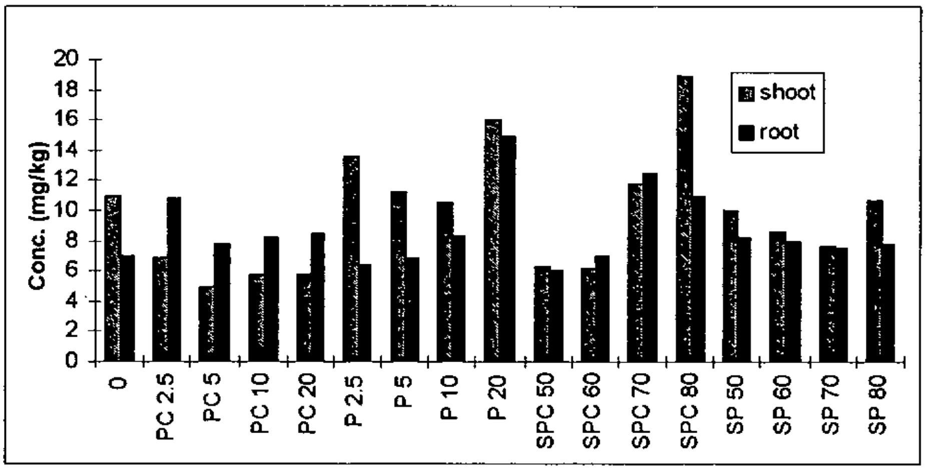

Fig. 7.4. 22: Concentrations of Pb in grass harvested from amended soil

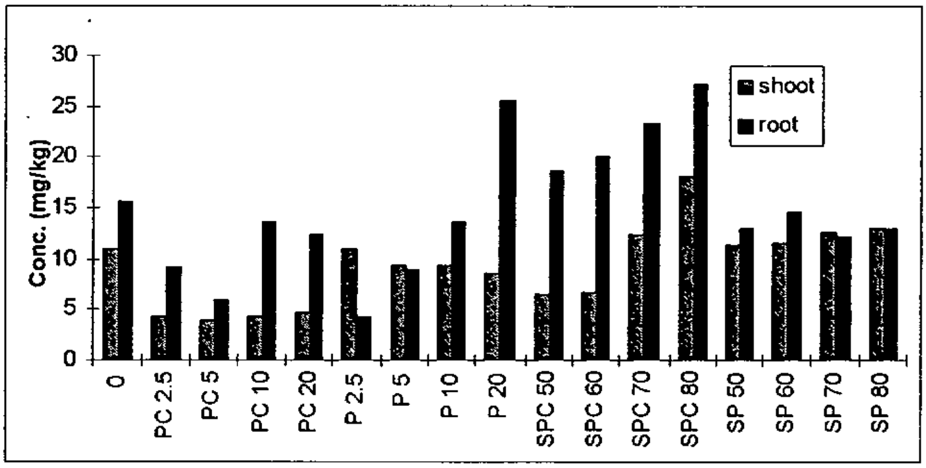

Fig. 7.4.23: Concentrations of Ni in grass harvested from amended soil

7.4.2.6 Effect of different sludge to PFA and lime ratios on elemental uptake of nutrients and metals by plant

There was various responses in Cu uptake after the addition of SP and SPC 50-80 mixtures (*Fig. 7.4. 20*). For Zn, its uptake was higher in the amended soil mixtures than the control (except shoot content from SP treatment). When the sludge to ash and lime ratio increased, the root uptake increased (*Fig. 7.4. 21*). No significant relationship were found in Pb uptake by the plant grown in different amended soil mixtures (*Fig. 7.4. 22*). The shoot Ni content increased correspondingly when the sludge to ash ratio increased (*Fig. 7.4. 23*). Applying stabilized sludge raised the N values in both the root and shoot of the grass. Similar to Ni, its concentration increased when the sludge to ash ratio increased (*Fig. 7.4. 24*). The K content of grass harvested from sludge amendments were higher than that of the control (*Fig. 7.4. 25*). The experimental results show that in most cases, as the sludge to fly ash or lime ratios increased, the accumulation of metals and nutrients in the grass would increase. It had been suggested that chemical interactions and mineralization take place during the composting of fly ash with organic compost that results in the release of additional quantities of nutrients into the system. The grass, may then absorb a larger amount of water soluble nutrients when they are available in the fertilizer soil (Menon et. al., 93). The sludge acted as a supplement of organic compounds. Thus, the higher the sludge to fly ash ratio, the more mineralization can occur. Again, no significant difference in elemental uptake could be observed between SPC and SP treatments.

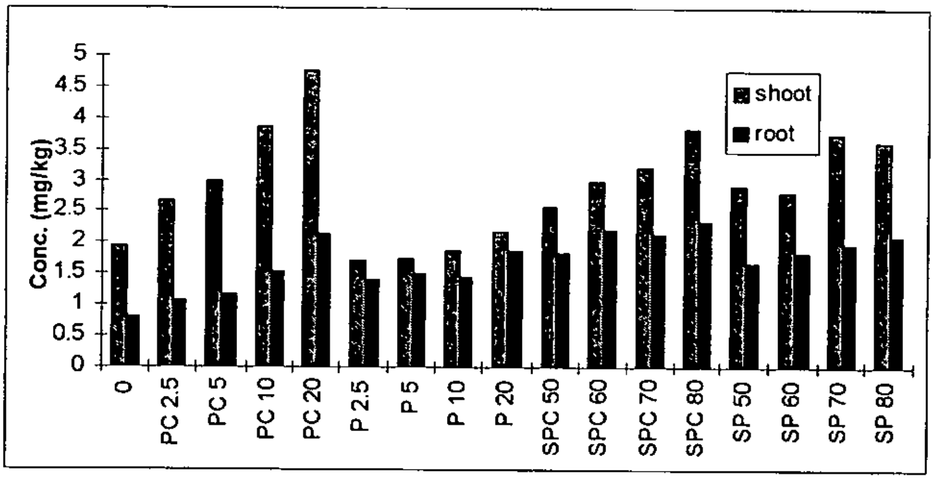

Fig. 7.4. 24: Concentrations of N in grass harvested from amended soil

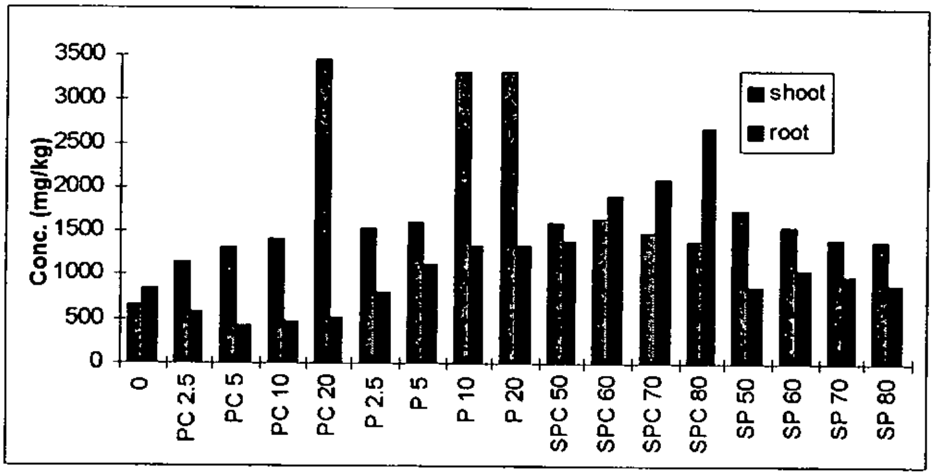

Fig. 7.4. 25: Concentrations of K in grass harvested from amended soil

7.4.2.7 Correlation between chemical concentrations in plants and soil

From Table 7.4.6, there were good correlations ($r > 0.7$) between Ni and N contents in the amended soil receiving PC 2.5 to 20 treatments and their contents in the plant tissue. The N, K and Zn concentrations in the grass harvested from P 2.5-20 treatments were corelated well ($r > 0.8$) with their corresponding contents in the root. Generally, the N content in the plant tissue had a close relationship with the application dosage of the stabilized sludge to the soil. The Cu concentration in the grass harvested from SPC 50-

80 treatments was inversely related (r> -0.7) with the concentration in the amended soil. As discussed before, the inverse relationship might be due to dilution of the metal concentrations resulting from yield increase. Whereas there were good correlations (r> 0.7) between Zn and Pb contents in amended soil and their contents in the shoot. For the grass harvested from SP 50-80 treatments, good coorelations were found for shoot Ni (r>0.8) and root Pb (r>-0.9) contents and the corresponding contents in the soil. Generally, more obvious relationship was observed in SPC mixture than SP mixture.

Table 7.4.6: Correlation coefficients of heavy metals in plant and soil

		Cu	Zn	Pb	Ni	N	K
PC 2.5-20	Shoot	-0.403	0.993	0.512	0.781	0.748	-0.856
	Root	-0.760	0.203	0.307	0.925	0.917	-0.061
P 2.5-20	Shoot	0.258	-0.585	-0.328	-0.208	-0.892	0.479
	Root	-0.383	0.945	0.258	0.625	0.986	0.842
SPC 50 -80	Shoot	-0.706	0.783	0.795	-0.171	-0.070	-0.074
	Root	-0.919	0.898	0.459	-0.345	-0.157	-0.348
SP 50 - 80	Shoot	-0.172	0.535	-0.641	0.852	-0.336	-0.309
	Root	0.161	-0.635	-0.983	-0.281	0.137	-0.396

7.4.2.8 Summary of Phase II experiment

From Table 7.4.7, it can be concluded that the optimal application dosage of the stabilized sludge was 20 % and the ratio of sludge to the stabilizing agents should be 1:1 (sludge: PFA+lime = 50:50). Besides, the germination rate and yield increased when the dosage increased, demonstrating that heavy metal accumulation by the plant receiving 20% application had not reached the toxicity level. On the other hand, when the sludge to fly ash and lime ratio increased, the productivity deceased. Thus, a lower sludge/ash ratio should be considered for agricultural purpose. And there was no significant difference in the effect of sludge- ash and sludge-ash-lime amendment. The possible explanation was that the proportion of lime added was relatively small. On the other hand, it clearly shows that fly ash alone may serve as a composting ingredient, along with sewage sludge. Its basic property could permit neutralization of the acidic sewage sludge, thereby minimizing the bioavailability of heavy metals and the injury to plants and crops.

Table 7.4.7. Stabilized sludge amended soil mixutres achieving optimal germination rate and yield

Mixture	PC	P	SPC	SP
Optimal Germination Rate	20	20	50	50
Optimal Yield	20	20	60	50

Also, it was found the accumulation of individual heavy metals in the plant tissue might or might not be dependent on the corresponding metal concentrations in the amended soil. Thus, it was hard to correlate the growth of the grass with the chemical constituents in the soil .

7.4.2. 9 Conslusion of plant bioassay

The trial in Series I revealed that the chemically treated sludge was not suitable for planting grass when compared to the biologically-treated sludge. Moreover, the 3 stabilized sludge samples inhibited germination rate of the grass. Though the yield was enhanced in stabilized sludge amended soil, it declined as the application dosage increased. On the contrary, the results of Series II showed that both germination rate and yield increased corresponding with the application dosage. And no growth inhibition of the grass was observed for all the treatments. This contradiction was mainly due to the different property in the two soil samples used. In fact, it was well demonstrated that yield was significantly higher for stabilized sludge amended loamy soil than sandy soil (Wong & Wong, 90). The main explanation was that sandy soil responded markedly to PFA in giving high pH and conductivity values resembling those of saline and alkaline soil. Thus, application of PFA stabilized sludge to sandy soil was not recommended .

As a whole, the experimental results of plant bioassay confirmed that stabilized sewage sludge had a positive fertilizer effect in growing crops. The resulting mixture was shown to be environmentally more acceptable, more economical, and thus enhancing the agricultural utilization of the two waste materials. However, the presence of many complex chemicals including toxic metals and nutrients in the stabilized sludge amended soil caused toxicological interactions varying from synergistic to antagonistic (Tam & Tiquia, 94), and made it difficult to identify which was the most significant factor affecting grass growth. Also, the correlation between chemical contents in soil and plant tissues is not simply a direct one.

7.5 Lysimeter tests

7.5.1 Effect of stabilization on leachate quality

Fig. 7.5.1. shows that the leachate pH from the raw sludge and stabilized sludge columns. The results of column 1 (pH: 7.26 to 6.6) and 2 (pH: 7.46-7.76) revealed that the sludge type clearly influenced pH . The chemically treated sludge favored decomposition whereas the anaerobically digested sludge caused a slow onset of the decomposition. The pH value varied over the entire period. For columns 3 and 4 , the sludges in these 2 columns were stabilized with both PFA and CaO, which produced a strongly alkaline leachate. Degradation of the waste was delayed because the alkalization of the medium inhibited almost all of the microbiota. Thus, the leachate pH values remained high during the whole period.

There was a drop in TOC value after the 34 weeks of incubation for the columns, as shown in *Fig. 7.5.2.* There was much great fluctuation in leachate TOC over the period with maximum values observed at week 3. This sharp increase in TOC in the first few weeks was probably due to the acetogenic activity which gave rise to high levels of volatile acids in the leachate which contributed significantly to the TOC concentrations (Craft & Blakey, 88). After the peak, the TOC dropped rapidly, indicating that some gasification of organic substances had taken place. When comparing with the sludge only columns , the leachate of CAPS sludge had a higher TOC concentration than that of the anaerobically digested sludge. This is reasonable as anaerobic digestion had already converted most of the organic acids to gaseous products. The effect of stabilization on the two types of sludge was also different. With TP sludge, stabilization increased the

TOC leaching at the first few weeks with small variation in value over the entire period. Adding PFA and lime to CAPS sludge, on the other hand, greatly increased the TOC release in the first few weeks but caused a drastic decrease in concentration at the end of sampling period. TOC, the products of biological processes, should decrease in concentration along the longevity of a landfill due to the transfer of carbon atoms from the mass to the leachate, and then to landfill gas (Ehrig, 88).

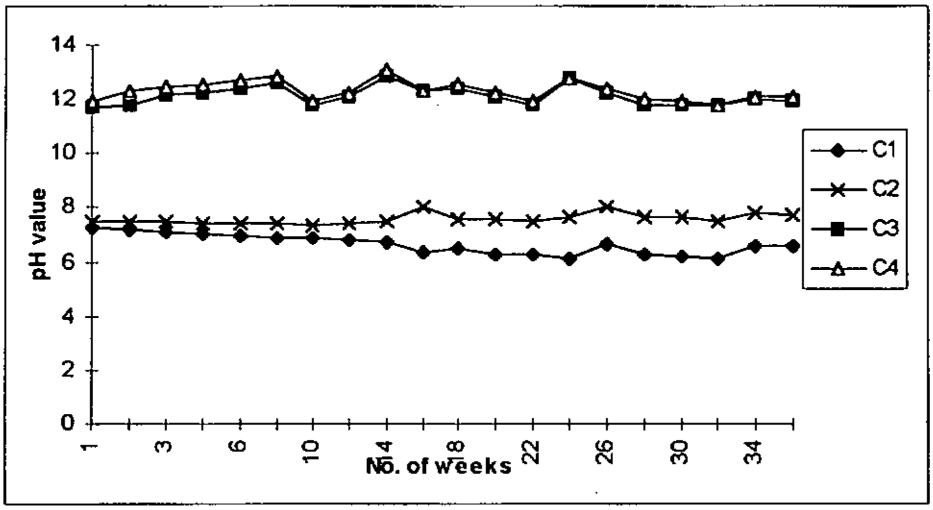

Fig. 7.5.1: pH value of leachate from columns 1, 2, 3 & 4

(C1: raw CAPS sludge; C2: raw TP sludge ; C3: PFA & CaO stabilized CAPS sludge; C4: PFA & CaO stabilized TP sludge)

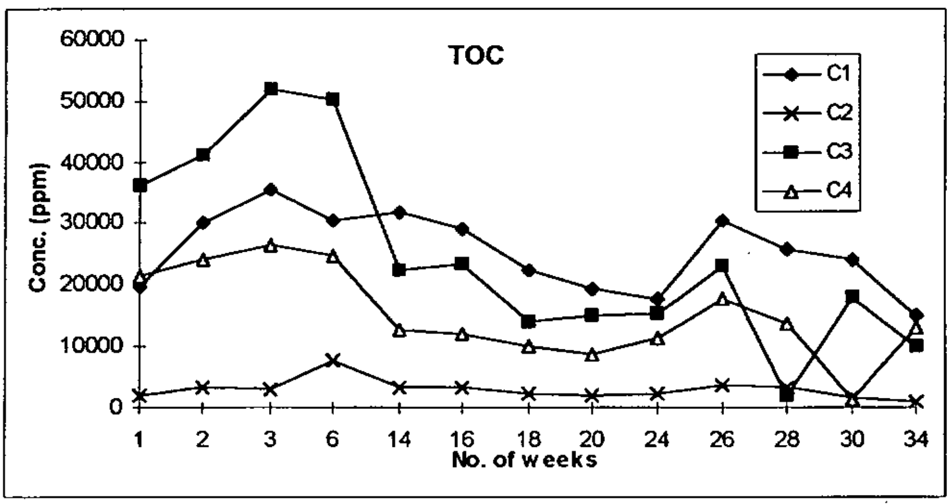

Fig. 7.5.2 : TOC concentration in leachate from columns 1, 2, 3 & 4

Fig. 7.5.3 - Fig. 7.5.5 show the concentrations of Cu , Zn and Ni detected in the leachate. The leachate metal concentrations of C1 and C2 increased at the end of sampling period. The leaching behavior of unstabilized sludge revealed that the leachate concentration was not dependent on the initial metal concentration in the sludge. Most of the metals seemed to be "locked" up in the raw sludge. For the remaining 2 columns, they showed a gradual decrease in concentration within the tested period except for C3 which showed a surge at week 4. Generally, stabilization greatly enhanced the initial leaching rate of metals from the PFA and lime stabilized sludge. Such behavior can be explained by the formation of soluble organo-metallic complexes in the alkaline environment, an example of this is $Cu_3(CO_3)_2(OH)_2$ (Cossu & Serra, 90).

In the later period, the behavior of metals is controlled by precipitation of metal in the form of insoluble sulfides (Pohland et. al., undated). Once active sulfate reduction/sulfide generation in the column started, the metal would be removed by precipitation as the respective sulfides and physical entrapment in the waste matrix. With sulfide formation, the metals were precipitated more rapidly than they could be redissolved for the sludge solids, and so the metal concentration commenced to decline. Apart from precipitation, absorption can also immobilize the heavy metal. This allows the separation of metals from the liquid phase and are then constituted into the solid phase which may remain in the waste matrix due to filtration and adsorption induced by the same solid matrix (Cossu & Serra, 90).

When comparing the leachate behavior of C3 & C4 , CAPS sludge showed faster release of metals than TP sludge. One possible explanation was due to the high chelating effects of Fe(III) ions in the $FeCl_3$-precipitated CAPS sludge that tended to form more organo-metallic complexes.

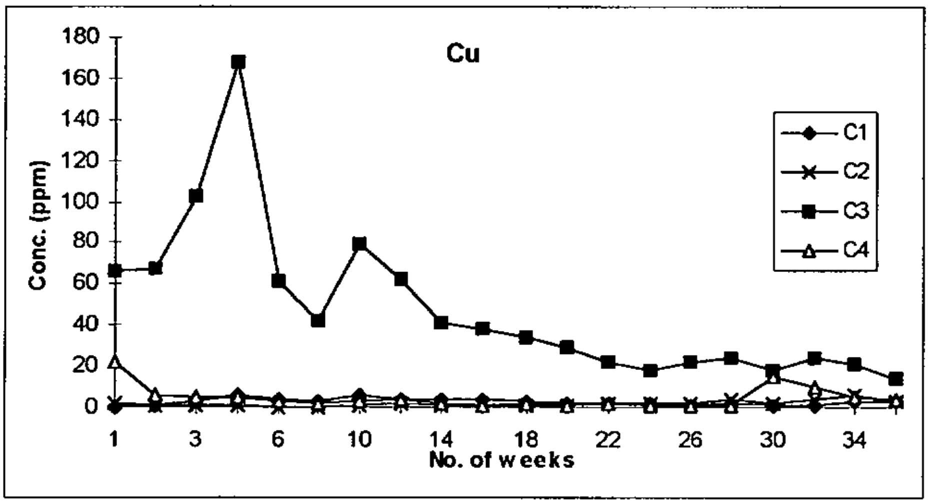

Fig. 7.5.3 : Cu concentration in leachate from columns 1, 2, 3 & 4

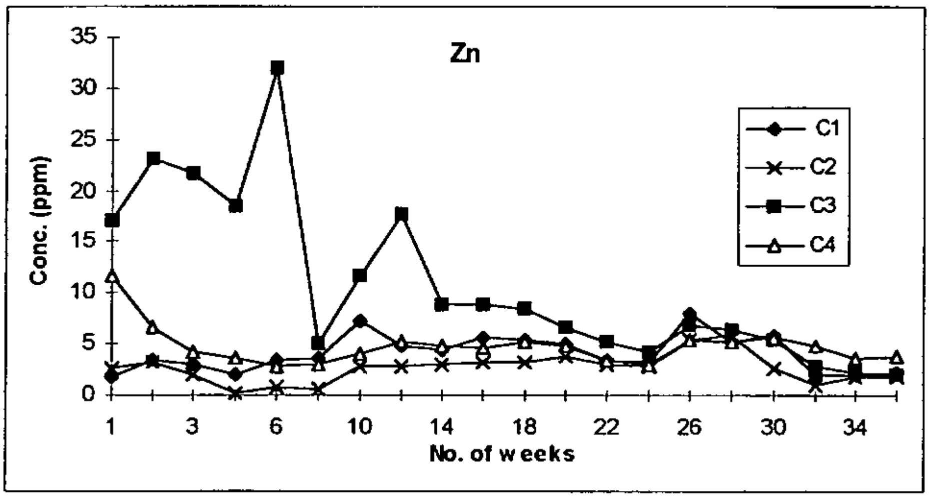

Fig. 7.5.4 : Zn concentration in leachate from columns 1, 2, 3 & 4

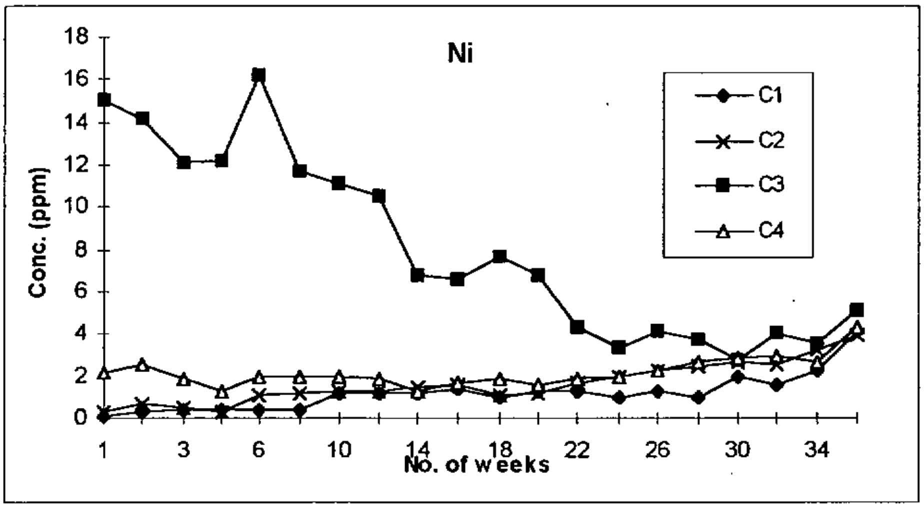

Fig. 7.5.5 : Ni concentration in leachate from columns 1, 2, 3 & 4

Fig. 7.5.6. shows that the leachate K concentrations fluctuated over the sampling period. Generally, there was a drop in concentration of the leachate from the stabilized sludge columns. There was no significant precipitant for K and it does not participate in any considerable way in complexion reactions. Thus, the behavior of K was expected to be that of a conservative tracer throughout the stabilization period (Pohland et. al., undated).

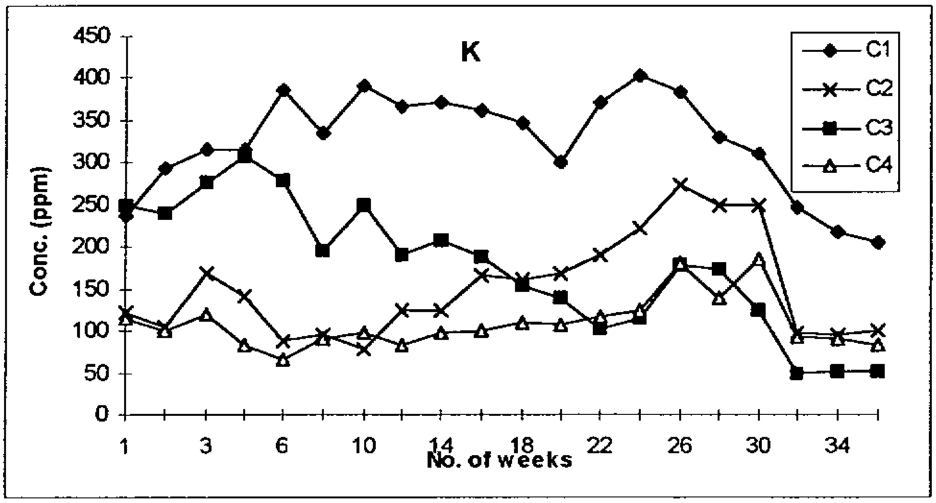

Fig. 7.5.6 : K concentration in leachate from columns 1, 2, 3 & 4

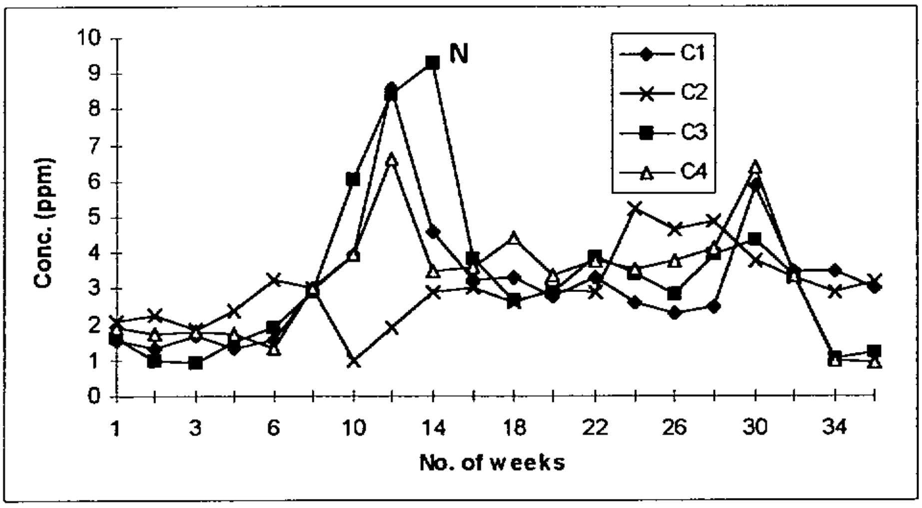

Fig. 7.5.7 : N concentration in leachate from columns 1, 2, 3 & 4

From *Fig. 7.5.7*, the leaching behavior of N of the stabilized sludge sample were the same as Zn and Cu, with a decrease in concentration at the end of sampling period. The organic-N compounds may be retained in the sludge by adsorption reactions , and calcium carbonate crystals, can precipitate with free calcium and give organo-calcic complexes, or form organocalcium salts (Liao & Randtke, 86). For the untreated sludge column, there was an overall increase in total N content at week 36. This was in direct response to the additional nutrient load present in the raw sludge. Besides, the absence of nitrification under the prevailing anaerobic conditions within the reactions has give rise to increased leaching of ammonical nitrogen, which also contributes to the increased N concentration in the leachate (Craft & Blakey, 88).

7.5.2 Comparison of the effect of PFA addition and PFA plus lime addition

From *Fig. 7.5.8*, for the sludge treated with PFA only , a decrease in leachate pH values was observed. This showed that the use of PFA only would allow a more rapid establishment of the methanogenic phase. Again, the PFA and lime stabilized sludge column maintained a high pH level over the whole period. On the other hand, the leachate pH of the column containing paper only dropped from 6.6. to 5.94 , and this change was probably due to the supplement of sludge which supplied nutrient for the microbes .

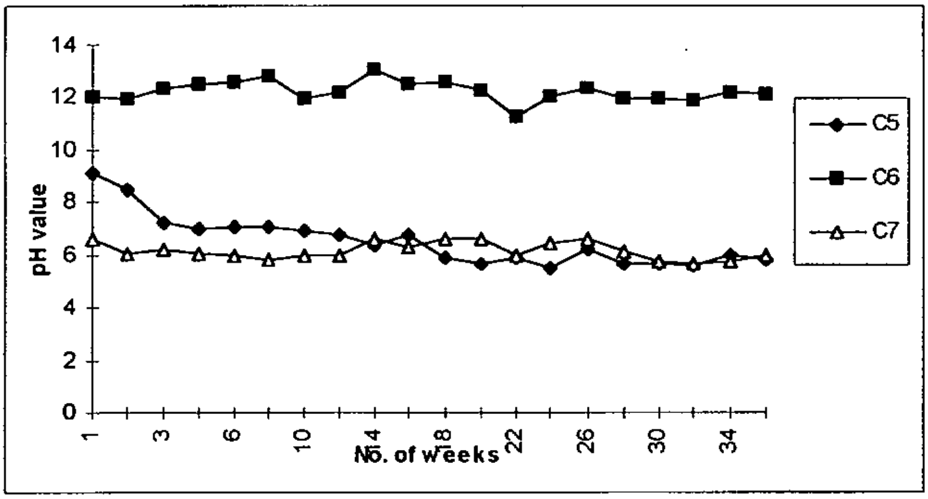

Fig. 7.5.8 pH value of leachate from columns 5, 6 & 7

(C5: PFA stabilized SC sludge + paper; C6: PFA & CaO stabilized CAPS sludge + paper; C7: paper +CAPS sludge)

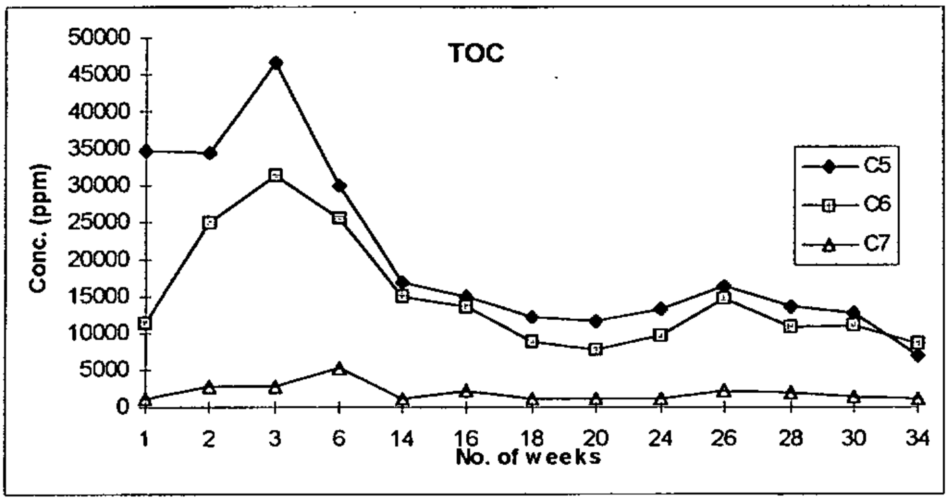

Fig. 7.5.9 TOC concentration in leachate from columns 5, 6 & 7

The TOC content in the leachate from the PFA stabilized column was greater than that of the PFA plus lime stabilized column, as shown in *Fig. 7. 5.9*. This can be attributed to the pH effect. The lower pH value favors the acetogenic activity which release more volatile acid.

Fig. 7.5.10 shows that the leaching patterns of Cu of C5 & C6 were very similar throughout the test period. Large amount of Cu was leached out in the first week, followed by a big drop at week 2 and another peak at week 4, and the concentration decreased with an erratic behavior, rapidly dropped in the following weeks. The concentration of Cu leached out from the PFA plus lime stabilized column was higher than that of the PFA stabilized column. For the column containing paper only, the Cu content, mainly contributed by the sludge , showed a gradual decrease until reaching the zero level at the middle of the sampling period.

The overall leachate Zn content in the PFA stabilized sludge column was higher than that of the PFA plus lime stabilized one (*Fig. 7.5.11*). This was the opposite trend to Cu. For the paper only column, its leaching behavior resembled that of the raw CAPS sludge, with only a small variation in Zn value over the entire period.

For columns 5 & 6 , there was a rapid drop in Ni concentration between week 3 and week 10, followed by a gradual increase until the end of sampling period (*Fig. 7.5.12*). The rate of the decrease in the PFA stabilized column was also greater than that of the PFA plus lime stabilized one. For the paper column, the leachate Ni concentration remained low throughout the tested period.

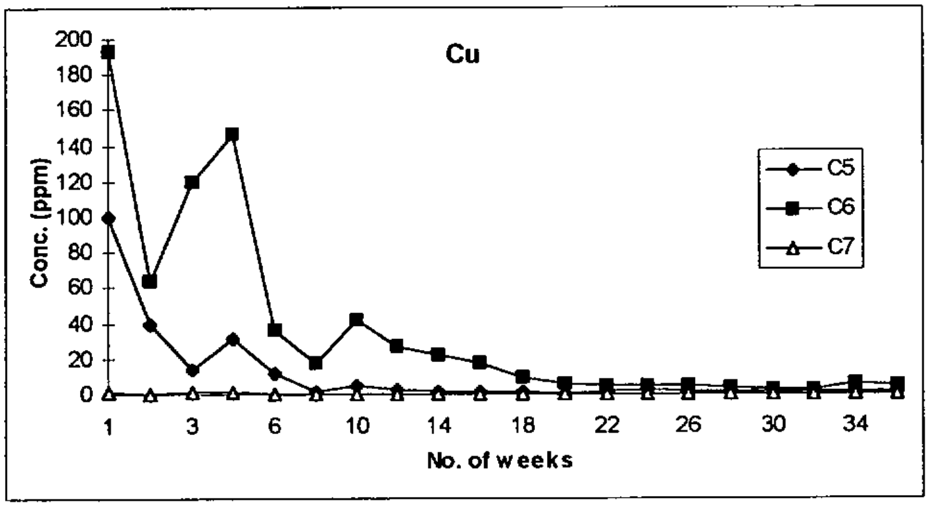

Fig. 7.5.10 Cu concentration in leachate from columns 5, 6 & 7

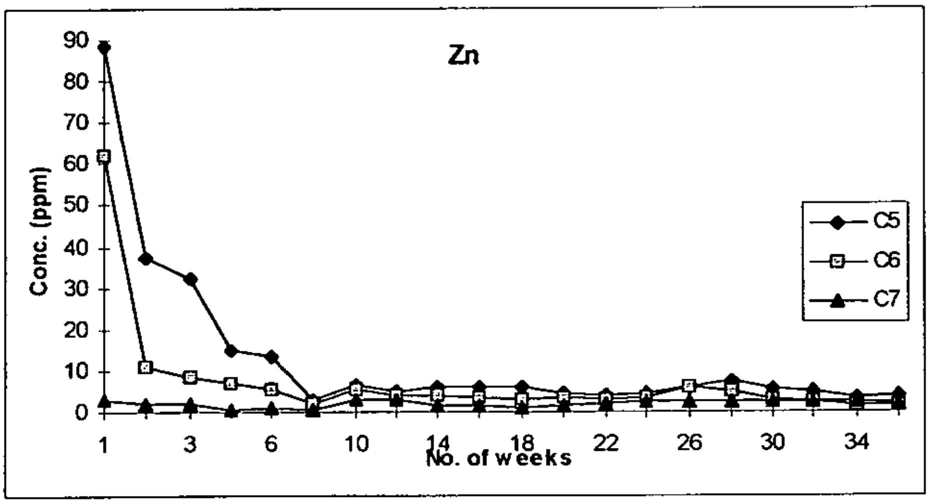

Fig. 7.5.11 Zn concentration in leachate from columns 5, 6 & 7

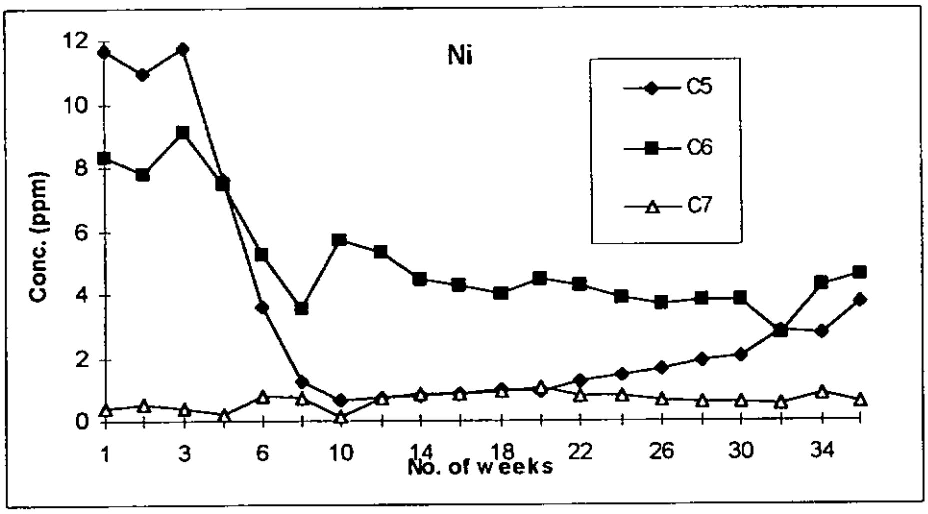

Fig. 7.5.12 Ni concentration in leachate from columns 5, 6 & 7

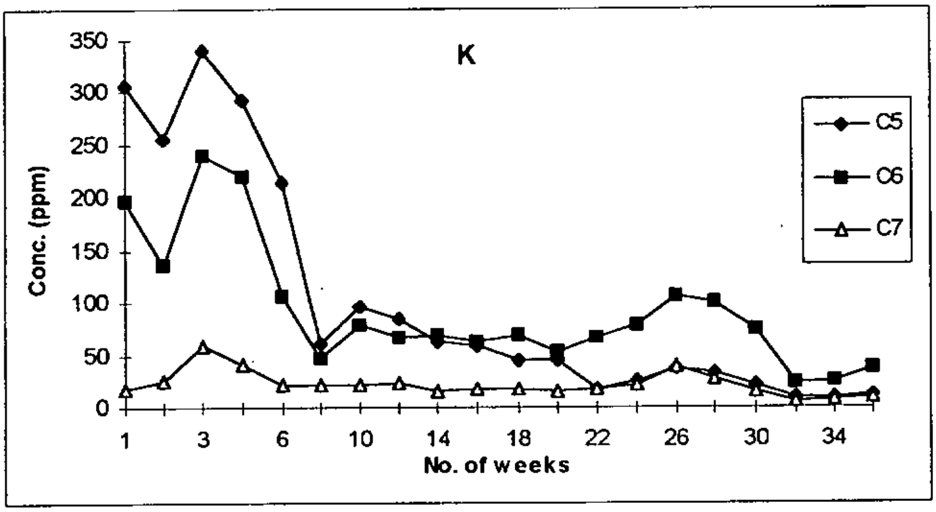

Fig. 7.5.13 K concentration in leachate from columns 5, 6 & 7

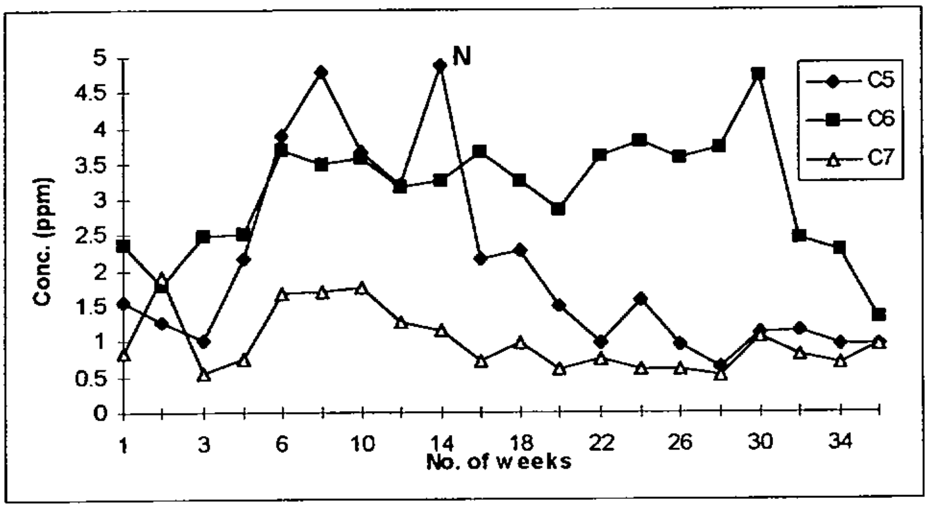

Fig. 7.5.14 N concentration in leachate from columns 5, 6 & 7

The leaching pattern of K in columns 5 and 6 also followed the similar pattern as Cu and Zn, as shown in *Fig. 7.5.13*. Also, the decrease in concentration in the PFA stabilized column was also more prominent than that of the PFA plus lime stabilized column.

The leachate N concentration of C 5 and 6 fluctuated greatly over the period with only a small drop in value at the end of sampling period (*Fig. 7.5. 14*). For the paper only column, there was a smaller variation over the period. The leaching pattern of the PFA stabilized column was quite different to that of the PFA plus lime stabilized one.

7.5.3. Summary of leachate characteristics

There was not much difference between the leaching pattern of various parameters of CAPS and TP sludge. This showed that the nature (chemical or biological)of the sludge treatment process might not influence the leachate characteristics in the landfill. However, once the sludge was alkaline stabilized , the CAPS sludge caused a faster release of heavy metals as well as TOC and K than the biologically treated sludge. When comparing the two modes of stabilization, PFA addition only caused more TOC, Ni, N and K decrease than PFA plus lime. For Cu and Zn, the opposite trend was observed.

7.5.4. Lysimeter leaching behavior and TCLP leachability

The earlier findings on TCLP leachability tests (section 7.3.4.) revealed that the addition of PFA and lime could reduce Cu & Ni leachability of the stabilized sewage sludge. The present results of lysimeter test indicated that the amount of metal leached out from the

PFA and lime stabilized sludge was much larger than that of raw sludge, particularly in the early stage of column operation. Though TCLP test is widely viewed as the 'worst case scenario" to assess the toxic effect of a hazardous waste in the landfill environment, the procedure may not be directly applied to this case. The main reason was that the stabilized samples has a very high alkalinity. Even if the stabilized sludge are subjected to severe acid condition created by the extraction fluids in TCLP test, the pH of the extracts were still quite high (at a value around 9.5-10). Thus, TCLP test might not provide an accurate estimate of the metal leaching under the landfill environment. The TCLP could only represent a simple extraction procedure under an equilibrium leaching environment. These make it quite difficult to correlate with the flow-through leaching environment in the lysimeter as the leaching condition of the latter is under a dynamic situation.

Nevertheless, one obvious finding in the experiments was that the amount of metal leaching from the stabilized sludge decreased as time progressed. This was shown both in the TCLP and lysimeter test results. This imply that once the degradation process in the lysimeter become stable, the metal leaching behavior might be easier to interpret.

7.5.5 Gas production

The rate of gas production from the 7 columns were very slow. Thus, analysis of gas could only be carried out at the end of the sampling period. Table 7.5.1. shows the gas compositions of 4 columns. For the remaining columns, only a trace amount of gas can be detected in the sampling bag. The concentration of CH_4 produced followed the order C1>C2>C7>C5. The amount of gas production in CAPS sludge was slightly higher than that of TP sludge. Also, the rate of gas formation in the PFA stabilized sludge column was slow. Based on these results, it could be seen that stabilization of sewage sludge did not favor methanogensis. In fact, it was found that gas emission of the columns had a close relationship with the leachate pH. A pH value lower than 7 was observed in the columns which generated methane . Besides, TOC concentration may also affect the methane generation process.

Table 7.5.1. Gas composition and quantity from the columns at week 36

Column	CO_2 (%)	CH_4 (%)	O_2 (%)	Volume (L)
1	15	14	70.1	2.64
5	0.3	2.95	96.5	0.24
2	11.9	9	79.1	0.48
7	7.5	4	88.5	0.96

Concerning gas generation, four stages are usually postulated (Pohland)

Stage I: aerobic decomposition in which entrained O_2 is converted to CO_2

Stage II: anaerobic decomposition starts as O_2 becomes depleted, CO_2 and H_2 are produced and the N_2 from air is progressively displaced

Stage III: anaerobic CH_4 production rises to a peak and CO_2 concentration fall, N_2 concentration drops to zero

Stage IV: a slow decline in CH_4 production rate occurs over many years, gas composition at this stage are usually in the CH_4 50-70% range and CO_2 50-30% range

Due to the limited quantity of gas generated, it was difficult to distinguish clearly the different stages of decomposition in the columns. From the ratio of CO_2/CH_4, it was estimated that columns 1, 2 and 7 might reach the beginning phase of Stage III.

7..5.6 Summary

The above results show that liming the sludge delayed the gas production by maintaining high pH levels. For the stabilized sludge columns, their Cu and Zn leachate concentrations reflected a relatively normal pattern of rapid initial washout/microbically mediated stabilization to a reduced/constant level as stabilization progressed. The leaching rates of heavy metals into the leachate in the stabilized CAPS sludge were higher than the stabilized TP sludge. CAPS sludge also caused an earlier onset of methanogensis than TP sludge. No conclusion can be drawn on the different effect of PFA or PFA plus lime stabilization on the landfill stabilization process. On the whole, CAPS sludge can be safely disposed of in the landfill environment despite its elevated heavy metal contents. The decomposition rate of the CAPS sludge is expected to be higher than the biological treated sludge. As a whole, when compared with the raw sludges, the stabilized sludge released more heavy metals in the early phase of landfill leaching.

CHAPTER 8: SUMMARY OF MAJOR EXPERIMENTAL FINDINGS

The jar test results showed that the optimum dosage for the removal of 60% of SS was 30 ppm of $FeCl_3$ with 0.5 ppm polymer . A larger scale pilot test further revealed that the addition of 30 ppm of $FeCl_3$ and 0.5 ppm polymer could provide a reduction of SS, total N and total P higher than 80%, 70% and 40%, respectively. Physical and chemical tests conducted on the sludge obtained from the large scale test also showed that the CAPS sludge had better filterability and dewaterability than the unassisted-settled sludge. And these suggest that CAPS can be used as an alternative for the treatment of sewage to traditional biological processes. Also, the sludge produced by CAPS may have better physical and chemical properties than that of biological treatment process.

Detailed characterization of the CAPS sludge and biological treated sludge was done to compare their different properties. It was found that CAPS sludge was better than the other sludge samples in terms of filterability, settleability and dewaterability. On the other hand, the concentrations of total Cu, Pb, Ni, Cd, Cr and K in CAPS sludge were also higher than other sludges. It is concluded that there are significantly differences in both physical and chemical properties between the chemically modified sludge and the biologically treated sludges. However, the elevated ammonia and heavy metal contents in CAPS sludge may pose hazardous effect on the environment when it is disposed in landfills or agriculturally utilized. Thus, the method of disposal of the CAPS sludge requires careful consideration.

Alkaline stabilization of sewage sludge is commonly used to minimize the nuisance conditions created during sludge disposal. From the results, PFA and lime stabilization of sewage sludge could reduce TCLP metal leachability (Cu & Ni), pasteurize the pathogens and increase the solid content in the CAPS sludge. Thus, it can be seen that the use of PFA together with lime could render the stabilized sewage sludge meeting the USEPA's criteria for PFRP in addition to producing a final product with improved handling characteristics than the raw sludge. Stabilization also caused Zn in the sludge to shift from the more available to the less available form. And the concentrations of the total heavy metals decreased after stabilization. So, the reuse of the CAPS sludge onto land can be made possible by chemical stabilization. Besides, the experimental results show that there was no significant difference in leaching behavior or metal speciations between the PFA plus lime stabilized sludge and the PFA stabilized sludge.

The Series I of the plant bioassay test showed that the total shoot yield of the grass harvested from the amended sandy soil was significantly higher than that of the natural soil. The percentage of seedling emergence as well as shoot yield were in the order of TP> YL> SC. Applying the stabilized anaerobically digested sludge to the soil reduced Zn, Cr and P concentrations in the root tissues of the grass. For CAPS sludge, the concentrations of the metal contaminants as well as the nutrient levels of the crops grown in the stabilized amended soil were increased as compared to the control. The above results reveal that chemically treated sludge exerted more toxic effect than the biologically treated sludge. This was mainly due to the higher elemental uptake by the grass grown on the soil receiving SC stabilized sludge amendments. The results of the Series II bioassay test showed that the optimal application dosage of the stabilized sludge in rocky soil was 20 % and the ratio of sludge to the stabilizing agents should be 1:1 by weight. Besides, the germination rate and yield of the grass increased when the dosage increased. But when the sludge to fly ash and lime ratio increased, the productivity decreased, thus, a lower sludge/ash ratio should be considered for agricultural purpose. Above all, there was no observed difference in the effect of sludge- ash and sludge-ash-lime amendment. This was consistent with the previous findings that there was no significant difference in the leaching behavior or metal speciations between the PFA plus lime stabilized sludge and the PFA stabilized sludge. The difference in growth behavior of the grass in Series I and Series II experiment was mainly due to the different soil samples used. The whole planting experiment demonstrated that alkaline stabilized CAPS sludge had positive fertilizer effect in growing crops, provided that the dosage is carefully controlled and the appropriate type of soil medium was selected .

The column tests revealed that liming the sludge delayed the gas production by maintaining high pH levels. The releasing rate of heavy metal into the leachate in stabilized CAPS sludge were higher than the stabilized TP sludge. CAPS sludge caused an earlier onset of methanogensis than TP sludge. No differentiation was found between the effect of PFA and PFA plus lime stabilization on the landfill stabilization process. On the whole, the results showed that unstabilized CAPS sludge can be safely disposed of in the landfill environment despite its elevated heavy metal contents. When compared with the raw sludges, the stabilized sludge released more heavy metals in the early phase of landfill leaching.

All in all, chemical stabilization can be viewed as an alternative means to treat the CAPS sludge. The use of PFA and lime together or PFA alone had no significant different effect on the final property of the stabilized sludge. Also, the stabilized product has great potential to be used as a soil conditioner for landscaping purposes.

CHAPTER 9 :CONCLUSION

1. CAPS could achieve superior removal efficiency of suspended solids, total nitrogen and phosphorous. It could be used as another alternative to treat wastewater other than traditional biological treatment processes.

2. There were significantly differences in both physical and chemical properties between chemically modified sludge and biological treated sludges. CAPS sludge was better than the anaerobically digested sludge in terms of filterability, settleablity and dewaterability.

3. The use of PFA and lime could render the stabilized CAPS sludge meeting the USEPA's criteria for PFRP in addition to producing a final product with improved handling characteristics. There was no significant differences in the leaching behavior or metal speciations between the PFA plus lime stabilized product and the PFA stabilized one.

4. It was feasible to plant on a mixture of natural soil and stabilized CAPS sludge provided that the dosage is carefully controlled and the appropriate type of soil is selected. A low sludge to PFA/lime ratio should be used for higher productivity.

5. The addition of lime to CAPS sludge delayed the gas production in the landfill. Alkaline stabilization generally increased the metal leaching in the early phase after disposing in the landfill followed by a gradual decrease in leachate metal concentration to a low level.

CHAPTER 10: RECOMMENDATIONS

The possibility of feeding/recycling the raw, liquid sludge produced by CAPS back into the primary sedimentation tank to further increase the capture of wastewater particles can be evaluated. Although extensive research on the mechanism of floc formation in conditioning of anaeorbically digested sludge with polymer had been conducted, for better design of the dewatering process, more detailed studies on the flocculation mechanism of CAPS sludge should be carried out as well.

The type of soil is an important factor governing the growth of grass in stabilized sludge amended soil mixtures. Thus, the effect of different soil types such as sandy soil , sandy loam or calcareous soil on grass growth should be studied. Besides, a wider range of different mixing ratios and application dosages should be tested so as to establish the optimal rate of stabilization and application.

Apart from chemical stabilization, fly ash can be used as a co-composting material for sewage sludge. Thus, the potential of using PFA and CAPS sludge can be evaluated by measuring the changes in microbial activity and heavy metal availability during the composting process.

The detailed leaching behavior and the maximum quantity of the material leached out of the stabilized CAPS sludge and raw CAPS sludge can be further studied by the equilibrium leach test (ELT) and long-term leaching test (LTLT) .

Besides the landscaping application, the use of stabilized CAPS sludge as a fill material for land reclamation and restoration can be investigated by means geotechnical testings such as compaction test, settlement test and shear strength test, etc.

As regards the lysimeter test, other important parameters such as total volatile acids (TVA), chemical oxygen demand (COD), biochemical oxygen demand (BOD), volatile solids (VS), nitrate and ammonia nitrogen, etc. can also be studied. The measurement of the above parameters can provide a more detailed picture of the assimilative capacity and degradation processes of the CAPS and stabilized sludges in the landfill environment.

In order to simulate the actual refuse composition in Hong Kong, municipal solid waste (a mixture of domestic , commercial, industrial and construction waste) can be used to codispose the stabilized sludge instead of using only paper waste in further research .

CHAPTER 11: REFERENCES

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Appendix I

Results of jar test & pilot scale test

SS removal efficiency (%) by different coagulants

Conc/ppm	Removal Efficiency /% PACl	FeCl3	Lime	PFS
0	30	30	30	30
20	71.25	61	59.33	57.1
50	77.5	67.1	64.11	60.41
100	84.5	69.3	66.33	73.45
250	88.7	80.7	70.29	66.5
500	77.1	58.9	77.04	54.3

SS removal efficiency (%) by FeCl3 in sewage with different SS

Conc/ppm	Removal efficiency/% SS 210.5	SS 228.5	SS 371.5
20	76.5	80.7	92
40	79.1	83.1	90.6
60	73.7	87.3	88.7

Turbidity removal removal efficiency (%) by different coagulants

Conc/ppm	Removal efficiency/% PACl	FeCl3	Lime	PFS
0	40	40	40	40
20	83.6	46.4	62.5	58.7
50	88.8	54.5	62.4	63.8
100	92.4	67.3	58.1	70
250	93.2	87.3	64.4	82.2
500	88.4	66.4	71.2	75.6

SS removal efficiency (%) by FeCl3 & Magnafloc in TP sewage

	Removal Efficiency /%			
Conc/ppm	0	30	60	90
0.25ppm	22	58	64	60
0.5ppm	21	61	57	59
0.75ppm	25	41	41	48
1ppm	20	35	36	32

SS removal efficiency (%) by FeCl3 & Magnafloc in SC sewage

	Removal Efficiency /%			
Conc/ppm	0	30	60	90
0.25ppm	22	58	64	60
0.5ppm	21	61	57	59
0.75ppm	25	41	41	48
1ppm	20	35	36	32

SS removal efficiency (%) by FeCl3 in TP & SC sewage

	Removal efficiency/%	
Conc/ppm	TP	SC
0	12.3	8.9
10	21.5	10.4
20	34.3	27.3
30	34.7	47.1
40	35.9	55.1
50	36.3	69.7
60	38.1	58.7
70	45.8	47.5
80	44.5	45.3
90	41.2	49.3
100	46.6	57.5

Appendix II

Results of sludge characterization

Concentratons (ppm) of different chemical parameters in sludge samples

	Conc./ppm				
Parameters	CAPS	rTP	rYL	dTP	dYL
Total solids	4630	24530	13680	9362	6004
Suspended solids	1184	6048	2826	4018	2079
Volatile solids	3375	13249	10688	5143	1600
Nitrate	5.02	5.63	2.63	1.02	1.14
Ammonia	16.22	8.7	19.08	2.55	6.5
Phosphate	29.47	13.55	30.24	1.1	2.43
N	121.89	71.46	127.9	67.16	27.83
P	136.93	37.53	156.93	22.9	73.56
K	1706.21	509.8	910.6	230.27	659.9
Cu	2068.98	107.37	100.78	63.88	92.63
Zn	545.94	454.5	5152.05	264.82	3122.6
Ni	264.58	72.93	126.65	60.86	72.91
Cd	50.44	14.4	32.31	33.46	31.92
Cr	724.19	157.7	607.13	61.06	96.34
Pb	482.72	207.72	358.44	91.5	73.41

Concentratons of Cu (ppm) in different phases of sludge samples

	Conc/ppm				
Phases	CAPS	dTP	dYL	rTP	rYL
Adsorbed	1.99	1.01	3.84	4.76	3.04
Carbonate	18.27	5.77	5.13	6.14	4.14
Organically	13.02	11.18	7.83	24.53	8.95
Exchangeable	2.14	6.76	8.34	12.99	6.27
Sulphide	34.7	53.33	42.78	35.76	30.56
Unextracted	29.88	21.95	32.08	15.76	47.04

Concentratons of Ni (ppm) in different phases of sludge samples

	Conc/ppm				
Phases	CAPS	dTP	dYL	rTP	rYL
Adsorbed	9.31	5.16	3.97	22.59	13.8
Carbonate	3.61	0.23	0	15.85	9.87
Organically	18.14	16.56	12.44	27.38	14.58
Exchangeable	24.74	16.37	13.61	22.38	20.58
Sulphide	14.41	16.95	24.69	9.9	14.23
Unextracted	29.79	40.73	45.29	1.89	2.94

Concentratons of Pb (ppm) in different phases of sludge samples

Phases	Conc/ppm CAPS	dTP	dYL	rTP	rYL
Adsorbed	11.2	10.7	13.8	16.24	17.78
Carbonate	11.58	9.53	16.27	0	0
Organically	26.86	28.62	27.83	26.43	20.94
Exchangeable	8.36	24.04	25.64	29.44	29.97
Sulphide	11.12	13.64	14.05	14.53	23.03
Unextracted	20.36	13.47	2.41	13.36	8.28

Concentratons of Cr (ppm) in different phases
of sludge samples

Phases	Conc/ppm CAPS	dTP	dYL	rTP	rYL
Adsorbed	2.3	4.6	3.14	13.48	11.05
Carbonate	3.09	2.26	13.11	28.16	11.5
Organically	15.3	5.82	36.88	27.65	16.58
Exchangeable	2.53	8.97	2.87	13.82	9.34
Sulphide	5.06	11.69	33.07	14.89	33.17
Unextracted	71.18	66.66	10.93	2.6	18.36

Concentratons of Zn (ppm) in different phases
of sludge samples

Phases	Conc/ppm CAPS	dTP	dYL	rTP	rYL
Adsorbed	21.92	2.98	3.34	20.13	1.04
Carbonate	8.71	21.89	56.19	18.78	33.27
Organically	27.8	14.96	18.38	22.83	25.37
Exchangeable	1.22	2.7	0.2	3	5.96
Sulphide	20.2	22.09	11.72	11.91	27.86
Unextracted	20.14	35.21	10.17	23.35	6.548

Concentratons of Cd (ppm) in different phases
of sludge samples

Phases	Conc/ppm CAPS	dTP	dYL	rTP	rYL
Adsorbed	8.76	23.5	16.02	21.52	14.78
Carbonate	0	0	0	16.7	10.61
Organically	18.99	38.95	11.92	31.91	20.96
Exchangeable	6.96	14.95	0	14.51	11.83
Sulphide	11.3	16.11	16.44	15.22	12.86
Unextracted	53.99	6.49	50.6	0.14	28.96

Appendix III

Results of sludge stabilization

Cu analysis of multiple extraction

	Conc/ppm			
No.	J	G	E	PFA
1	0.05	0.22	0.97	0
2	0.11	0.49	0.16	0.05
3	0.8	0.77	0.61	0.06
4	1.23	0.61	0.56	0.02
5	1.46	0.51	0.37	0

Zn analysis of multiple extraction

	Conc/ppm			
No.	J	G	E	PFA
1	0.02	9.37	2.73	0.78
2	6.13	5.77	10.58	0.4
3	7.08	2.41	3.16	0.19
4	3.59	1.36	1.33	0.12
5	1.79	1.08	0.65	0.082

Ni analysis of multiple extraction

	Conc/ppm			
No	J	G	E	PFA
1	1.35	1.26	0.91	0.15
2	0.44	0.48	0.73	0.044
3	0.46	0.26	0.26	0.04
4	0.3	0.24	0.17	0.014
5	0.21	0.18	0.11	0.009

Cd analysis of multiple extraction

	Conc/ppm		
No.	J	G	E
1	0.023	0.043	0.035
2	0.06	0.043	0.097
3	0.072	0.047	0.052
4	0.054	0.075	0.056
5	0.048	0.07	0.051

Concentratons of Cu (ppm) in different phases
of sludge samples

	Conc/ppm			
Phases	J	G	E	PFA
exchangeable	20.6	19.7	28.7	0
adsorbed	8.3	11.8	11.5	0
organically	22.3	10.6	4.8	8.7
carbonate	9.4	6.2	10.9	43.3
sulphide	20.2	10.4	3.6	31.1
unextracted	20.2	47.3	47.1	16.9

Concentratons of Zn (ppm) in different phases
of sludge samples

	Conc/ppm			
Phases	J	G	E	PFA
exchangeable	2.8	2.7	0.12	2.58
adsorbed	2.8	3.8	3.5	1.07
organically	29.57	25.1	13.7	17.78
carbonate	26.9	33	55.8	19.43
sulphide	22.3	14	20	12.54
unextracted	15.7	27.4	6.88	46.6

Concentratons of Ni (ppm) in different phases
of sludge samples

	Conc/ppm			
Phases	J	G	E	PFA
exchangeable	26.7	28.1	21.3	10.59
adsorbed	9.8	12.6	8.8	11.28
organically	15	9.7	5.8	18.98
carbonate	12.1	10.7	11.3	29.09
sulphide	16.1	17.6	32.9	15.83
unextracted	20.3	21.3	19.9	14.23

Concentratons of Cd (ppm) in different phases
of sludge samples

	Conc/ppm		
Phases	J	G	E
exchangeable	20.24	22.71	35.11
adsorbed	13.14	16.29	15.35
organically	12.31	19.75	14.85
carbonate	14.36	15.86	20.33
sulphide	9.43	10.09	10.73
unextracted	30.52	15.3	3.63

Concentratons (ppm) of different chemical parameters in sludge samples

	Conc/ppm		
	J	G	E
Nitrate	4.34	1.9	0.51
Ammonia	15.13	14.97	2.11
Phosphate	18.6	9.34	6.25
Cu	96.75	55.97	51.85
Zn	305.04	159.11	145.76
Pb	14.07	8.75	8.51
Ni	60.35	33.24	48.99
Cd	18.03	13.87	14.07
N	73.21	46.58	49.87
P	40.03	28.97	31.43

Appendix IV

Results of Series I of plant assay

Concentratons (ppm) of different chemical parameters in sludge samples

	Conc/ppm rTP	sTP	rSC	sSC	rYL	sYL
Nitrate	169.01	84.21	66.56	50.31	120.99	58.17
Phosphate	83.96	79.26	81.99	59.65	71.87	33
Ammonia	56.72	25.22	45.09	5.71	61.91	41.21
Ext. Cr	1.95	2.18	3.57	4.24	7.38	3.46
Ext. Cd	2.68	2.13	2.64	2.81	2.34	2.47
Ext. Cu	11.85	6.79	518.15	386.47	6.25	1.76
Ext. Zn	226.22	117.62	262.41	165.8	336.1	315.1
Ext. Pb	7.84	3.1	3.57	3.83	3.34	3.72
Ext. Ni	10.98	7.03	237.8	117.32	9.67	7.12
Ext. B	7.34	9.43	8.71	10.26	12.06	13.06
Cr	10.39	7.21	127.66	41.87	174.96	73.29
Cd	14.78	7.9	29.42	15.2	19.337	13.37
Cu	115.56	54.17	4429.61	2304.85	77.28	44.06
Zn	524.99	354.87	611.86	383.3	1908.63	1299.62
Pb	5.58	5.26	46.38	22.76	7.23	3.38
Ni	15.41	8.69	192.93	89.1	13.33	8.9
B	66.53	56	64.07	81.95	56	77.44
N	713.63	203.03	573.21	320.25	439.23	247
P	266.29	191.95	400.03	350.29	181.45	133.14
K	4220.34	2109.95	10168.5	5169.44	5235.31	7451.1

Seedling emergence (%) of Chinese Radish & barley

	Seedling emergence (%)	
Dosage	RADISH	BARLEY
0	83.3	90
TP2.5	50	66
TP5	63.3	70
TP10	60	66.7
TP20	73.3	46.7
SC2.5	66.7	80
SC5	53.3	53.3
SC10	40	40
SC20	40	33.3
YL2.5	73.3	66.7
YL5	40	50
YL10	10	26.7
YL20	13.3	30

Root & shoot length (mm) of Chinese Radish & barley

	Radish		Barley	
Dosage	ROOT	SHOOT	ROOT	SHOOT
0	44.41	65.29	125	100
TP2.5	43.67	58.33	83.33	88.06
TP5	28.68	31.21	64.29	74.77
TP10	11.11	28.88	22.25	38.25
TP20	5	16.09	22.5	28.21
SC2.5	74.23	81.92	109.17	92.5
SC5	52.19	82.5	53.75	74.06
SC10	39.82	27.5	42.92	71.43
SC20	11.25	13.75	23	22
YL2.5	67.73	78.8	99.25	77.78
YL5	32.17	47.92	118	98.8
YL10	20	48.33	78.13	75
YL20	13.75	30	39.11	37.22

Shoot dry weight yield (g per two pots) of tall wheat grass

	Yield (g)
0	1.13
TP2.5	3.46
TP5	4.96
TP10	4.29
TP20	1.79
SC2.5	1.39
SC5	1.28
SC10	1.18
SC20	1.01
YL2.5	1.29
YL5	1.41
YL10	1.43
YL20	1.64

Seedling emergence (%) of tall wheat grass

Dosage	Seedling emergence (%)
0	17.6
TP2.5	31.5
TP5	25.3
TP10	23
TP20	9
SC2.5	13.8
SC5	15.5
SC10	16.8
SC20	12.2
YL2.5	14.8
YL5	15.2
YL10	14.3
YL20	14.2

Concentratons (ppm) of different chemical parameters in shoot of grass

Conc/ppm

	Cu	Zn	Ni	Cr	B	N	P	K
0	25.37	83.19	3.89	2.69	21.8	115.5	68.98	1966.79
TP 2.5	44.7	73.91	6.5	3.83	45.88	211.61	38.99	1852.93
TP 5	50.78	94.93	6.07	5.74	57.66	381.27	46.09	2157.06
TP 10	52.04	92.72	8.63	6.07	78.06	162.3	59.87	2306.56
TP 20	18.7	89.07	10.14	7.77	96.69	354.13	40.36	2889.02
SC 2.5	37.82	175.64	5.9	15.04	39.77	277.33	40.36	2841.82
SC 5	65.41	165.83	20.42	1.42	52.91	357.83	36.96	2385.58
SC 10	87.46	260.55	27.11	1.52	75.27	557.57	164.61	4012.74
SC 20	120	310	51.67	2.06	85.09	961.5	248.27	4479.05
YL 2.5	68	165	58	6.4	27	108	71	3936
YL 5	42	159	73	2	57	216	105	3840
YL 10	43	140	123	1.9	81	140	101	4143
YL 20	67	248	17.2	2.1	93	34	165	4456

Concentratons (ppm) of different chemical parameters in root of grass

Conc/ppm

	Cu	Zn	Cr	Cd	N	P	K
0	47.46	120.75	7.05	1.49	141.87	116.57	1442.32
TP 2.5	29.05	90.22	3.03	0.5	105.7	51.32	1682.74
TP 5	64.29	85.72	2.46	0.56	85.8	51.03	1581.18
TP 10	115.6	112.48	2.41	1.32	114.4	84	2241.54
TP 20	80.1	152.64	4.06	3.98	327.37	142.72	2570.23
SC 2.5	71.52	133.3	4.42	4.52	155.13	96.92	3161.58
SC 5	132.22	402.22	20.33	7.01	255	229.87	3401.66
SC 10	135	370	58	7.45	613	322	3888
SC 20	139.65	629	76.25	7.75	719.5	384.07	4075
YL 2.5	108	395	2.97	1.43	255.4	125	2817.64
YL 5	54	214	9.9	2.59	157	163	3193
YL 10	66	225	10.51	3.02	128.57	159	3654
YL 20	61	387	16.09	2.28	73.3	192	3886

Appendix V

Results of Series II of plant assay

Concentratons (ppm) of chemical parameters in stabilized sludge amended mixtures

	K	Ni	Conc /ppm N	Zn	Cu	Pb
PC 2.5	2615	6.3	2.75	68.85	18	5.4
PC 5	2439.5	6.15	2.8	71.9	17.5	3.25
PC 10	2786	10.75	13.5	70.85	19.5	5
PC 20	1888	10.9	13.15	60.15	15.5	6.9
P 2.5	1404	16.7	2.2	71.35	20.5	3.2
P 5	2015	11.8	2.45	67.8	21.5	3.45
P 10	1939.5	16.35	2.85	69.4	18.5	5.3
P 20	1920	19.4	3.3	80.8	19.5	4.1
SPC 50	2029.5	16.6	3.5	60.85	16.5	3.1
SPC 60	1459	14.9	4	69.25	17.5	2.7
SPC 70	1470	11.85	3.1	73.65	22.5	3.05
SPC 80	1775.5	15.2	3.75	82.9	20	3.35
SP 50	2085	12.15	2.9	67.45	18	2.3
SP 60	2084	12.2	2.6	49.5	21	2.45
SP 70	1974	12.7	2.4	51.8	20	2.75
SP 80	2364	15.65	2.75	61.35	19	2.51

Seedling emergence (%) & shoot yield (g) of tall wheat grass

	Emergence (%)	Yield (g)
0	22.7	1.8
PC 2.5	36	3.01
PC 5	45	3.56
PC 10	46.3	4.01
PC 20	62.3	5.89
P 2.5	29	3.27
P 5	37.3	4.59
P 10	42.7	4.87
P 20	51.3	6.01
SPC 50	30.7	3.66
SPC 60	30	3.81
SPC 70	28.7	3.76
SPC 80	26.7	2.63
SP 50	40.3	3.97
SP 60	32.3	3.63
SP 70	32.7	3.21
SP 80	29.7	3.01

Concentratons (ppm) of different chemical parameters in shoot of grass

Conc /ppm

	Cu	Zn	Pb	Ni	N	K
0	0.95	36	10.95	10.95	1.96	664.3
PC 2.5	1.4	16.4	6.8	4.27	2.67	1155
PC 5	0.9	16.9	4.9	3.84	2.97	1312
PC 10	1	16.7	5.7	4.34	3.86	1412
PC 20	1.3	13.3	5.7	4.73	4.78	3460
P 2.5	1.3	28.67	13.57	10.9	1.7	1533
P 5	1.2	23.4	11.2	9.38	1.76	1604
P 10	1.2	21.8	10.6	9.42	1.89	3302
P 20	1.2	18.2	16	8.5	2.17	3312
SPC 50	1.1	20.8	6.31	6.52	2.57	1591.7
SPC 60	1	21.3	6.13	6.6	2.97	1641.3
SPC 70	0.75	37	11.75	12.45	3.21	1482.5
SPC 80	0.94	34.4	18.89	18	3.81	1383.3
SP 50	1.1	37.86	10	11.38	2.92	1742.9
SP 60	1.1	35.91	8.64	11.55	2.81	1547.7
SP 70	0.83	31.88	7.71	12.5	3.76	1400
SP 80	1	46.5	10.75	12.98	3.61	1377.5

Concentratons (ppm) of different chemical parameters in shoot of grass

Conc /ppm

0	2.05	29	7	15.7	0.8	835
PC 2.5	2.2	25	10.8	9.08	1.08	590
PC 5	1.75	26.3	7.87	5.96	1.17	430.8
PC 10	1.5	32	8.25	13.58	1.56	475
PC 20	2.25	27	8.5	12.28	2.16	522
P 2.5	2	22	6.5	4.25	1.4	796
P 5	2.4	21.4	6.8	8.86	1.52	1119
P 10	2.5	27.5	8.3	13.67	1.43	1347
P 20	3	47	15	25.45	1.87	1348
SPC 50	2.05	41.5	6	18.75	1.86	1379
SPC 60	2.13	54	7	20.15	2.21	1910
SPC 70	2.16	71	12.5	23.35	2.14	2100
SPC 80	2.78	70	11	27.15	2.36	2680
SP 50	1.84	38.68	8.16	12.97	1.67	862.6
SP 60	1.76	40.29	7.94	14.56	1.86	1066
SP 70	2	49	7.5	12.25	1.97	984
SP 80	1.5	50.25	7.75	12.9	2.12	902

Appendix VI

Results of lysimeter tests

pH value of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7
1	7.26	11.71	11.92	9.13	12.03	7.46	6.6
2	7.18	11.81	12.31	8.53	11.96	7.47	6.09
3	7.09	12.16	12.49	7.21	12.34	7.49	6.23
4	7.02	12.26	12.56	7.01	12.51	7.44	6.06
6	6.98	12.42	12.67	7.08	12.62	7.45	5.95
8	6.89	12.66	12.88	7.08	12.82	7.45	5.82
10	6.88	11.8	11.97	6.95	11.93	7.38	5.98
12	6.82	12.06	12.25	6.74	12.22	7.42	5.95
14	6.7	12.88	13.1	6.34	13.08	7.47	6.62
16	6.37	12.35	12.35	6.8	12.52	8.05	6.26
18	6.49	12.41	12.57	5.87	12.57	7.56	6.62
20	6.29	12.05	12.25	5.65	12.27	7.56	6.62
22	6.28	11.76	11.94	5.88	11.25	7.51	5.96
24	6.11	12.77	12.81	5.53	12.03	7.67	6.45
26	6.69	12.22	12.36	6.19	12.34	8.03	6.63
28	6.28	11.81	11.98	5.7	11.95	7.67	6.15
30	6.17	11.77	11.91	5.67	11.94	7.62	5.77
32	6.15	11.75	11.79	5.59	11.87	7.49	5.66
34	6.6	12.03	12.12	5.94	12.19	7.82	5.76
36	6.6	11.97	12.1	5.79	12.12	7.76	5.94

TOC concentration (ppm) of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7
1	19816.7	36133.3	21550	34850	11525	2049.2	1125
2	30008.3	41158.3	23983.3	34350	24933.3	3381.7	2660
3	35425	51841.7	26358.3	46666.7	31258.3	3166.7	2683.3
6	30513.3	50316.7	24966.7	30108.3	25450	7575	5266.7
14	31933.3	22358.3	12725	17016.7	15091.7	3289.2	1009.2
16	29183.3	23608.3	12008.3	14933.3	13475	3280.8	2197.5
18	22358.3	13958.3	10150	12325	8825	2269.2	1168.3
20	19425	15066.7	8741.7	11791.7	7900	2158.3	1079
24	17655	15404	11358	13441	9766	2336	1131
26	30450	23150	17825	16283	14733	3841	2100
28	25875	1850	13600	13583	10708	3203	1935
30	24058	17950	1440	12850	11166	1757	1424
34	15050	9908	13008	6941	8691	930	1055

Cu concentration (ppm) of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7	
1	0.48	66.57	22.15	99.95	192.6	2.03	1.07	
2	1.07	67.02	5.88	39.67	64.53	1.47	0.4	
3	3.18	102.8	4.58	13.85	119.35	0.83	0.72	
4	6.25	167.85	5.53	31.89	146.35	1.28	0.83	
6	4.25	61.7	2.82	12.17	35.63	0.25	0.22	
8	2.73	42.53	2.28	1.72	17	0.4	0.08	
10	5.94	79.09	3.26	4.17	42.36	1.17	0.46	
12	4.23	62.47	3.7	2.69	26.96	2.46	0.24	
14	3.6	41.48	1.75	1.42	22.1	0.75	0.05	
16	3.82	38.3	1.48	1.27	17.5	0.8	0.05	
18	2.68	33.88	1.97	0.83	9.47	0.85	0	
20	2.1	29.4	1.1	0.57	5.37	1.02	0	
22	1.62	22.3	2.42	1.55	4.8	2.15	0	
24	1.88	18.5	1.13	1.77	4.78	2.17	0	
26	0.72	22.25	1.32	1.63	4.98	2.12	0	
28	1.9	24.05	1.12	1.42	3.77	4.01	0	
30	0.9	18.47	14.77	0.63	2.73	2.2	0	
32	0.57	23.78	10	1.03	2.75	4.13	0	
34	3.48	21.6	4.63	1.03	5.58	5.73	0	
36	2.95	14.07	3.82	1.27	4.42	3.25	0	

Zn concentration (ppm) of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7	
1	1.78	17.15	11.62	88.33	61.97	2.57	2.8	
2	3.5	23.22	6.65	37.2	10.85	3.18	1.92	
3	3.07	21.65	4.15	32.48	8.6	1.92	1.85	
4	2.03	18.48	3.58	14.75	6.98	0.28	0.27	
6	3.32	31.9	2.83	13.62	5.33	0.82	0.88	
8	3.58	4.95	2.97	2.93	1.9	0.58	0.7	
10	7.18	11.57	3.95	6.38	5.25	2.73	2.98	
12	4.77	17.8	5.25	5.22	4.05	2.83	2.75	
14	4.4	8.85	4.8	5.73	3.79	3.03	1.35	
16	5.58	8.78	4.55	6.01	3.6	3.28	1.5	
18	5.45	8.44	5.3	5.72	3.22	3.24	1.01	
20	5.04	6.69	4.9	4.33	3.34	3.74	1.63	
22	3.32	5.15	3.5	3.83	3.07	2.92	1.88	
24	3.3	4.27	3.07	4.45	3.68	2.87	2.65	
26	8.05	6.82	5.48	5.82	5.93	5.42	2.35	
28	5.23	6.37	5.18	7.48	5.12	5.87	2.43	
30	5.83	5.5	5.57	5.57	3.12	2.63	2.4	
32	1.95	2.82	4.78	4.78	2.4	0.98	2.25	
34	2.05	2.27	3.63	3.63	1.47	1.72	2.35	
36	2.17	1.97	3.9	3.9	1.33	1.77	1.88	

Ni concentration (ppm) of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7
1	0.05	15.02	2.13	11.68	8.35	0.25	0.42
2	0.33	14.15	2.58	10.97	7.83	0.7	0.55
3	0.37	12.08	1.9	11.73	9.1	0.47	0.42
4	0.4	12.2	1.23	7.62	7.48	0.28	0.22
6	0.4	16.2	1.92	3.6	5.23	1.08	0.77
8	0.35	11.67	1.92	1.27	3.52	1.22	0.72
10	1.2	11.13	1.94	0.67	5.69	1.28	0.16
12	1.21	10.5	1.88	0.75	5.33	1.28	0.69
14	1.2	6.82	1.3	0.8	4.43	1.5	0.82
16	1.4	6.6	1.67	0.83	4.23	1.53	0.87
18	1.01	7.66	1.82	0.99	4.01	1.1	0.93
20	1.31	6.77	1.61	0.89	4.48	1.14	1.03
22	1.26	4.35	1.82	1.26	4.23	1.68	0.76
24	1.02	3.38	1.97	1.45	3.86	1.98	0.81
26	1.31	4.1	2.25	1.67	3.65	2.26	0.63
28	0.98	3.72	2.63	1.89	3.81	2.46	0.6
30	1.97	2.8	2.81	2.02	3.82	2.67	0.58
32	1.53	4.05	2.95	2.8	2.73	2.55	0.5
34	2.25	3.5	2.68	2.78	4.28	3.27	0.85
36	4.18	5.1	4.28	3.75	4.6	3.92	0.62

N concentration (ppm) of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7
1	1.55	1.63	1.92	1.55	2.37	2.07	0.85
2	1.33	1.01	1.72	1.28	1.78	2.27	1.9
3	1.68	0.92	1.8	1.02	2.5	1.85	0.56
4	1.31	1.49	1.76	2.17	2.51	2.37	0.75
6	1.57	1.9	1.31	3.89	3.69	3.27	1.69
8	2.98	2.91	3.03	4.81	3.49	3.02	1.71
10	3.98	6.05	3.97	3.67	3.58	1	1.77
12	8.63	8.42	6.6	3.22	3.18	1.9	1.27
14	4.59	9.28	3.48	4.87	3.28	2.9	1.17
16	3.28	3.86	3.59	2.18	3.68	3	0.72
18	3.29	2.68	4.41	2.28	3.26	2.6	0.99
20	2.81	2.91	3.37	1.5	2.87	2.99	0.6
22	3.33	3.87	3.79	0.97	3.62	2.9	0.75
24	2.62	3.45	3.54	1.59	3.81	5.24	0.62
26	2.32	2.86	3.79	0.958	3.58	4.65	0.6
28	2.5	3.95	4.14	0.64	3.72	4.86	0.53
30	5.88	4.35	6.4	1.14	4.73	3.76	1.07
32	3.46	3.4	3.39	1.15	2.45	3.32	0.82
34	3.51	1.03	0.96	0.96	2.28	2.91	0.68
36	3.05	1.22	0.94	0.94	1.34	3.22	0.96

K concentration (ppm) of leachate from columns

Week	C1	C3	C4	C5	C6	C2	C7
1	236.9	249.5	115.45	306.8	196.9	121.7	18.35
2	292.3	240.3	101.1	255.6	135.23	104.7	24.77
3	315.7	275.5	121	340.8	240	169.6	58.23
4	316.4	308.4	82.3	293.9	220.4	142.1	41.58
6	386.02	278.9	66.68	215.17	105.72	88.8	21.57
8	336.2	196.08	91.47	61.3	47.08	94.5	21.78
10	391.2	250.1	96.9	96	79.3	78.6	21.6
12	367.5	189.7	84.1	83.9	66.6	125.3	22.7
14	372.4	208	96.9	62.9	69	124.6	16.36
16	361.8	188.6	99.9	59.7	62.5	166.2	16.91
18	346.8	154	109.1	45.37	68.7	162.3	17.8
20	300.5	138.3	106.9	45.6	52.7	169.6	15.4
22	371.5	103.7	116.4	17.5	67.7	189.9	18.5
24	402.7	114.7	125.9	26	78.4	223.4	21.2
26	382.8	179.4	182.1	36.4	105.9	274.8	40.3
28	330.2	173.5	139.2	33.7	99.9	250.1	27.5
30	309.7	125.5	185.8	20.7	73.9	250.6	15.07
32	247.2	47.7	92.3	9.03	22.7	98.7	6.72
34	217.2	52	90.7	10.3	25	94.9	6.9
36	205.9	52.5	82.3	11.1	37.1	100.5	9.88

Photo 1: Lysimeter

Photo 2: Gas outlet of lysimeter

Photo 3: Growth of grass in selected stabilized sludge amended soil mixtures in Series II of plant bioassay

Photo 4: Growth of grass in selected stabilized sludge amended soil mixtures in Series II of plant bioassay

Photo 5: Growth of grass in selected stabilized sludge amended soil mixtures in Series II of plant bioassay

Photo 6: Growth of grass in selected stabilized sludge amended soil mixtures in Series II of plant bioassay

Photo 7: Growth of grass in selected stabilized sludge amended soil mixtures in Series II of plant bioassay