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Sustainable reuse potential of municipal sewage sludge in south-east Australia

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Abstract: With the aim of reusing municipal sewage sludge, this paper presents the chemical and organic properties of sludge from a major sewage treatment plant in south-eastern Australia. The results show that the concentrations of all OCPs and majority of PAHs were below or close to laboratory detection limits. Concentrations of heavy metals in sludge samples were compared with typical sludge testing results from the USA and UK. Concentrations of heavy metals from the south-eastern Australian sludge samples were noted to be much lower than concentrations of same metals reported in the UK but slightly higher than in the USA. Concentrations of lead in south-eastern Australian sludge samples were however found to be lower than the US sludge samples. Results on the leachate testing on aerated and nitrogen purged samples revealed minor differences in the results. Potential reuse options for the sewage sludge in agricultural applications are also discussed.

Keywords: sewage sludge; treatment plant; leachate; heavy metals; Australia.

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1 Introduction

With the ever-increasing demands of virgin materials as well as reduction in suitable landfill sites, reuse and recycling options are emerging need of the current world. Several researchers have investigated different options of reuse and recycling for various different types of materials (Rahman et al., 2013; Imteaz et al., 2012, 2011). Sewage sludges are residues generated in treatment lagoons (ponds) at typical centralised wastewater treatment plants (WWTPs) as a result of the treatment of wastes released from a variety of sources including dwellings, industries and commercial facilities. In Australia, approximately 360,000 dry tones of sewage sludge are produced annually (Pritchard et al., 2010). With the increase of urban population and hence amount of wastewater generation, there is a gradual progression towards improved wastewater treatment and wastewater sludge management throughout the world (Gale, 2008). In Australia, the secondary treatment of sewage sludge is common, with a unanimous view amongst state regulators in the short and medium term to manage the stabilised sludge (biosolids) in a beneficial way to take advantage of nutrients and desirable soil enhancing properties (Pritchard et al., 2010). However, in the long term potential newer technology and economic drivers are expected to dictate future trends (Dixon and Anderson, 2007).

Geotechnical aspects of sewage sludge have been studied in recent years in various countries. Treatment of sewage sludge is noted to vary from country to country. In south-eastern Australia, the sewage sludge from the wastewater treatment lagoons are air-dried in sludge drying pans and stored as biosolids in a stockpile area. In the case of other countries such as the UK and Hong Kong untreated sludge is disposed of directly in landfill and is not treated to enable them to be termed biosolids. O'Kelly (2004, 2005, 2006) has reported on the various geotechnical characteristics of sludge at the Tullamore wastewater treatment plant in the UK in terms of their strength, compaction, compressibility and other geotechnical properties. O'Kelly (2004) reported that in the UK, the sewage sludge is eventually disposed of in landfill (sludge-to-landfill) which is different from the typical requirement of air-drying and subsequent minimum stockpiling period required of biosolids in Australia. O'Kelly (2004) stated that sludge material in various treatment plants can have different engineering properties due to different input levels of domestic and industrial wastewater. O'Kelly (2004) reported that the undrained shear strength of the wastewater sludge increases exponentially with reducing water content. He reported that sludge which was wetter than 180% of water content had negligible shear strength.

Chu et al. (2005) and Goi (2004) have reported on the geotechnical properties of sewage sludge in Singapore and proposed the option of using cement-treated sewage sludge as a fill material for land reclamation activities in Singapore. Chu et al. (2005) has reported on the consolidation properties of cement-treated anaerobically digested sewage sludge in the Republic of Singapore with the use of prefabricated vertical drains. Lo et al. (2002) reported on the geotechnical characterisation of dewatered sewage sludge

generated from the Stonecutters Island treatment plant in Hong Kong. Compaction tests carried out indicated that the dewatered sewage sludge exhibits compaction characteristics similar to that of clayey soils. The practice in Hong Kong is noted to be similar to the UK in that sewage sludge is disposed into landfills. Lo et al. (2002) also confirmed the findings of Klein and Sarsby (2000) and Klein (1995) that sludge once placed in landfills can be considered as geotechnical material similar to non-consolidated cohesive material with high organic content. In addition to consolidation and compaction tests, direct shear tests were also carried out on the sludge mixtures.

Biosolids, which is basically air-dried sludge having the characteristics of a solid typically containing 50 to 70% by weight of oven dried solids, has been investigated successfully as a geotechnical fill material (Arulrajah et al., 2011; Suthagaran et al., 2010). All the proposed geotechnical applications of sludge have risks of getting contaminated through leaching, especially for some heavy metals which are not easy to treat/remove. As sewage sludges contain nutrients and organic matter that can provide soil benefits, the use of these sludges as soil amendments is widely practiced in Australia and around the world (Gale, 2007, 2008; Gerba and Smith, 2005; Morris et al., 2003; Pritchard et al., 2008). However, as these sludges contain contaminants including heavy metals, pathogens, and organic pollutants, their widespread use is restricted and management is subject to much public scrutiny (Gale, 2007; Quilbé et al., 2005). Several researchers have reported accumulation of heavy metals in the soil and plants grown on sludge enriched soil (Nogueirol et al., 2013; Leblebici, 2010; Jamali et al., 2009). Applying this phenomenon, some researchers have reported successes on removing some heavy metals through biomass growth (Butcher, 200; Peng et al., 2009; Alonso-Castro et al., 2009). However, if plants/weeds are used for this purpose, life-cycle of these plants/weeds needs to be controlled, lest accumulation of contaminants in those plants/weeds pose any threat to the environment.

2 Materials and methods

The sludge sampling programme was undertaken at two lagoons (Lagoons A and B) at a wastewater treatment plant in south-eastern Australia. The sludge sampling was performed at seven locations in the lagoons. Samples were collected from six locations at Lagoon A, with two locations in the covered anaerobic section and four in the uncovered aerobic section. Sampling at Lagoon B involved one sample location in the anaerobic section adjacent to the covers. Two samples were collected from each sample location, one just below the approximate sludge/liquid interface and one immediately above the base of the lagoon. A total of 14 primary samples were therefore retrieved.

The sludge was sampled using a 40 mm diameter piston sampler and brought to the surface for collection in buckets and glass jars. All sampling equipment was decontaminated by washing with a mixture of water and a decontamination liquid, and was subsequently rinsed with deionised water. The physical characteristics of the sludge that was collected from the lagoons were observed on-site. pH, temperature, electrical conductivity (EC) and redox potential were measured in the field for all the sludge samples that were collected. Collected sludge samples were sent to an accredited laboratory for detailed analysis. EC can be used as an indication of samples salinity magnitude, whereas 'redox potential' is the indicator of potential mass reductions due to

bio-chemical processes. As the potential reuses of the sludge are being proposed, it is necessary to know the 'redox potential', as the sludge which will be reused would likely to go through storage and subsequent reductions. Storage would cause a reduction of sludge mass. The potential users should be aware of this matter.

The sludge samples were separated in the laboratory into filtered pore water samples (the water component of the sludge) and solids samples (the solid component of the sludge). A portion of several samples was removed prior to filtering, for decanting. A portion of one sample was also aerated prior to analysis, with another portion of the same sample being sparged with nitrogen prior to analysis. The following analytes were tested for the collected samples:

- Inorganic species: Heavy metals (aluminium, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, tellurium, thallium, tin, vanadium and zinc), including leachability using the Australian Standard Leachate Procedure (ASLP); major cations and anions; total ionic strength; total organic carbon (TOC); EC; pH; ammonia as nitrogen; reactive phosphate; sulphide; total Kjeldahl nitrogen; total dissolved solids (TDS); total solids; suspended solids; volatile solids; and solids content.
- Organic species: Organochlorine pesticides (OCPs); and polycyclic aromatic hydrocarbons (PAHs).

3 Test results

Table 1 shows the physical characteristics (temperature, pH, EC and redox potential) and solid contents of the sludge samples. Table 1 reveals the means, standard deviations and ranges of the parameters for 14 samples. From Table 1, it is evident that the sludge samples are predominantly acidic. Also, it is apparent that the solids components of the samples ranges from 3.4 to 21%w/w, based on the concentration of suspended solids in those samples. It is to be noted that the solids contents were calculated from the suspended solids results, assuming an average density of 1.0 kg/L.

Table 1 Physical property of sludge samples in the field

<i>Parameter</i>	<i>Mean</i>	<i>SD</i>	<i>Range</i>
Electrical conductivity (mS/cm)	2,058.8	410.9	1,557~2,787
Salinity (ppm) [#]			778,500~1,950,900
pH	6.4	0.2	6.13~6.74
Temperature (°C)	19.7	1.2	17.8~22
Redox potential (mV)	-202.8	48.4	-287~-113
Total suspended solids (mg/L)	91,375	58,583	34,000~210,000
Solids contents (%w/w)	9.1	5.9	3.4~21
Volatile solids (%w/v)	47.1	11.24	39.1~55
Total solids (%w/v)	14.0	6.3	9.5~18.4

Note: [#]Salinity was calculated from the measured EC values, using a conversion factor of 1 EC (mS/cm) equals to salinity of 500~700 ppm (depending on types of salt).

The analytical results for the filtered pore water samples retrieved from the site are summarised in Table 2. The results show that the concentrations of all OCPs and the majority of PAHs were below detection limits. Concentrations of beryllium, mercury, selenium, silver, tellurium, and thallium were less than or close to the detection limits for these analytes.

Table 2 Summary of analytical results for filtered pore water samples

<i>Parameter</i>	<i>Mean</i>	<i>SD</i>	<i>Range</i>
<i>Metals</i>			
Aluminium (mg/L)	0.43	0.53	0.08–2.1
Antimony (mg/L)	< 0.0043	-	< 0.001–0.019
Arsenic (mg/L)	0.01	0.00	0.002–0.018
Barium (mg/L)	0.32	0.34	0.041–1.4
Beryllium (mg/L)	< 0.001	-	< 0.001
Boron (mg/L)	0.37	0.12	0.2–0.58
Cadmium (mg/L)	< .0014	-	< 0.0002–0.0066
Chromium (mg/L)	0.02	0.02	0.01–0.067
Cobalt (mg/L)	0.01	0.01	0.002–0.019
Copper (mg/L)	0.08	0.08	0.017–0.31
Iron (mg/L)	0.64	0.63	0.1–2
Lead (mg/L)	< .0066	-	< 0.001–0.027
Manganese (mg/L)	0.23	0.10	0.086–0.41
Mercury (mg/L)	< .0001	-	< 0.0001–0.0004
Molybdenum (mg/L)	< .009	-	< 0.001–0.045
Nickel (mg/L)	0.04	0.02	0.019–0.093
Selenium (mg/L)	< 0.0011	-	< 0.001–0.002
Silver (mg/L)	< 0.005	-	< 0.005
Tellurium (mg/L)	< 0.001	-	< 0.001
Thallium (mg/L)	< 0.1	-	< 0.1
Tin (mg/L)	< .002	-	< 0.001–0.016
Vanadium (mg/L)	0.004	0.00	0.002–0.009
Zinc (mg/L)	0.179	0.15	0.049–0.63
<i>Major cations</i>			
Calcium (mg/L)	52.43	20.02	32–110
Magnesium (mg/L)	30.74	12.59	0.3–57
Potassium (mg/L)	36.71	7.37	27–50
Sodium (mg/L)	244.3	15.55	220–270

Table 2 Summary of analytical results for filtered pore water samples (continued)

<i>Parameter</i>	<i>Mean</i>	<i>SD</i>	<i>Range</i>
<i>Major anions</i>			
Bicarbonate (mg/L)	1,237.9	654.2	530–2300
Carbonate (mg/L)	< 2.4	-	< 1–11
Chloride (mg/L)	352.9	53.12	310–490
Nitrate (mg/L)	< 0.01	-	< 0.01
Nitrate + Nitrite (mg/L)	0.20	0.19	0.04–0.72
Sulphate (mg/L)	22.64	9.82	10–41
<i>Polycyclic aromatic hydrocarbons</i>			
Naphthalene (ug/L)	2.67	-	< 1–4
Phenanthrene (ug/L)	1.67	-	< 1–2
Total PAHs (ug/L)	< 10.38	-	< 8–16
Ammonia as nitrogen (mg/L)	175.8	123.8	54–380
Reactive phosphate (mg/L)	18.3	10.85	7.7–40
Sulphide (mg/L)	1.0	1.54	< 0.1–3.3
Total Kjeldahl nitrogen (mg/L)	205.4	164.2	66–470
Total organic carbon (mg/L)	73.4	58.3	35–210
Total dissolved solids (mg/L)	1,044	158.4	860–1,400
Electrical conductivity ($\mu\text{s}/\text{cm}$)	2,829	734.2	2,200–4,100
pH	7.9	0.47	7.1–8.4
Total ionic strength (meq/L)	27.7	8.65	19.5–47.6

The results for the leachate testing of the samples are shown in Table 3. Results also show that the leachability of many metals were less than the laboratory detection limits.

Table 3 Summary of analytical results for leachability of metals

<i>Metals (mg/L)</i>	<i>Mean</i>	<i>SD</i>	<i>Range</i>
Aluminium	0.404	0.242	0.14–0.85
Antimony	0.042	0.026	0.011–0.081
Arsenic	0.005	0.002	0.003–0.008
Barium	0.275	0.112	0.14–0.44
Beryllium	< 0.010	-	< 0.010
Boron	0.200	0.123	0.1–0.38
Cadmium	< 0.001	-	< 0.001
Chromium	0.014	0.005	0.01–0.02
Cobalt	< 0.01	-	< 0.01
Copper	0.033	0.013	0.02–0.05
Iron	2.745	2.564	0.24–6.2
Lead	< 0.01	-	< 0.01
Manganese	0.131	0.065	0.06–0.21

Table 3 Summary of analytical results for leachability of metals (continued)

<i>Metals (mg/L)</i>	<i>Mean</i>	<i>SD</i>	<i>Range</i>
Mercury	< 0.0010	-	< 0.0010
Molybdenum	0.094	0.050	0.01–0.14
Nickel	0.029	0.021	0.01–0.07
Selenium	< 0.001	-	< 0.001–0.001
Silver	< 0.010	-	< 0.010
Tellurium	< 0.001	-	< 0.001
Thallium	< 0.01	-	< 0.01
Tin	< 0.01	-	< 0.01
Vanadium	< 0.01	-	< 0.01
Zinc	0.544	0.140	0.36–0.79

The analytical results for the leachate testing on the aerated and sparged samples are summarised in Table 4. It is found that there are minor differences in the results for the two analyses. Also, it was found that silver, tellurium, thallium and beryllium were below the laboratory detection limits for both the samples.

Table 4 Summary of analytical results for leachability with aerated and sparged samples

<i>Metals (mg/L)</i>	<i>Aerated sample</i>	<i>Sparged with nitrogen</i>
Aluminium	0.36	0.41
Antimony	0.088	0.047
Arsenic	0.008	0.011
Barium	0.71	0.81
Beryllium	< 0.001	<0.001
Boron	0.26	0.36
Cadmium	0.001	0.0006
Chromium	0.019	0.018
Cobalt	0.006	0.004
Copper	0.11	0.098
Iron	0.42	0.44
Lead	0.006	0.004
Manganese	0.009	0.003
Mercury	0.0006	0.0006
Molybdenum	0.41	0.21
Nickel	0.035	0.028
Selenium	0.002	< 0.001
Silver	< 0.005	< 0.005
Tellurium	< 0.001	< 0.001
Thallium	< 0.1	< 0.1
Tin	0.003	0.002
Vanadium	0.009	0.011
Zinc	0.16	0.15

Table 5 shows the laboratory results for decanted water samples. Again it was found that concentrations of beryllium, thallium, tellurium and carbonate were all less than the laboratory detection limits. Most of the pollutants concentrations in decanted water are within the ranges found for pollutants concentrations in pore water samples.

Table 5 Summary of analytical results for solid samples and comparison with the USA, UK samples and EU standard

<i>Metals (mg/L)</i>	
Aluminium	10
Antimony	0.016
Arsenic	0.007
Barium	0.2
Beryllium	< 0.001
Boron	0.43
Cadmium	0.0064
Chromium	0.12
Cobalt	0.007
Copper	0.6
Iron	9.7
Lead	0.05
Manganese	0.14
Mercury	0.0008
Molybdenum	0.05
Nickel	0.085
Selenium	0.002
Silver	0.018
Tellurium	< 0.001
Thallium	< 0.1
Tin	0.007
Vanadium	0.014
Zinc	0.85
<i>Major cations (mg/L)</i>	
Calcium	46
Magnesium	27
Potassium	32
Sodium	270
<i>Major anions (mg/L)</i>	
Bicarbonate	680
Carbonate	< 1
Chloride	390
Sulphate	17
<i>Other</i>	
pH	7.7
Electrical conductivity ($\mu\text{s}/\text{cm}$)	2,500
Total ionic strength (meq/L)	22.6

Table 6 summarises the analytical results for the solids samples. It was found that concentrations of beryllium, selenium, thallium and carbonate in solid samples were less than the laboratory detection limits for these analytes. The concentrations of major cations and anions in the solids samples were generally significantly higher than those reported for the equivalent pore water samples. In addition to mean, standard deviation and ranges of the pollutants in the sludge solid samples, the table also provides ranges of some of the contaminants found in many sludge samples in the USA and UK. It is found that for all the available test results from the UK (Sterritt and Lester, 1980), concentrations of pollutants (cadmium, chromium, cobalt, copper, lead, manganese, molybdenum, nickel, tin and zinc) in sludge samples were much higher than concentrations of same pollutants in East Australian sludge samples. For US sludge samples (Nkegbe, 2005), only concentrations of arsenic, lead, nickel and zinc were available. For US sludge samples, concentrations of arsenic, nickel and zinc were lower than the concentrations of same metals in East Australian sludge samples. However, concentrations of lead in US sludge samples were found to be higher than in East Australian sludge samples. Countries yet to develop a full-scale recommended maximum limits of heavy metals concentrations in the sludge to be used for soil enrichments. European Union has outlined limits for some specific heavy metals for raw sludge to be used for agricultural purpose (Zufiaurre et al., 1998). All the tested samples showed heavy metals concentrations lower than those specified limits.

Table 6 Summary of analytical results for decanted samples

<i>In mg/kg dry weight</i>	<i>Australian values</i>			<i>UK range</i>	<i>USA range</i>	<i>EU limit[#]</i>
	<i>Mean</i>	<i>SD</i>	<i>Range</i>			
<i>Metals</i>						
Aluminium	11,540	1,599.4	9,700–13,000			
Antimony	18.6	5.9	13–26			
Arsenic	< 6	1.0	5–7		0.75–1.23	
Barium	292	39.0	230–330			
Beryllium	< 5	-	< 5			
Boron	18.6	11.9	10–39			
Cadmium	5.96	1.3	4.5–7.7	1.54–110		20
Chromium	214	46.2	150–270	57.2–5,190		1,000
Cobalt	9.4	1.3	8–11	11.3–2,490		
Copper	740	84.6	600–800	170–2,080		1,000
Iron	13,140	2,048.9	9,700–15,000			
Lead	86	37.3	59–150	27.5–45,400	445–482.1	750
Manganese	147.2	65.1	86–250	131–6,120		
Mercury	2.06	0.7	1.2–3			
Molybdenum	32.6	10.4	17–44	0.102–214		
Nickel	103.8	24.1	74–140	16.2–2,020	33.1–127.5	300
Selenium	< 5	-	< 5			
Silver	13.8	2.8	11–17			
Tellurium	< 0.01	-	< 0.01			

Note: [#]Zufiaurre et al. (1998).

Table 6 Summary of analytical results for decanted samples (continued)

<i>In mg/kg dry weight</i>	<i>Australian values</i>			<i>UK range</i>	<i>USA range</i>	<i>EU limit[#]</i>
	<i>Mean</i>	<i>SD</i>	<i>Range</i>			
<i>Metals</i>						
Thallium	< 5	-	< 5			
Tin	50.8	8.6	41–61	2.64–329		
Vanadium	16.8	4.0	10–20			
Zinc	1,070	193.1	840–1,300	93.5–9,210	291–446.1	2,500
<i>Major cations</i>						
Calcium	10,860	1,203.3	9,300–12,000			
Magnesium	2,480	327.1	2,100–2,800			
Potassium	1,580	216.8	1,300–1,800			
Sodium	40,000	7,314.4	31,000–50,000			
<i>Major anions</i>						
Bicarbonate	208	90.9	70–300			
Carbonate	< 10	-	< 10			
Chloride	2,218	1,340.4	290–3,800			
Nitrate + Nitrite	26	16.8	10–56			
Sulphate	3,522	3,576.3	110–9,400			

Note: [#]Zufiaurre et al. (1998).

4 Conclusions

In order to assess suitability of using raw sludge from a sewage treatment plant in south-east Australia, this paper presents details of chemical and organic properties of the sludge. The introduction of new chemicals into commerce, suggests that there is a need for a testing of raw sludge samples in order to better characterise sludges with respect to the presence and concentration of contemporary contaminants. Fourteen primary sludge samples were retrieved from seven locations from two different lagoons within the treatment plant. The samples were separated by the laboratories into filtered pore water and solids samples and subsequently analysed. Decanted, aerated and sparged samples were also prepared and analysed. Although testing of some other heavy metals and pollutants were not performed, the test result has enabled detailed information on the chemical properties of the raw sludge.

The concentrations of all OCPs and majority PAHs in pore water samples were below the laboratory detection limits. Also, concentrations of beryllium, mercury, selenium, silver, tellurium, and thallium were less than or close to the detection limits for these analytes. In regards to leachability of heavy metals, the results for the leachate testing of the samples show that most of the metals were less than the laboratory detection limits. It is found that there are minor differences among analytical results for the leachate testing on the aerated and sparged samples. In regards to decanted water samples, concentrations of beryllium, thallium, tellurium and carbonate were all less than the laboratory detection limits. Also, it is found that most of the pollutants concentrations in the decanted water are within the ranges found for pollutants concentrations in pore water samples. In

regards to the solids samples, it was found that concentrations of beryllium, selenium, thallium and carbonate were less than the laboratory detection limits for these analytes. The concentrations of major cations and anions in the solids samples were generally significantly higher than those reported for the equivalent pore water samples. Concentrations of heavy metals from the south-eastern Australian sludge samples were noted to be much lower than concentrations of same metals reported in the UK but slightly higher than that reported in the USA. However, concentrations of lead in south-eastern Australian sludge samples were found to be lower than in US sludge samples. As per available recommended limits of some heavy metals for the purpose of using raw sludge for agricultural use, all the concentrations of south-east Australian sludge were found to be within the limits recommended by European Union. As such it can be concluded that municipal raw sludge from south-east Australia can be used for agricultural purposes, however more investigations needed to avoid contaminants getting into our food chain. Also, dried sludge can be used for different engineering applications (road pavement, pipe backfilling, etc.) subject to fulfilling the engineering requirements of individual application.

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