Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 20(2008) 710–716
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Solubility of ion and trace metals from stabilized sewage sludge by fly ash and alkaline mine tailing

ZHANG Hongling[1,2,3], SUN Lina[2,*], SUN Tieheng[1]

1. Key Laboratory of Terrestrial Ecological Process, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China. E-mail: zhl19792002@163.com
2. Key Laboratory for Environmental Engineering of Shenyang University, Shenyang 110041, China
3. Graduate University of Chinese Academy of Sciences, Beijing 100039, China

Received 30 August 2007; revised 18 September 2007; Accepted 26 November 2007

Abstract

Stabilized sewage sludge (SS) by fly ash (FA) and alkaline mine tailing as artificial soil, to be applied on the ecological rehabilitation at mining junkyards, offers a potentially viable utilization of the industrial by-product, as well as solves the shortage of soil resource in the mine area. An incubation experiment with different ratios of SS and FA was conducted to evaluate the solubility of ions and trace elements from stabilized sewage sludge. Results showed that fly ash offset a decrease in pH value of sewage sludge. The pH of (C) treatment (FA:SS = 1:1) was stable and tended to neutrality. The SO_4^{2-} and Cl^- concentrations of the solution in the mixture were significantly decreased in the stabilized sewage sludge by alkaline fly ash and mine tailing, compared to the single SS treatment. Stabilized sewage sludge by FA weakened the nitrification of total nitrogen from SS when the proportion of FA in the mixture was more than 50%. The Cr, Ni, and Cu concentrations in the solution were gradually decreased and achieved a stable level after 22 days, for all treatments over the duration of the incubation. Moreover stabilized sewage sludge by fly ash and/or mine tailing notably decreased the trace metal solubility. The final Cr, Cu, and Ni concentrations in the solution for all mixtures of treatments were lower than 2.5, 15, and 50 μg/L, respectively.

Key words: stabilized sewage sludge; fly ash; mine tailing; artificial soil; trace element solubility

Introduction

In China, mines, especially the dumping sites containing mostly bedrocks and kingles, often locate in areas lacking soil resources. Many mine enterprises have to buy the plowland soil to cover the barrier for rehabilitation. However this method of buying nature soil has many disadvantages, it not only wastes both manpower and material resources, but also cannot solve the long-term shortage of soil resource. At present, mine rehabilitation is an important and urgent subject (Shen *et al*., 2004; Campbell, 1998; Hu *et al*., 2002; Wang and Cai, 2006).

Fly ash is a byproduct of coal combustion, composed of particulate matter. In China, 1.8×10^8 t fly ash (FA) was produced each year for generation of electricity (Ben and An, 2004). Land filling is the traditional method of disposal for FA, however, the dual factors of increased cost and stricter legislation have prompted research on alternative methods of disposal or utilization of this waste material (Abbott *et al*., 2001; Kriesel *et al*., 1994). Over the last 25 years, numerous studies on the use of fly ash as a soil amendment have been performed (Adriano *et al*., 1980). Although the benefits of FA application to soils have been reported, the potentially toxic elements are more of a concern in the agricultural area (Carlson and Adriano, 1993). Sewage sludge (SS) is a useful source of organic matter and also a pool of slow-release of essential nutrients (nitrogen, phosphorus, sulfur, and magnesium) and microorganisms. An organic waster product mixed with fly ash has been proposed to increase the macronutrient content in the mixture, even as it reduces the odor and improves the handling properties of the organic waste (Jackson and Miller, 2000; Belmonte *et al*., 2006). Field trials utilizing mixtures of FA/organic waste as fertilizers for maize produce yields comparable to those produced by the conventional fertilization techniques (Schumann, 1997). The results of potting plants show that coal ash, reservoir sediments, and sewage sludge mixed in proper proportions can greatly promote plant growing and increase production obviously (Li *et al*., 2001). Notwithstanding these factors, land application of fly ash and sewage sludge, with heavy metals, is still a matter that must be further investigated. Many researchers have noted an increased availability of trace elements in fly ash-amended soil (Tolle *et al*., 1983). Adriano *et al*. (1982) have reported that cadmium uptake in sudan grass is from sewage sludge application and they have found that Cd can be reduced in the presence of fly ash. Although when a

* Corresponding author. E-mail: sln629@163.com.

sewage sludge potting medium is mixed with fly ash, Cd, Zn, and Mn uptake in tall wheat grass has been reduced.

Availability of heavy metals is mostly a function of solubility, therefore, extracting a solution from the soil is a reliable technique for assessing whether a trace element is available for plant uptake or leaching. Trace element availability from land application of a single FA or SS is well documented (Lake *et al*., 1984; El-Mogazi *et al*., 1988; Carlson and Adriano, 1993; Gibbs *et al*., 2006; Li *et al*., 2001; Belmonte *et al*., 2006). However, few attempts have been made to investigate trace element availability from land application of FA/SS mixtures without natural soil, and the feasibility of the mixtures used, for the ecological remediation of the dumping site for mullock in China.

The specific objectives of this article were to evaluate the solubility of anions (SO_4^{2-}, Cl^-, NO_3^-) and trace elements (Ni, Cr, Cu) from stabilized sewage sludge and to assess the potential contamination of heavy metals. This study will provide valuable information and data on the application of these artificial soils to the mining areas.

1 Materials and methods

1.1 Sampling

The mine spoil material (MT) was collected from the Dagushan iron mine (123°03′36.6″E and 41°03′03″N) in Anshan City, Liaoning Province, China. FA used in this study was obtained from a Power Plant of the Anshan Steel Company and SS was from the North Waste Water Treatment Facility located in Haicheng City, China. Fly ash and mine tailing samples were air dried before being mixed with the sewage sludge. The basic chemical properties of the fly ash, sewage sludge, and mine tailing were determined as shown in Table 1.

The sewage sludge used in the experiment was composted outdoors for several days after collection. When the water content of SS was 55%–60%, it was well mixed with dry fly ash and mine tailing. Then the mixture materials were air dried and ground to pass through a 2-mm sieve. Mixtures of FA/SS were prepared at the ratios of 3:1 (A), 2:1 (B), 1:1 (C), and 0.5:1 (D), respectively; FA/SS/MT were prepared at only one ratio of 2:1:1 (E). All treatments of stabilized SS (called artificial soil) are listed in Table 2.

1.2 Pot incubation experiment

One thousand grams of every dry artificial soil sample was placed in a plastic bucket. The details of treatments A, B, C, D, and E are listed in Table 2. Three replicates were designed. All treatments were wet to the moisture of 17% (*W/W*) by adding deionized water and re-wet to this moisture content throughout the incubation period, on the day prior to every soil solution sampling. The plastic buckets were open to the atmosphere (25°C), but were strictly controlled to avoid any leaching. By this approach, the authors minimized the effect of soil loss during sampling, and thus were better able to keep each treatment at an equivalent moisture content for the duration of the study.

Table 2 Artificial soils of sewage sludge (SS) mixed with mine tailing (MT) and fly ash (FA) in weight proportions

Composition	Treatment of stabilized sewage sludge				
	A	B	C	D	E
Fly ash	3	2	1	0.5	2
Sewage sludge	1	1	1	1	1
Mine tailing	0	0	0	0	1

The soil solution was periodically extracted (on day 1, 5, 7, 15, 22, and 35) from the incubated treatments, by centrifugation. One hundred grams of moist soil was sampled from each plastic bucket and then put into a plastic bottle and 10 ml of deionized water was added. Although the artificial soil was at 17% moisture content, it was still necessary to add a further 10 ml of deionized water to the soil sample prior to centrifugation, to extract a sufficient volume of the soil solution (approximately 3–4 ml from 100 g moist soil). Sufficient time was allowed for this added water to percolate into the soil, because the soil was still below field holding capacity and this was a rapid process. The artificial soil was centrifuged at 3000 r/min for 25 min. After centrifugation, the soil solution in the bottle was filtered (0.22 μm). The solid cake collected on the filter paper was carefully returned to the corresponding bucket and remixed evenly with the remaining soil.

1.3 Chemicals and analytical methods

Aliquots of the filtered soil solution were taken for measurement of organic carbon by TOC (GO-TOC 1000, Germany). The anions of Cl^-, NO_3^-, SO_4^{2-}, and cation of NH_4^+ were determined by ion chromatography (IC1010, China). Measurement of pH was made with a slurry (1:1 soil/ H_2O) of the incubated soil. Cu, Ni, and Cr contents in the artificial soil solutions were analyzed by means of atomic absorption spectrophotometry (AA-6300, Shimadzu, Japan).

1.4 Statistical analysis

SPSS 12.0 statistical package was employed for statistical analysis. Analysis of variance was used to test for significant differences in the trace element solubility in individual treatments and interactive effects of the mixed waste treatments.

Table 1 Basic physicochemical properties of the compositions

Composition	OM (%)	Available N (mg/kg)	Olsen P (mg/kg)	Available K (mg/kg)	pH	Cu (mg/kg)	Cr (mg/kg)	Ni (mg/kg)
Coal fly ash	2.66	0.55	115.92	169.49	10.88	77.42	29.44	281.64
Sewage sludge	36.69	216.71	324.33	1,531.43	7.65	192.33	124.88	33.18
Mine tailing	0.54	3.15	70.28	312.24	8.71	0.39	89.08	19.96

OM: organic matter.

2 Results and discussion

2.1 Change of pH in soil solution

High application rate of the municipal sewage sludge on land remediation resulted in environmental contamination of many major and trace elements, such as, Cu, Cr, Ni, S, N, and so on. A lot of research have focused on the total content and transformation of heavy metals in soil. However, the total number of elements does not actually reflect the availability or solubility of these elements in the mixtures. In this study, the artificial soil solution pH, and Cr, Ni, Cu, SO_4^{2-}, Cl^-, NH_4^+, and NO_3^- concentrations were evaluated through a 35-d incubation experiment.

The change of pH in artificial soil solution could alter soil properties, such as, surface charges, electrical conductivity or organisms in the soil. All these effects could result in changes in the form and solubility of elements. Fig.1 shows the soil solution pH of the SS-only treatment rapidly declined, falling from 7.39 to 6.27 in the incubation, consistent with the liberation of protons during nitrification (Sumner, 1991). However, the pH of the FA-only treatment increased from 7.8 to 8.8, keeping higher than all treatments during incubation, probably because of the low sulfur content of coal and the presence of hydroxides and carbonates of calcium and magnesium (Abbott *et al*., 2001). Soil solution pH of iron mine tailing was close to neutral (7.16–7.68). One of the potentially beneficial attributes of alkaline FA mixed with organic waste as an artificial soil was that the liming effect of the FA could offset decreases in soil pH caused by the decomposition of organic waste (Jackson and Miller, 2000). The ameliorating effect of FA on the soil acidifying nature of organic wastes was observed, and the pH of FA/SS mixtures increased with the ratio of FA increasing. During the incubation, the artificial soil solution pH decreased slightly. The finial pH of mixture treatments were much higher than those of sewage sludge, the sequence was FA (8.80) > A (8.13) > MT (7.68) > B (7.66) > E (7.46) > C (7.24) > D (6.99) > SS (6.27). It suggested that FA/SS/MT mixtures had a stable and neutral soil solution pH, which was suitable for plants growth in mine areas.

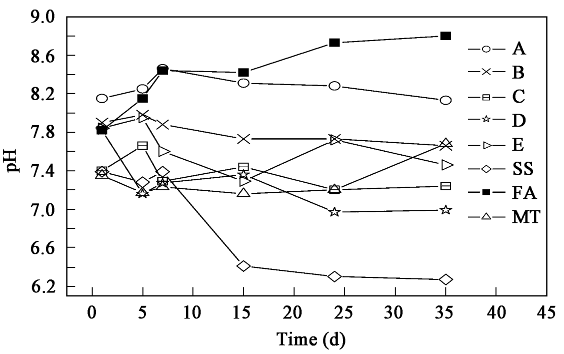

Fig. 1 Soil solution pH. A–E: artificial soil treatments; SS: sewage sludge; FA: fly ash; MT: mine tailing.

2.2 Sulfate and chloride in artificial soil solution

Water soluble salts, such as, SO_4^{2-}, Cl^-, NO_3^-, and so on, are a cause of worry, as they not only induce salinity stress to the growing plants, but can also leach out and contaminate the soil and groundwater. On the other hand, some of the salts can affect the mobility and bioavailability of heavy metals by binding with them (Egiarte *et al*., 2006).

Figure 2 shows the SO_4^{2-} and Cl^- concentration in artificial soil solution, respectively. Sulfate has been identified as the most prevalent anion in coal fly ash leachates (EPRI, 1987). However, the characteristics and compositions of FA and SS in different areas are greatly dissimilar (Li *et al*., 2001; Belmonte *et al*., 2006).

In this study, it was found that the solution concentration of SO_4^{2-} for FA, which collected from Anshan City (China) was significantly lower than that of SS, and was lower than 200 mg/L after 7 days (Fig.2a). This was probably because of the low sulfur content of coal used in Anshan, China (Ben and An, 2004). The soluble SO_4^{2-} concentration of mine tailing was similar to the FA treatment and was low (< 200 mg/L) throughout the duration of the incubation experiment. However, the highest SO_4^{2-} concentration appeared in the solution of the SS treatment. Added fly ash and mine tailing to municipal sewage sludge resulted in a decrease in soluble SO_4^{2-}. Moreover, with a decrease of fly ash in artificial soil, the soluble SO_4^{2-} concentration increased. For example the D treatment (the ratio of FA to SS was 0.5:1) exhibited

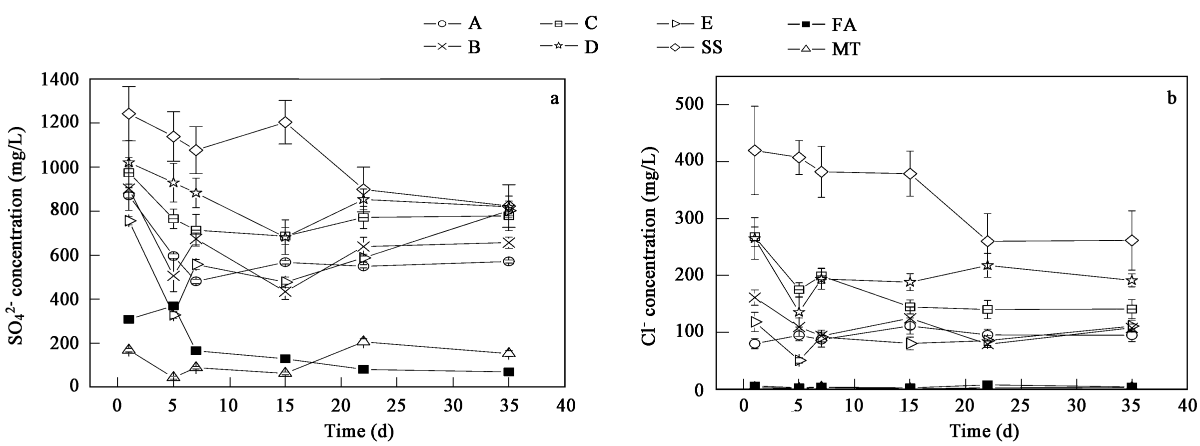

Fig. 2 Solution SO_4^{2-} (a) and Cl^- (b) concentration in artificial soil.

the highest concentrations of SO_4^{2-} in all the artificial soil treatments. Sulfate concentration for artificial soil treatments gradually declined during the 15 d incubation, and then slightly increased and achieved a stable level by the end of the incubation. Fly ash comprised of very fine particles, usually containing silica (SiO_2), magnesium oxides (MgO), calcium oxides (CaO), and small quantities of other oxides (Rodriguez, 1996). When sewage sludge was mixed with fly ash, the high SO_4^{2-} concentration of SS was declined by the reaction of CaO, MgO with SO_4^{2-} forming $CaSO_4$, and $MgSO_4$. In addition, under alkaline conditions, many trace elements complexes with SO_4^{2-} or decreased organic anions contributed to a decrease in soluble SO_4^{2-} (Jackson and Miller, 2000).

Soil solution Cl^- concentration for SS treatment decreased slowly during the 22 d incubation, and reached a constant level after 22 d (Fig.2b). It could be because of an increase in the anion exchange capacity of the soil as a result of the pH decrease in the period of 1–22 d. Except for the SS treatment, the solution Cl^- concentrations for FA, MT, and mixtures were stable and did not obviously change over the duration of the incubation, especially for FA and MT treatments. The soluble Cl^- was lower than 10 mg/L in all treatments. The solution Cl^- concentration in the five artificial soil treatments were lower than those in the SS treatment, but were not significantly different from each other by the end of the experiment. There were no significant differences in the final solution of SO_4^{2-} and Cl^- concentrations among the five artificial soil treatments (Fig.2), which indicated that fly ash application had little effect on the concentration of sulfate and chloride in the solution.

2.3 Nitrate in artificial soil solution

The fate of nitrogen (N) in the soil amended by sewage sludge is quite complex and varied in many alternative pathways, which probably include mineralization, nitrification, immobilization, fixation, plant uptake, denitrification, and volatilization, however, only volatilization and denitrification can be considered as direct removal from the soil and ground water supplies (Sommers *et al*., 1979; Harris *et al*., 1984; Li *et al*., 2003). From Fig.3a, it was found that solution NH_4^+ concentration in sewage sludge and mixtures rose significantly for the period of 1–5 d, and then decreased. After incubation for 22 d, the NH_4^+ kept at a stable level, although the solution NH_4^+ for FA was always low (< 40 mg/L) during the incubation. This was consistent with the general view that coal fly ash was a poor source of N, and most N is volatilized during coal combustion, and residual N is present in the refractory organic compounds (Carlson and Adrian, 1993). From Fig.3b, after 7 days there was an order of magnitude increase in solution NO_3^- concentrations in SS and D treatment. This increase probably corresponded to the decrease in soil solution NH_4^+ observed after this time, because nitrification could oxidize NH_4^+ to NO_3^-. Solution NO_3^- concentrations reached the highest levels in the SS and D treatments, representing 53% and 62% of nitrification of total N loading from the SS, respectively, but that of other artificial soils (A, B, C, and E) were significantly lower than SS. It indicated that mixing FA with the stabilized sewage sludge could weaken the nitrification of total N from SS when the proportion of FA in the mixture was more than 50%. However, the nitrification in the D treatment was greater than in the SS. Similar high nitrification rates, however, have been reported for other incubation studies. For example, mineralization rates of 42%–85% of total organic N were reported for 15 poultry litters mixed with a Cowarts sandy loam (Gordillo and Cabrera, 1997). Nitrification of total Nitrogen loading from

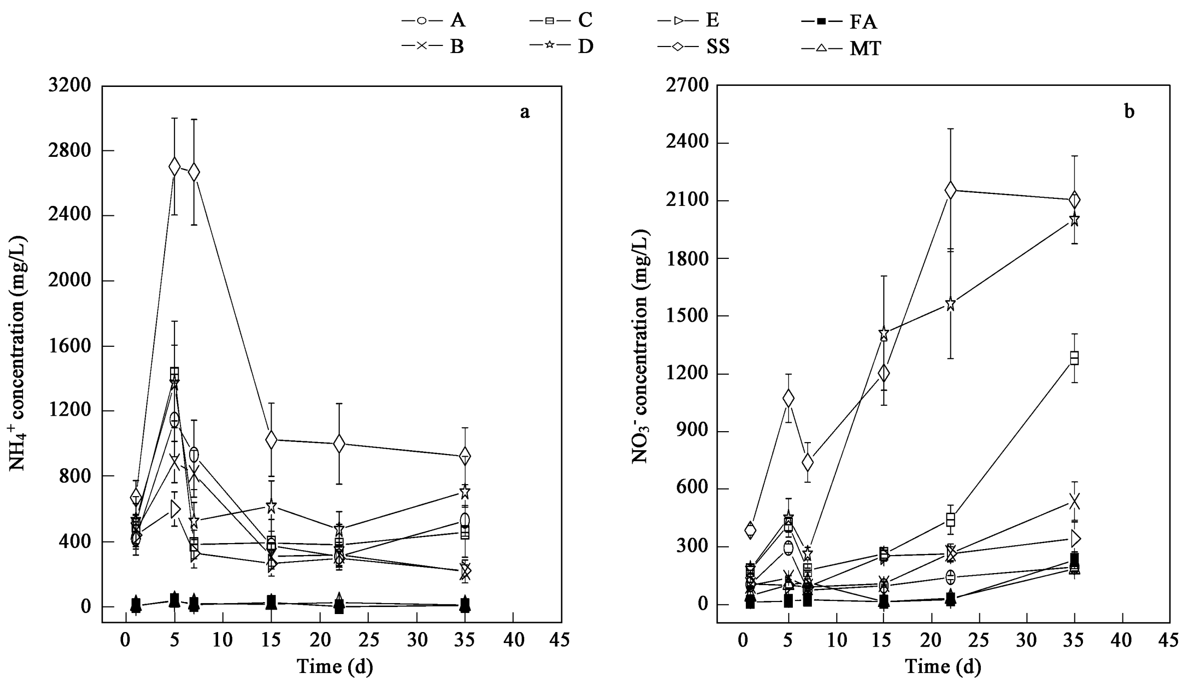

Fig. 3 Solution NH_4^+ (a), NO_3^- (b) concentration in artificial soil.

fly ash/poultry litter and poultry litter reached 50% and 73%, respectively (Jackson and Miller, 2000).

Nitrogen in the form of nitrate (NO_3^-) is mobile and readily leaches from sludge. Furthermore, nitrate leaching from sludge-amended soils may have concentrations greater than the acceptable levels in water (Sommers *et al.*, 1979; Harris *et al.*, 1984). Mixing fly ash and alkaline mine tailing could decrease the nitrification effectively and also decrease the volatilization of nitrogen.

2.4 Cr, Ni, and Cu in artificial soil solution

The mobility, bioavailability, and related ecotoxicity of trace metals depend strongly on their specific chemical forms or ways of binding rather than their total content (Fuentes *et al.*, 2006). Therefore, the analysis of soluble Cr, Ni, and Cu from municipal sewage sludge and fly ash is essential for assessing the bioavailability (Umesh and Gupta, 1998). The original hypothesis of this research was that mixing alkaline fly ash (pH 10.88) and mine tailing (pH 8.71) with organic waste might stabilize and affect the solubility of these heavy metals from SS because of changes in the mixture chemistry.

Soil solution Cr, Ni, and Cu are shown in Fig.4. Solution

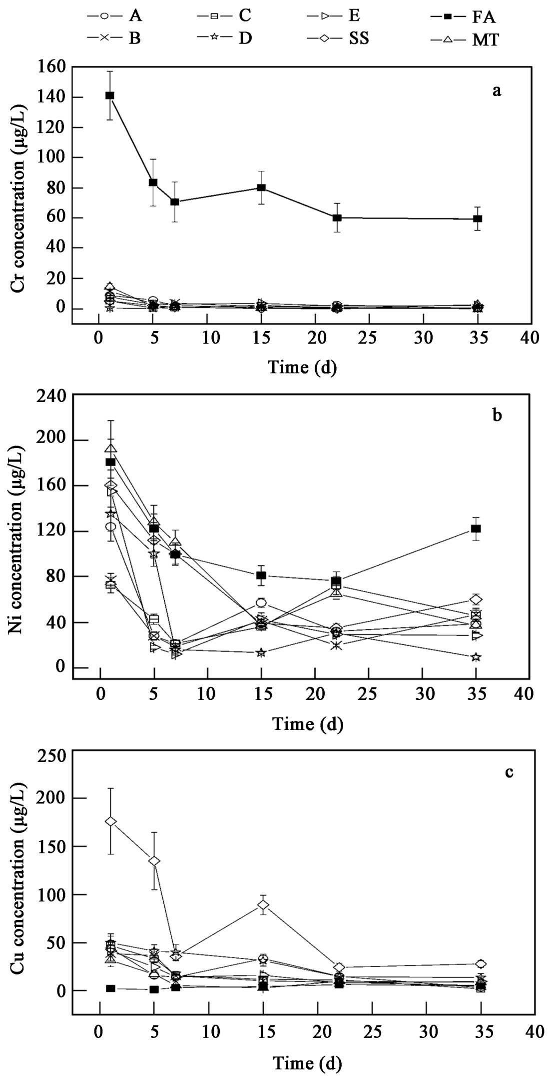

Fig. 4 Solution Cr (a), Ni (b), and Cu (c) concentrations in artificial soil.

Cr concentration in the FA-only treatment was notably higher than that in the SS-only treatment (Fig.4a). Stabilized sewage sludge by fly ash significantly decreased the soluble Cr concentration in artificial soils when compared with the FA treatment. The initial (on day 1) Cr concentrations for all mixtures were lower than 20 μg/L, whereas, those of the FA treatment were 151.04 μg/L. During incubation, solution Cr concentration gradually declined and achieved a constant level after 7 d, with the finial solution Cr concentrations for all mixtures being lower than 0.5 μg/L, except in the case of the E treatment (2.06 μg/L), where they were significantly below the EU drinking water threshold of 50 μg/L (Schumann, 1997). The results indicated that mixing FA with SS notably affected and declined the solubility of chromium in artificial soil solution.

Chromium exists in two possible oxidation states in soils: Cr(III) and Cr(VI). As a trivalent cation, it has a strong affinity for negatively charged ions and collides in soils and it is therefore relatively immobile and nontoxic in these environments (McGrath, 1995; Fendorf, 1995). Moreover, sewage sludge has been reported to contain mainly Cr(III), either bound to organic compounds or as an inorganic precipitate (Milacic and Stupar, 1995). In contrast, Cr(VI) is more soluble, mobile, bioavailable, and toxic, and its presence is favored under highly oxidizing conditions or in the presence of Mn oxides (Guertion *et al.*, 2005). Adding sewage sludge to fly ash increases the organic matter content, whereas, decreases the pH of mixtures. Under this condition, the abundant organic matter and colloids will tend to reduce any Cr(VI) in fly ash, if present (Bartlett and Kimble, 1976; Bolan and Duraisamy, 2003). Thus, Cr is probably present as Cr(III) and, as such, it must have been relatively immobile in FA/SS/MT mixtures. The result is in agreement with the report of Abbott *et al.* (2001), which stated that greater than 90% of the total Cr was found in the immobile fraction for a fly ash-organic wastes amended soil.

Nickel solubility over the duration of the incubation experiment had a decreased trend (Fig.4b). In the period of 1–7 d, it had significantly declined and then changed only gradually. In all treatments, solution Ni concentration for FA-only treatment was the highest. In addition, stabilized sewage sludge notably decreased the soluble Ni by the end of the incubation experiment. The result was not in accordance with the report that Ni was shifted to more available forms in sludge-amended soils (Lake *et al.*, 1984). It was probably that the mixtures used in this study were fly ash mixed with wet sewage sludge (water content around 60%) and then air-dried. During the air drying and incubation process, the soluble Ni in the fly ash combined with the organic or colloid matter of the sewage sludge. Final Ni concentrations of the solution in the mixtures ranged from 9.33 to 46.67 μg/L, which was near the EU drinking water threshold of 20 μg/L (Schumann, 1997).

Solution Cu concentration in the FA treatment was lower than 7 μg/L during the incubation (Fig.4c), in spite of the total Cu content in FA being 77.42 mg/kg (Table 1). Stabilized sewage sludge notably declined the solubility of

Cu. The initial solution Cu concentration for all mixtures was three times lower than those of the SS-only treatment (175.9 μg/L). Except FA treatment, soil solution Cu concentration in all other treatments decreased and achieved a constant level after 22 d. The solution Cu concentration for all mixtures ranged from 49.88 to 1.86 μg/L, and was always below the EU drinking water threshold of 2 mg/L (Schumann, 1997). By contrast, solution Cu concentration in all the artificial soil treatments (mixing FA, MT with SS) was much lower, and was presumably a function of the decreased carbon solubility observed for these treatments, in comparison with the SS treatment (Fig.4c). Complexation with dissolved organic carbon is acknowledged as a mechanism that enhances Cu solubility in the absence of complexation, Cu is strongly bound by variably charged surfaces in soils at pH >5.5 (Baker and Senft, 1995; Sara *et al*., 1996). Therefore, as decomposition of dissolved organic matter occurred during the course of the incubation experiment, the adsorption processes became the dominant control on Cu solubility. Other reasons for the decrease of soluble Cu in the FA/SS/MT mixtures could be the presence of high concentrations of other metals such as Ca, Mg, Al, and Fe in fly ash, which compete for organic ligands with Cu, or the formation of complexes with inorganic ligands such as SO_4^{2-} (Egiarte *et al*., 2006), abundant in these soil solutions (Fig.1).

3 Conclusions

Using wastes such as fly ash, poultry, and municipal sewage sludge mixtures without natural soil for ecological rehabilitation in mining areas, to solve the shortage of soil resource, would be a tendency in the future. pH value of FA/SS mixtures slightly decreased during the incubation experiment, the final solution pH for the treatment (FA:SS:MT = 2:1:1) was 7.46, which was justified to neutral. Compared with the SS-only treatment, mixing fly ash with sewage sludge significantly decreased the solution SO_4^{2-} and Cl^- concentrations. With the exception of the D (FA:SS = 0.5:1) treatment, solution NO_3^- concentration for artificial soil mixtures was obviously lower than that in the SS-only treatment. It indicated that stabilized sewage sludge could weaken the nitrification of total N from SS when the proportion of FA in the mixture was more than 50%. The solution Cr, Ni, and Cu concentrations were gradually decreased and achieved stable level after 22 days in all treatments, over the duration of the incubation. Further, stabilized sewage sludge by fly ash and/or mine tailing notably decreased the heavy metal solubility, and the final solution Cr, Cu, and Ni concentrations for all mixtures were lower than 2.5, 15, and 50 μg/L, respectively. Except for Ni, solution Cr and Cu concentration were much lower than the EU drinking water threshold (Schumann, 1997).

Acknowledgements

This study was supported by the National Basic Research Project (973) of China (No. 2004CB418503), the National Natural Science Foundation of China (No. 20477029, 20337010), and the Natural Science Foundation of Liaoning (No. 20062002).

References

Abbott D E, Essington M E, Mullen M D, Ammons J T, 2001. Fly ash and lime-stabilized biosolid mixtures in mine spoil reclamation. *J Environ Qual*, 30: 608–616.

Adriano D C, Page A L, Elseewi A A, Chang A C, Straughan I, 1980. Utilization and disposal of fly ash and other coal residues in terrestrial ecosystems: A review. *J Environ Qual*, 9: 333–344.

Baker D E, Senft J P, 1995. Copper. In: Heavy Metals in Soils (Alloway B. J., ed.). London: Blackie. 179–205.

Bartlett R, Kimble J M, 1976. Behaviour of chromium in soils: II. Hexavalent forms. *J Environ Qual*, 5: 383–386.

Belmonte M, Decap J, Martínez M, Vidal G, 2006. Effect of aerobic sludge with increasing level of adaptation on abietic acid biodegradation. *Bull Environ Contam Toxicol*, 77: 861–867.

Bolan N S, Duraisamy V P, 2003. Role of inorganic and organic soil amendments on immobilization and phytoavailability of heavy metals: a review involving specific case studies. *Aust J Soil Res*, 42: 533–555.

Ben Y J, An X Q, 2004. Present status and future development of the comprehensive utilization of coal ash. *Coal Chemical Industry*, 2: 35–37.

Campbell D E, 1998. Energy analysis of human carrying capacity and regional sustainability: An example using the state of Maine. *Environ Monitoring and Assessment*, 51(1-2): 83–94.

Carlson C L, Adriano D C, 1993. Environmental impacts of coal combustion residues. *J Environ Qual*, 22: 227–243.

Egiarte G, Arbestain M C, Ruíz-Romera E, Pinto M, 2006. Study of the chemistry of an acid soil column and of the corresponding leachates after the addition of an anaerobic municipal sludge. *Chemosphere*, 65: 2456–2467.

El-Mogazi D, Lisk D J, Weinstein L H, 1988. A review of physical, chemical and biological properties of fly ash and effects on agricultural ecosystems. *Sci Total Environ*, 74: 1–37.

EPRI (Electrical Power Research Institute), 1987. Inorganic and organic constituents in fossil fuel combustion residues. Vol. 1: A critical review. EPRI EA-5176. Electr Power Res Inst Palo Alto, CA.

Fendorf S, 1995. Surface reactions of chromium in soils and waters. *Geoderma*, 67: 55–71.

Fuentes M, Kittel T G F, Nychka D, 2006. Sensitivity of ecological models to their climate drivers: statistical esembles forcig. *Ecol Appl*, 16(1): 99–116.

Gibbs P A, Chambers B J, Chaudri A M, McGrath S P, Carlton-Smith C H, Bacon J R, Campbell C D, Aitken M N, 2006. Initial results from a long-term, multi-site field study of the effects on soil fertility and microbial activity of sludge cakes containing heavy metals. *Soil Use and Management*, 22(1): 11–21.

Gordillo R M, Cabrera M L, 1997. Mineralizable nitrogen in broiler litter: I. Effects of selected litter chemical characteristics. *J Environ Qual*, 26: 1672–1679.

Guertion J, Jacobs J A, Avakian C P, 2005. Chromium(VI) Handbook. Boca Raton: CRC Press.

Harris A R, Urie D H, Cooley J H, 1984. Sludge fertilization of pine and aspen forests on sand soils in Michigan. In: Forest Soils and Treatment Impacts (Stone E. L., ed.). *University of Tennessee, Knoxville, TN*. 193–206.

Hu Z Q, Qi J Z, Si J T, 2002. Physical and chemical properties of reclaimed soil filled with fly ash. *Journal of China Coal Society*, 27(6): 639–643.

Jackson B P, Miller W P, 2000. Soil solution chemistry of a fly ash, poultry litter, and sewage sludge-amended soil. *J Environ Qual*, 29: 2430–2436.

Kriesel W, Mclntosh C S, Miller W P, 1994. The potential for beneficial re-use of sewage sludge and coal combustion by-products. *J Environ Manage*, 42: 299–315.

Lake D L, Kirk W W, Lester J N, 1984. Fractionation, characterization, and speciation of heavy metals in sewage sludge and sludge-amended soils. *J Environ Qual*, 13(2): 175–183.

Li G H, Sun D S, Li S R, Shen J F, 2001. Feasible research on soil improvement with solid wastes. *Geology Geochemistry*, 29(2): 86–90.

Li J M, Wang Z H, Li S X, 2003. Significance of soil organix matter, total N and mineralizable nitrogen in reflection soil N supplying capacity. *Acta Pedologica Sinica*, 40(2): 232–238.

McGrath S P, 1995. Chromium and Nickel. In: Heavy Metals in Soils (Alloway B. J., ed.). London, U.K.: Blackie. 152–178.

Milacic R, Stupar J, 1995. Fractionation and oxidation of chromium in tannery waste- and sewage sludge-amended soil. *Environ Sci Technol*, 29: 506–514.

Rodriguez C G, 1996. Agricultural use of organic wastes stabilized with fluidized-bed combustion solid residues. *University of Puerto Rico Mayaguez Campus, Puerto Rico*. 19–39.

Sara B, Robert B H, Charles L H, Charles L H, Xue D S, 1996. Liming effect on availability of Cd, Cu, Ni, and Zn in a soil amendent 16 years previously. *Water Air and Soil Pollution*, 36(6): 195–206.

Schumann A W, 1997. Plant nutrient supply from fly ash-biosolid mixtures. Ph.D Dissertation, University of Georgia, Athens.

Shen W S, Cao X Z, Jin Y, 2004. The ecological damage and ecological reconstruction of mining areas. Beijing: Environment science of china Press. 1–8.

Sommers L E, Nelson D W, Silviera D J, 1979. Transformations of carbon, nitrogen and metals in soils treated with waste materials. *J Environ Qual*, 8: 287–294.

Sumner M E, 1991. Soil acidity control under the impact of industrial society. In: Interaction at the soil colloid-soil solution interface (Bolt G. H., ed.). The Netherlands: Kluwer Academic Press. 517–541.

Tolle D A, Arthur M F, Vanvoris P, 1983. Microcosm-field comparison of trace element uptake in crops grown on fly ash amended soil. *Sci Total Environ*, 31: 243–261.

Gupta U C, Gupta S C, 1998. Trace element toxicity relationships to crop production and livestock and human health: Implications for management. *Commun Soil Sci Plant Anal*, 29(11): 1491–1522.

Wang X, Cai Q S, 2006. Steel slag as an iron fertilizer for corn growth and soil improvement in a pot experiment. *Pedosphere*, 16(4): 519–524.