Improvement of Saline-Alkaline Soil via Flue Gas Desulfurization Gypsum and Safety Analysis of the Associated Heavy Metals

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Abstract. Flue gas desulfurization gypsum (FGDG) is an effective soil amendment. However, some heavy metals present in FGDG may enter soil or groundwater due to surface rainfall, causing environmental risks. This study used a washing plant to investigate the improvement of saline-alkaline soil via treatment with different mass ratios of FGDG and analyzed the effects of FGDG treatment on the soil physicochemical properties, the distribution characteristics of heavy metals at different soil depths, and the changes in the heavy metal contents of the leachate to explore the migration characteristics of heavy metals and their influence on the groundwater environment. The results showed that an appropriate amount of FGDG could effectively improve the properties of saline-alkaline soil. For example, the soil bulk density decreased significantly, the porosity increased, and the infiltration rate increased by up to 3.42-fold with the addition of FGDG. The contents of exchangeable sodium (EX-Na+) in the soil layers analyzed (0-10 cm, 10-20 cm, and 20-30 cm) decreased by 26.4-40.4%, 16.4-34.4%, and 18.9-40.3%, respectively. After treatment with 6% FGDG, the alkalinity of the soil layers decreased by 67.7%, 61.6%, and 58.2%, respectively, and the pH was close to 7.30. The mass fraction of As in the soil first increased and then decreased with increasing amounts of FGDG, decreasing to the minimum under the treatment with 6% FGDG. The mass fraction of Hg in the soil was positively correlated with the amount of FGDG, while the mass fractions of other heavy metals in the soil layers decreased with increasing amounts of FGDG. The mass fraction of Hg in the leachate was also positively correlated with the amount of FGDG, and the increase in the mass fraction ranged from 0.6 to 30.2% under different treatments. The mass fractions of other heavy metals in the leachate reached the minimum value with the maximum amount of FGDG. The heavy metal contents in the soil conformed to the category 2 limits of the Environmental Quality Standard for Soils (GB 15618-1995), and the heavy metal contents in the leachate were far lower than the category 3 limits of the Standard for Groundwater Quality (GB14848-2017), indicating that the use of FGDG to treat soil does not pollute groundwater. The results expand the understanding of the safety of FGDG (in terms of the contained heavy metals) for improving saline-alkali soil and provide a reference for further environmental risk assessments when recycling FGDG.

1. Introduction
In coal-fired power plants, a wet limestone-gypsum process is used to remove mid-sulfur coal, producing a large quantity of industrial waste in the form of desulfurization gypsum (CaSO₄ • 2H₂O). In recent years, flue gas desulfurization gypsum (FGDG) has been widely used in soil improvement, mine reclamation, and the desalination and remediation of saline-alkali land (Xiao et al.2020;
Favaretto et al. 2012; Tobert & Watt 2014; Cheng et al. 2014). This material can reduce soil pH (Chen et al. 2008) and alkalinity (exchangeable sodium percentage, ESP) (Mao et al. 2016) as well as the transport of nutrients, sediments, pesticides, and other pollutants from soil to water (Buckley & Wolkowski 2011; Favaretto et al. 2012), while improving the physical structure and chemical properties of soil. FGDG also plays an important role in controlling phosphorus levels in farmland runoff (He et al. 2017; He et al. 2019).

Fly ash in coal-fired power plants usually contains heavy metals. FGDG is often mixed with fly ash and therefore may contain traces of heavy metals (Tong et al. 2009; Chen et al. 2015). Studies (Mao et al. 2016) have shown that the contents of heavy metals, such as mercury (Hg) and arsenic (As), in some FGDG samples in China exceed national soil environmental and groundwater quality standards to varying degrees. Therefore, although FGDG can improve saline-alkali soils and control nonpoint-source pollution, elemental heavy metals in FGDG may migrate under the differentiation effect of surface rain and enter the soil or groundwater system along with beneficial compounds, presenting a hidden danger to environmental safety (Chen et al. 2008). The soil heavy metal mass fraction has been shown to be strongly correlated with the soil pH; that is, the higher the pH is, the weaker the activity of heavy metals is. As saline soil has a relatively high pH, the migration of heavy metals is not significant (Chen et al. 2015). However, the application of FGDG to soil decreases the soil pH, which may increase the activity of heavy metals. Heavy metals that enter soil with FGDG have poor migration properties, causing problems such as long retention times, strong concealment, and high toxicity. These heavy metals may enter the human food chain after being absorbed by crops, thus threatening human health (Wang et al. 2013). Therefore, safety issues related to the presence of heavy metals in soil after FGDG application have begun to attract attention. Domestic and foreign scholars have conducted preliminary studies on the heavy metal contents of FGDG in China (Ruiqiang & Rattan 2013) and on the changes in the heavy metal contents in soils, leachates, and plants after FGDG applications (Stout & Priddy 2008; Li et al. 2015; Mao & Li 2016). However, few studies have been conducted on the migration characteristics of heavy metals in FGDG and the environmental impact of FGDG on groundwater.

In this study, the improvement of saline-alkali soils by FGDG was investigated using a soil leaching test. The distribution of heavy metals at different soil depths and the changes in the heavy metal content in the leachate were determined to correctly assess the risks posed by the use of FGDG in soil and environmental improvement. This study provides a scientific basis for the large-scale promotion of FGDG application.

2. Materials and Methods

2.1 Experimental Materials

Soil samples were obtained from the Shanghai Institute of Technology, located in the inland Shanghai Fengxian District on the northern shore of Hangzhou Bay, which was a rice field before the study. The soil consisted of yellow sandy soil that was dark yellow when wet. The soil bulk density was 0.92-1.22 g/cm³, and the water content was 16.7-18.0%; the other physicochemical properties are listed in Table 1. The FGDG, which was obtained from Power Generation Co. Ltd. in Shanghai, was a creamy yellow powdered solid. The main component was CaSO₄·2H₂O, accounting for 94% of the total mass, and the particle size was approximately 0.04 mm. Before the experiment, the soil samples were fully air-dried, ground, and filtered through a standard sieve with a pore size of 5 mm. The FGDG powder sample was dried at 85 °C for 30 min to remove the free water, making it easy to mix thoroughly with soil.
Table 1. Chemical properties and heavy metal contents of the tested soil and FGDG

| Material   | Chemical properties | Heavy metals/mg kg⁻¹ |
|------------|---------------------|----------------------|
|            | pH  | EC/mS  | ESP/ | EXNa | As  | Cr  | Pb  | Hg  | Cu  | Cd  |
| Tested soil| 8.34 | 1.31   | 30.1 | 6.5   | 7.2 | 72.2| 24.3| 0.07| 23.0| 0.08|
| FGDG       | 7.02 | /      | 0.17 | /     | 5.1 | 0.47| 14.7| 0.20| 11.5| 0.40|

As shown in Table 1, the FGDG contained low levels of heavy metals that were similar to the concentrations in the tested soil. Although the concentrations of cadmium (Cd) and especially Hg in the gypsum were higher than those in the soil, they were far below the limits set by the Chinese Environmental Quality Standard for Soils (GB15618-1995). The concentration of zinc (Zn) was not investigated in this work because the results of previous studies showed that the concentrations of Zn in FGDG-treated soils were much lower than the limits specified in GB15616-1995 (Chen et al. 2015). Therefore, only six heavy metals, As, Hg, Cd, chromium (Cr), copper (Cu) and lead (Pb), were investigated in this work since they are mostly toxic and have few known vital or beneficial effects on crops.

2.2 Experimental Design

The soil washing plant was made of organic plastic with a wall thickness of 3 mm; the dimensions were a length of 60 cm, a width of 35 cm, and a height of 40 cm. The bottom 3 cm of the box acted as a leachate storage area, above which a 5 mm-thick filter plate supporting multiple layers of fiberglass was placed. Finally, the water flowed into a liquid-receiving bottle through a rubber tube for testing (Fig. 1).

Figure 1. Figure with short caption (caption centred)

Four mass ratios of FGDG were used according to the commonly used optimum ratios of FGDG for improving soil (0%, 1.5%, 3.0% and 6.0% of the total mass). The thoroughly mixed soil and FGDG samples were loaded into the washing plant to a height of 30 cm, and each treatment (FGDG mass ratio) was tested in triplicate.

2.3 Sample Measurements

In the summer two years after the application of FGDG, a simple artificial rainfall device was installed at the top of the washing plant to apply uniform rainfall. The natural rainfall of the Shanghai area in
China was simulated to irrigate the soil. Rainfall was simulated once every 5 days, and the rainfall duration was 15 min. The leachate was collected in a collection bottle. After approximately 5 L of leachate was collected, the test was terminated. The collected aqueous solution was filtered through a 4.5-μm membrane filter, and the supernatant was collected to determine the heavy metal contents. Subsequently, soil samples from 3 soil layers (0-10 cm, 10-20 cm and 20-30 cm) were collected from each soil washing test to determine the physicochemical properties of the soil.

The soil pH was measured with a pH meter. The soil electrical conductivity (EC) was measured with a conductivity meter (Chen et al. 2015). Exchangeable sodium (EX-Na+) was first extracted using ammonium acetate-ammonium hydroxide, and the content was determined by a flame photometer. The cation exchange capacity was determined by the soil-ammonium acetate method (Yang et al. 2015). The ESP (degree of soil alkalinity) is expressed using the amount of EX-Na+ at saturation (Mao et al. 2016). The contents of Hg and As were determined by an atomic fluorescence spectrophotometer (AFS-830, Beijing Titan Instruments Co., Ltd.), and the contents of the other heavy metals were determined by an inductively coupled plasma spectrometer (OPTIMA8300DV, PerkinElmer, Inc.) (Mao et al. 2016).

2.4 Statistical Analysis
The experimental data were processed and analyzed using SPSS 22.0 and Excel. The analysis of variance for the phosphorus index between the different FGDG treatments was performed at a significance level of P<0.05 and compared using the Duncan multiple comparison method.

3. Results and Analysis
3.1 Effects of FGDG on Physical Soil Structure
Table 2 shows that two years after the application of FGDG, changes occurred in the soil density, porosity and permeability to different degrees. Compared to the control, the soil density at the depth of 0-10 cm decreased by 5.08-8.47%, and the porosity increased by 4.09-6.84%; the soil density at the depth of 10-20 cm decreased by 1.75-4.39%, and the porosity increased by 0.18-3.31%; and the soil density at the depth of 20-30 cm decreased by 4.17-10.83%, and the porosity increased by 3.43-8.95%.

The results indicate that FGDG decreases soil density, increases total porosity and improves the structure of soil, thus benefiting water infiltration and the transport of nutrients and heavy metals in soil.

Table 2. Changes in physical soil structure characteristics

| Treatment | Volume weight/(g·cm⁻³) | Porosity/% | Infiltration rate/mm·min⁻¹ |
|-----------|------------------------|------------|---------------------------|
| \(0\)     | 1.18a 1.14a 1.20a 55.47a 56.98a 54.72b | 8.30a 56.74b 58.78b 56.60a 58.49b 57.74b | 19.8c 15.6b 28.4d |
| \(1.5\)%  | 1.12b 1.09b 1.15a 57.74b 58.78b 56.60a | 15.6b 58.49b 57.74b 57.74b 59.62c | 28.4d |
| \(3.0\)%  | 1.10b 1.12c 1.12b 58.49b 57.08a 57.74b | 19.8c 59.62c 58.49b 57.74b 59.62c | 28.4d |
| \(6.0\)%  | 1.08b 1.10d 1.07b 59.25c 58.49b 59.62c | 28.4d 58.49b 59.62c 59.62c 59.62c | 28.4d |

Results with the same letter in the same row within the same sampling time are not significantly different at \(p<0.05\).

Soil permeability is an important physical property index because it reflects the movement and storage of water in soil. Table 2 shows that the soil treated with FGDG exhibited a significant increase in the soil infiltration rate compared to the control and that increasing the application rate of FGDG increased the soil infiltration rate. The maximum infiltration rate was 28.4 mm/min, which was 3.42
times higher than that of the control. This result indicates that the application of FGDG improves the physical conditions related to water in the soil and increases soil permeability.

### 3.2 Effects of FGDG on Soil Chemical Properties

The variations in the concentrations of EX-Na+ in the soil samples can offer some insights into whether alkalinization occurred in the saline alkali soil and determine the alkalinization degree and its influence on the physical and chemical properties of the soil.

![Graph of EX-Na+ Concentration vs Soil Depth](image1)

**Figure 2.** Changes in the EX-Na and EC of the soil

From Fig. 2, after application of FGDG, the EX-Na+ concentrations in all soil layers significantly decreased; the largest decrease (26.4–40.4%) occurred in the topsoil layer (0-10 cm), and the magnitude increased with increasing FGDG application rate. In the other soil layers (10-20 cm and 20-30 cm), the EX-Na+ concentration showed similar decreasing trends, with reductions of 16.4–34.4% and 18.9–40.3%, respectively. A similar result was observed by Wang et al. (2005) in a laboratory soil column leaching experiment. The soil EX-Na+ concentration gradually decreased with increasing amounts of FGDG. The results showed that the FGDG had been thoroughly mixed with the soil and gradually dissolved in the two years after application. Ca2+ in the FGDG replaced Na+ in the soil over time, and the replaced Na+ was removed with the leachate as a certain amount of exchangeable Na +
can be removed with leachate. Soil EC is a very important soil property that significantly affects plant growth.

**Figure 3.** Changes in the pH and ESP of the soil

Fig. 3 shows that FGDG significantly increased the EC of the soil; EC significantly increased in all layers with increasing FGDG application rate, and compared with the control treatment, the EC of all soil layers increased by 4.0- to 6.0-fold. FGDG itself is an inorganic salt. Under the action of rainfall (washing), the FGDG dissolved, producing a large amount of soluble Ca²⁺ and SO₄²⁻, which cannot be removed effectively by washing, thus increasing the soluble salt content in the soil (Mao & Li 2016). There was no significant increase in EC in any of the FGDG treatments because FGDG has a low solubility and cannot be completely dissolved in a short period of time; with the action of rainfall (washing), the excess soluble salts gradually infiltrated the deep layers of soil or were removed.

The original soil sample had a high pH (>8.3) and ESP (>30.2%), indicating that the soil was moderately alkaline.
As shown in Fig. 4, FGDG treatment significantly decreased the pH of all soil layers. As the amount of FGDG increased, the magnitude of the decrease gradually increased. The soil pH of each soil layer under the treatment of 6% FGDG was close to 7.30, which is suitable for the growth of most plants. Similarly, FGDG treatment significantly reduced the soil alkalinity, and the average alkalinity of all soil layers was significantly lower than that of the control. Compared with the control, under the treatment of 6% FGDG, the soil alkalinity of the 0-10 cm, 10-20 cm and 20-30 cm soil layers was reduced by 67.7%, 61.6% and 58.2%, respectively, and the ESP of all soil layers was lower than 10%, which was basically consistent with the results of Mao et al. [13], who conducted a study in Dongtan, Chongming, China, and stated that FGDG can significantly reduce soil alkalinity.
3.3 Effects of FGDG on Changes in the Mass Fractions of Soil Heavy Metals

Calcium sulfate, the main component of FGDG, is slightly soluble. Appropriately increasing the amount of FGDG can achieve a better soil improvement effect, but an excessive amount may cause heavy metals to accumulate in the soil, resulting in potential risks (Wang et al., 2018). The adsorption of heavy metals in soil could result in the enrichment of heavy metals in the soil layers. Fig. 2 shows the distributions of heavy metals along the soil layers in the leaching device after two years. The results show that except for As and Hg, the mass fractions of heavy metals in all soil layers decreased with increasing amounts of FGDG. The mass fraction of As first increased and then decreased with increasing amounts of FGDG, and the mass fraction of As under the treatment of 6.0% FGDG was the lowest. Compared with the control, the mass fraction of Hg in each soil layer gradually increased with increasing amounts of FGDG, and the mass fraction of Hg in the high-percentage treatments was significantly different from that of the control.

Overall, the application of FGDG did not result in heavy metal contamination of the soil solution in a short time, which is consistent with previous studies (He et al., 2018). Using Cd as an example, the mass fraction of Cd in the FGDG was 8 times that in the soil. However, after the application of FGDG, the mass fraction of Cd in all soil layers was less than that in the control. Dissolved Cd in soil may exist as a complex; the solubility of Cd complexes in soil is related to Cl-, SO42-, and HCO3-, and complexion with Cl- can enhance the absorption and movement of Cd. The application of FGDG can increase salt movement in soil, and under the action of rainfall and runoff, water-soluble Cd2+ migrates to deep soil or is removed, thus reducing the content of Cd in the soil (Grant et al., 1999). The mass fraction of Pb in FGDG was relatively high, and the low-percentage FGDG treatments did not result in significant changes in the mass fraction of Pb in the soil. After entering soil, Pb is quickly transformed into insoluble compounds, such as Pb(OH)2, PbCO3, and PbS; therefore, its mobility is low. Additionally, FGDG increases the concentrations of SO42-, OH-, and S2- in soil, which causes Pb2+ to precipitate in large quantities and form substances that do not easily migrate and are not easily absorbed by plants; therefore, these substances accumulate in the soil (Han et al., 2005).

The addition of FGDG had no significant effect on the distribution of heavy metals in different soil layers. As the soil depth increased, the mass fraction of Hg in the soil gradually decreased; additionally, the Hg concentrations in the treated soils increased with the FGDG application ratio. The mass fractions of Cu and As decreased gradually with increasing soil depth, except for the treatment of 1.5% FGDG (in which the mass fractions increased with increasing soil depth), but the decreasing trend was not significant. For other heavy metals, the mass fractions remained basically unchanged with increasing soil depth. The different distribution characteristics of the heavy metals were determined by their migration characteristics in the soil. Due to the high leachability of Hg, Hg in topsoil could migrate to deep soil under the action of rainfall.

A correlation test showed that the relationship between the changes in the soil heavy metal concentrations and the amount of FGDG was significant. The effect of FGDG on the total amount of heavy metals in the soil was further analyzed by averaging the heavy metal concentrations in each soil layer. As shown in Fig. 3, the average Hg concentration in the treated soil increased with increasing amounts of FGDG, and the Hg concentration was positively correlated with the percentage of FGDG, with a Pearson correlation coefficient of 0.985 (P < 0.01). The average As concentration first increased and then decreased with increasing amounts of FGDG, but the As concentration was negatively correlated with the percentage of FGDG, and the Pearson correlation coefficient was -0.828 (P < 0.01). The concentrations of other heavy metals decreased with increasing amounts of FGDG, and all Pearson correlation coefficients were < -0.9 (P < 0.01).

3.4 Effects of FGDG on Changes in the Mass Fractions of Heavy Metals in the Leachate

Heavy metals in soils can be subject to desorption, extraction, and migration in the soil column and can dissolve into the leachate. These heavy metals in soil leachate then contaminate groundwater. Thus, the effects of FGDG addition on the heavy metal concentrations in the leachate were further investigated.
Fig. 5 shows the trends of the mass fractions of the various heavy metals in the soil leachate with respect to the application amount of FGDG. The results showed that the mass fraction of each heavy metal in the leachate reached the minimum value when the amount of FGDG was the maximum. With increasing amounts of FGDG, the mass fractions of Cr, Pb and Cu in the soil leachate decreased gradually, with decreases of 15.5-26.2%, 43.1-70.8% and 31.0-61.5%, respectively. After the application of FGDG, the mass fraction of As in all the treatments was lower than that in the control, but it increased slightly under the treatment of 3.0% FGDG and decreased to the minimum under the treatment of 6.0% FGDG, with a decrease of 12.4%. The trend in the mass fraction of As in the leachate was consistent with that in the soil, and the differences were not significant.
The mass fraction of Hg in the leachate gradually increased with increasing amounts of FGDG, and the increase ranged from 0.6% to 30.2%. The mass fraction of Hg was positively correlated with the percentage of FGDG (p = 0.862). The mass fraction of Cd in the leachate first increased and then decreased with increasing amounts of FGDG and reached the highest value under the treatment of 3.0% FGDG, with an increase of 18.9%. The mass fraction of Cd dropped to the lowest value under the treatment of 6.0% FGDG, which was 11.4% lower than that of the control. The mass fractions of all heavy metals in the leachate were all far below the requirements in the Standard for Groundwater Quality (GB14848-2017).

4. Discussion

4.1 Effects of FGDG on Soil Physicochemical Properties

FGDG can enhance the adsorption capacities of soil ions: Ca\(^{2+}\) can replace Na\(^{+}\) in soil colloids, so the soil colloids mainly absorb Ca and form a soil aggregate structure, which ensures suitable soil porosity; therefore, the ventilation and water permeability of the soil are improved, which facilitates the entry and discharge of water(Chen & Dick 2012; Chen et al. 2017). The results showed that the application of FGDG to the soil improved the physical properties of the soil, reduced the bulk density, increased the porosity, and improved the permeability by 1.87- to 3.42-fold. Under rainfall or irrigation, increased soil permeability can, to a certain extent, increase runoff infiltration, which can cause salts and heavy metals in the soil to migrate to deep soil layers through leaching or to transfer to groundwater, change the state or activity of heavy metals in the soil, and reduce the probability of surface heavy metal loss to nearby waters with surface runoff.

Studies have shown that FGDG can reduce the pH of agricultural soils and maintain a stable soil pH over time, mainly due to the reaction of FGDG and EX-Na\(^{+}\) in soil colloids acting to simultaneously replace Na\(^{+}\) in the soil. The produced soluble salt Na\(_2\)SO\(_4\) can penetrate to deep soil layers, and the Na concentration on the surface of the soil continuously decreases, thus lowering the pH of the soil. The exchanged Na ions migrate to the deep soil(Mao et al. 2016; Chun et al.2005) or are lost to the surrounding water through natural rainfall ( Ruiqiang & Rattan 2013) . With decreasing EX-Na\(^{+}\) in soil, the content of exchangeable Ca\(^{2+}\) in the soil increases significantly, which reduces the alkalinity of the soil to some extent but also significantly increases the salt ion concentration in the soil in a short time(He et al.2018).

4.2 Effects of FGDG on the Mass Fractions of Heavy Metals in the Soil and Leachate

The mass fractions of most heavy metals in the FGDG were lower than those in the soil, and the amount of FGDG applied to the soil was small; therefore, the contribution of heavy metals from the FGDG to the soil was negligible. However, the mass fractions of As and Hg in FGDG samples from some power plants may be high due to the use of different coal production areas and different desulfurization processes (Li et al.2014). If the mass fractions of heavy metals in FGDG are higher than the soil background values, the heavy metal contents in the soil and leachate may increase when FGDG is applied to the soil. In addition, reduced pH may increase the solubility and activity of heavy metals. Therefore, the safety of heavy metals in FGDG must be considered. The results showed that two years after the application of FGDG, the mass fractions (in all soil layers) of heavy metals, except As and Hg, decreased with increasing amounts of FGDG. The total mass fraction of As increased first and then decreased with increasing amounts of FGDG and was negatively correlated with the percentage of FGDG. A relevant study (Wang et al.2013) showed that applying FGDG in a certain percentage range does not lead to serious As soil pollution, and As was mostly concentrated in the subsoil; therefore, the possibility of its uptake by plant roots in the topsoil was low. In this study, because the Hg content in the FGDG was higher than the soil background value, the soil Hg content increased with increasing amounts of FGDG. Therefore, the Hg content should be determined before the application of FGDG. In this study, the concentrations of all heavy metals, including Hg, were lower than the category 2 limits of the Environmental Quality Standard for Soils (GB 15618-1995). Currently, the Hg concentration in many FGDG samples in China ranges from 10 to 1400 g·kg\(^{-1}\), which may be higher than the background level of some soils. Moreover, due to the extremely low
national standard limit for Hg, the leaching of trace Hg may cause great environmental risks; therefore, considerable attention should be paid to Hg when applying FGDG (Li et al.2014).

As the amount of FGDG increased, the mass fractions of Cr, Pb and Cu in the soil leachate gradually decreased. The mass fraction of As was lower than that of the control, and the variation in the mass fraction of As in the leachate was similar to that in the soil. The mass fraction of Hg gradually increased with increasing amounts of FGDG, which was consistent with the variation in Hg in the soil. The behavior of heavy metals in soil involves complex processes, such as desorption, migration through pores, adsorption, and dissolution. The migration characteristics of heavy metals in FGDG are affected by multiple factors, such as the forms of the heavy metals, the acidity of the leachate, and the leaching time. When soil undergoes leaching, heavy metals may follow the path of leaching, migrating from upper layers to the lower layers, infiltrating groundwater, or accumulating in some soil layers (Shaheen et al.2013). The basic mechanism of such migration remains to be further studied and could be the focus of future research.

In general, the addition of FGDG did not cause significant changes in the heavy metal contents in the soil or leachate; the contents of some heavy metals even decreased, and there was no risk of water or soil contamination. FGDG has a certain desorption effect on heavy metals and can reduce the adsorption of heavy metals in soil to different degrees and change the forms of heavy metal ions in soil, thus reducing the bioavailability and migration of heavy metals (Tong et al.2009). FGDG can reduce the adsorption of Cd, Cu, Pb and Cr in soil to different degrees, and exchange adsorption between Ca ions and other exchangeable heavy metals can lead to an increase in the removal rate of heavy metals under leaching. Some studies have noted that the dissolution of heavy metals in FGDG mostly occurs for a short time after application. If the soil is not disturbed, the dissolved heavy metals could soon be adsorbed by the upper humus layer or soil (Clark et al.2001). Therefore, over time, the heavy metal contents of As, Pb, Cr and Cd in soil could gradually return to their original background values.

4.3 Comprehensive Assessment of the Safety of FGDG in Agricultural Production
At present, the results regarding the improvement of the environment by FGDG are mostly positive, and it is safe to use FGDG at a high application rate of 280 t/hm2 on reclaimed land from abandoned coal mines (Chen et al.2015). After the application of FGDG to soil, the contained heavy metals, their absorption by plants, and their potential release to surrounding water bodies do not cause serious environmental issues (Tobert & Watt 2014). In the reclamation of coastal saline soil in Dongtan, Nanhui, China, the heavy metal contents of the soil did not increase in the two years after the application of FGDG, and even at an application rate as high as 60 t/hm2, no heavy metal soil contamination was observed (He et al.2018). Xu et al. used FGDG to treat soil used for growing peanuts, rice, etc., and no excessive accumulation of heavy metals was found in the edible portion of the plants. FGDG did not lead to the enrichment or residual pollution of heavy metals in agricultural products and did not affect the safety or quality of agricultural products. All the above studies have shown that the use of FGDG to improve saline alkali soil has little effect on the heavy metal contents in the soil. The Chinese government has been applying strict environmental protection measures, and more stringent regulations will be imposed on power plants to control flue gas emissions in the coming decade. These results provide a safe and reliable basis for the large-scale demonstration and popularization of the use of FGDG to improve soil. However, in FGDG samples from different regions, the chemical composition and the forms and contents of heavy metals can be different. Moreover, the environmental hazards of heavy metals in soil are related not only to their total amount but also to their activities in soil, and soil properties greatly influence the activity of heavy metals in soil. Relevant studies have shown that heavy metals in soil are generally in the forms of exchangeable ions, carbonates, iron and manganese oxides, organic matter, and residues, and the activities of heavy metals in different forms can vary substantially, so their mobilities can differ greatly (Wu & Pan 2003).

Moreover, heavy metals have a long residence time in soil and do not degrade in nature, which may have some influence on the properties and utilization of soil. Therefore, in the utilization process of FGDG, targeted measures should be taken according to the specific FGDG used to minimize the risk of environmental hazards.
5. Conclusion
In this paper, a soil washing plant was used to study the improvement of saline-alkaline soil under FGDG treatment at different percentages. In addition, the variations in the mass fractions of heavy metals in the soil and leachate were analyzed, and the following conclusions were obtained:

1) Adding an appropriate amount of FGDG can effectively improve saline-alkaline (coastal saline) soil. After the application of FGDG, the physicochemical properties of the soil can be significantly improved, the bulk density can be reduced, the porosity can be increased, the EX-Na+ content can be reduced, and the pH and ESP can be significantly reduced.

2) The addition of FGDG does not cause significant changes in the mass fractions of heavy metals in saline-alkaline soil. The mass fractions of heavy metals in the soil after the application of FGDG conformed to the category 2 limits in the Environmental Quality Standard for Soils (GB 15618-1995). The migration and distribution characteristics of the heavy metals in different soil layers were different, and the basic mechanism of heavy metal migration needs further comprehensive study.

3) The mass fractions of soil heavy metals in the leachate were far below the category 3 limits of the Standard for Groundwater Quality (GB14848-2017) and did not pollute the groundwater. With increasing amounts of FGDG, the mass fraction of Hg in the leachate increased; therefore, more attention should be paid to the Hg content when applying FGDG.

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