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Reprocessing and Resource Utilization of Landfill Sludge—A Case Study in a Chinese Megacity

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Abstract: In the past, due to improper sludge treatment technology and the absence of treatment standards, some municipal sludge was simply dewatered and then sent to landfills, occupying a significant amount of land and posing a serious threat of secondary pollution. To free up land in the landfill area for the expansion of a large-scale wastewater treatment plant (WWTP) in Shanghai, in this study, we conducted comprehensive pilot research on the entire chain of landfill sludge reprocessing and resource utilization. Both the combination of polyferric silicate sulfate (PFSS) and polyetheramine (PEA) and the combination of polyaluminum silicate (PAS) and polyetheramine (PEA) were used for sludge conditioning before dewatering, resulting in dewatered sludge with approximately 60% moisture content. The combined process involved coagulation and sedimentation, flocculation, and oxidation to treat the leachate generated during dewatering. The treatment process successfully met the specified water pollutant discharge concentration limits for the leachate, with the concentration of ammonia nitrogen in the effluent as low as 15.6 mg/L. Co-incineration in a power plant and modification were applied to stabilize and harmlessly dispose of the dewatered sludge. The coal-generating system ran stably, and no obvious problems were observed in the blending process. In the modification experiment, adding 5% to 7% of the solidifying agent increased the sludge bearing ratio by 53% and 57%, respectively. This process effectively reduced levels of fecal coliforms and heavy metals in the sludge but had a less noticeable effect on organic matter content. The modified sludge proved suitable for use as backfill material in construction areas without requirements for organic matter. The results of this study provide valuable insights for a completed full-scale landfill sludge reclamation and land resource release project.

Keywords: landfill sludge treatment; conditioning; dewatering; co-incineration; leachate treatment

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1. Introduction

Municipal sludge is the byproduct of municipal wastewater treatment, consisting of complex materials such as organic matter, microbial biomass, protozoans, inorganic particles, and colloids [1]. The raw sludge is characterized by a high moisture content, high organic matter content, and strong smell. With the continuous increase in wastewater treatment during China's urbanization process, the generation of municipal sludge has also increased [2]. In the past few decades, landfilling has been the conventional method for municipal sludge treatment in China due to its simplicity and cost advantage in handling large quantities of sludge [3]. However, sludge that was directly dumped into landfills without proper pretreatment was not stabilized. Long-term storage of sludge with a high moisture content could easily lead to secondary pollution of the surrounding soil, water, and air [4,5].

Subsequent dumping of garbage in the landfill could cause compression of the sludge, excessive deformation, and insufficient strength, which might lead to landfill engineering accidents. Furthermore, in the context of increasingly limited urban construction land, landfill sites for sludge have occupied large areas and had a significant restraining effect on the development of surrounding areas [6]. Therefore, the removal and reprocessing of municipal sludge from landfill sites to mitigate the historical sludge accumulation has become a new direction in the field of municipal sludge treatment. Typically, to handle and recycle the landfill sludge, the sludge must be taken out from the landfill site first and then dewatered and disposed of properly. Moreover, the leachate generated during the dewatering process must be treated to meet the discharge standard. Co-incineration of sludge in power plants has been widely used as an alternative method to utilize sludge [7–9]. In China's megacities, like Shanghai, the use of dewatered sludge for co-treatment in coal-fired power plants is encouraged [10,11]. However, few studies have reported the co-treatment in power plants of sludge that has been landfilled and then dewatered. Leachate, as a byproduct of landfill sludge, is characterized by high concentrations of nitrogen and phosphorus. Comparatively, the concentration of nitrogen in sludge landfill leachate is typically even higher than that in traditional solid waste landfill leachate [12].

Some researchers have used chemical and biological technology to remove ammonium nitrogen from landfill sludge leachate [13–17]. It is worth noting that biological treatment methods, such as the activated sludge process, usually cost too much energy and occupy a large land area. On the other hand, only biological treatment of leachate can meet discharge standards due to the high concentrations of pollutants [18]. Therefore, the combination of physio-chemical technology for the simultaneous removal of nitrogen and phosphorus is becoming a promising method to handle high nitrogen concentrations in leachate.

The temporary sludge landfill site used in this study is located on the east side of a large-scale WWTP, adjacent to the Yangtze River, with a landfill area of approximately 25 ha. It was constructed in 2004 to address the issue of municipal sludge disposal. Starting in June 2010, to control the odor from the landfill site and its impact on the surrounding environment, the WWTP implemented capping and covering measures on the entire sludge landfill area. Currently, with limited available land for the Phase III expansion of the wastewater treatment plant, the urgency and necessity of releasing the land within the sludge temporary storage area have become apparent.

Through this study, we aim to restore the sludge landfill to its original state by focusing on the withdrawal, treatment, disposal, and resource utilization of landfill sludge. The research includes a comprehensive technical examination and demonstration of the sludge temporary storage area. Additionally, we aim to promote key technologies such as sludge pollution diagnosis, risk control, and resource utilization. The ultimate goal is to achieve reduction, harmlessness, stabilization, and resource utilization of the sludge stored in the temporary landfill site. The long-term landfilling of sludge under a High-Density Polyethylene (HDPE) geomembrane has led to anaerobic fermentation, producing a significant amount of toxic and harmful gases [19]. The anaerobic fermentation has resulted in changes to the properties of both the sludge and leachate, leading to higher environmental risks. Therefore, the current focus and challenges of the research involve completing the treatment and disposal of the sludge and leachate with minimal environmental impact and safely reclaiming the land resources in the storage area. This research demonstrates a complete chain of technologies, including dewatering aged landfill sludge, co-incineration in a power plant, solidified modification of sludge for use as backfill material, and the treatment process for the leachate generated during sludge dewatering. The result provides a theoretical basis and enables recommendations for the future reclamation of landfill sludge.

2. Materials and Methods

2.1. Overview of Sludge Landfill Site and Sludge Extraction Equipment

The sludge landfill site comprises 12 pits, each with a length of approximately 180 m, a width ranging from 80 to 120 m, and a depth of 8 m. To prevent the release of pollutants, half of the upper portion of the landfill cells is covered with an HDPE geomembrane. In this study, a suspended cable-based equipment system was used for the extraction of sludge from the landfill site.

The equipment consists of five main components: the sub-membrane sludge removal system, the onshore towing system, the cable winding system, the control system, and the maintenance system. The suspended cable system utilizes power to drive water pumps, generating high-pressure water flow that enters the spray pipes. The water is then sprayed out through the nozzles installed on the spray pipes, agitating the sludge at the bottom of the sedimentation pit into a turbid water-like state. This allows the sludge to flow out without opening the geomembrane, ensuring that sludge odors do not spread extensively. The sludge extraction equipment and the construction section are depicted in Figure 1.

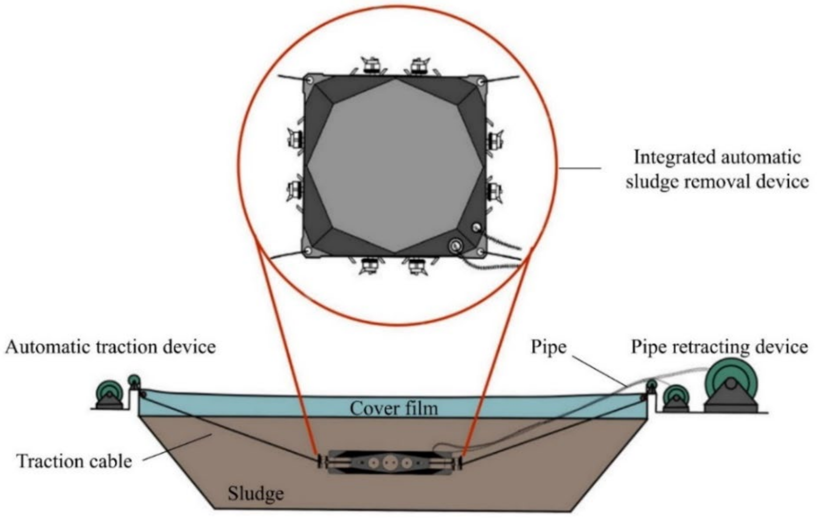

Figure 1. Suspended cable sludge removal equipment under plastic film and a construction cross-section diagram.

2.2. Materials

Due to the landfilling process, the majority of the sludge was directly deposited into the sludge pit after undergoing thickening and dewatering, resulting in a relatively high organic matter concentration and moisture content. Within the covered pit, the sludge underwent further digestion under anaerobic conditions, leading to complex changes in its physicochemical properties. Samples were collected from the aged sludge at depths of 1 m and 4 m within the covered area, and relevant indicators were tested. On-site sampling revealed that the surface layer of the test pit primarily consisted of sludge, with the sludge concentration gradually increasing from top to bottom. In some pits, the lower layers even exhibited compacted conditions. The thickness of the liquid sludge layer ranged from approximately 0.5 to 2.2 m, while the thickness of the solid sludge layer ranged from approximately 5.2 to 6.1 m. The data for sludge at different depths are presented in Table 1.

The leachate from the sludge landfill site shared certain similarities with the leachate from traditional solid waste landfills, but with higher concentrations of specific pollutants. In this study, the sludge leachate used was generated through the dewatering process of sludge that had been conditioned with chemicals and passed through a plate-and-frame filter press. Through testing and analysis of the properties of the leachate, it was found that the C/N ratio of the leachate was extremely low. The biodegradability of the leachate was poor, and the main pollutant was ammonia nitrogen. Table 2 presents the water quality of the sludge leachate and the operating conditions of the treatment equipment.

Table 1. Physicochemical properties of landfilled sludge at depths of 1 m and 4 m.

Depth	**1 m**	**4 m**
pH	7.58	7.84
Moisture content	85.14%	72.09%
Organic matter	37.70%	39.62%
Low heating value (kJ/kg)	6954	6343
C (%)	15.6	14.2
S (%)	1.47	1.62
Ca (mg/kg)	3.429×10^4	3.203×10^4
Al (mg/kg)	5.392×10^4	7.909×10^4
Fe (mg/kg)	2.771×10^4	2.717×10^4
Cl (mg/L)	1036	1478

Table 2. The water quality of the sludge leachate and the operating conditions of the treatment equipment.

Item	**Treatment Standard**	**Influent**	**Effluent**
pH	6–9	5.53	6.67
SS (mg/L)	400	595	98
COD_{cr} (mg/L)	n.a.	479	392
NH_3-N (mg/L)	40	1.26×10^3	15.6
TP (mg/L)	8	7.00	1.98
TN (mg/L)	n.a.	2.12×10^3	161

Notes: n.a. means not available.

The results indicated that after sludge leachate continuous treatment, the effluent water quality met the required treatment standards. The coagulation–flocculation–filtration–oxidation process employed in the experiment is feasible.

2.3. Treatment and Disposal Methods for Landfill Sludge

The treatment and disposal technology route for landfill sludge and leachate in this study is shown in Figure 2.

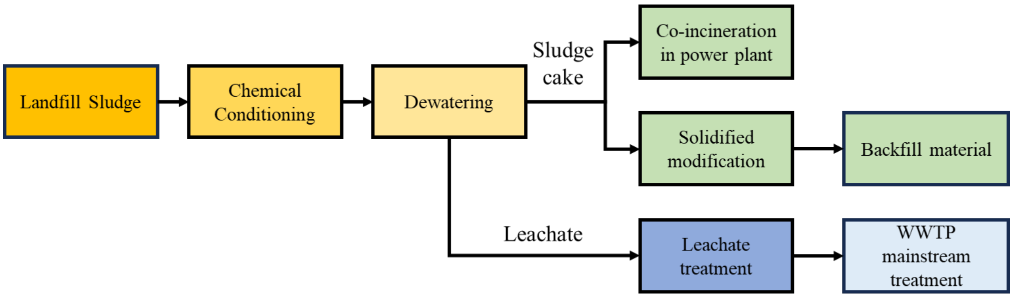

Figure 2. The treatment and disposal technology pathway for landfill sludge and leachate.

2.3.1. Chemical Conditioning and Dewatering

The main components of the chemicals used for sludge conditioning and dewatering were polyferric silicate sulfate (PFSS) and PEA. Among these, the molecular weight control of PFSS directly affects the efficacy of sludge dewatering [20]. It is crucial to select the appropriate silicon-to-iron molar ratio and quantity of hydroxy polymers. PEA is a high-molecular-weight amine-based coagulant that is in emulsion form. It is characterized by a low molecular weight, high charge density, and the ability to flocculate sludge particles. Unlike polyacrylamide, PEA is almost completely soluble in water and could not lead to clogging of filter cloths or increased viscosity of the sludge [21].

Based on the characteristics of the sludge and the performance of the deep dewatering equipment, experiments were conducted to examine the dewatering efficiency, cost-effectiveness, and safety of the dewatering agents. Sludge dewatering was carried out using a plate-and-frame filter press (04YLJ-20 Jingjin, Shandong) in the dewatering workshop, with a maximum daily sludge processing capacity of 10 t DS/day.

2.3.2. Sludge Modification

The experimental sludge used was collected from the discharge outlet of the frame filter press machine. The chemicals applied are patented agents developed independently by the Shanghai Municipal Engineering Design Institute, known as the "SHGT-16 Soil Stabilizer (NOWA-SH)". These agents belong to the category of calcium-based activator-type composite soil stabilizers. The main components of the agents are Portland cement, steel slag powder, industrial byproduct gypsum, mineral admixtures, and surfactant.

After dewatering, the water content of solid sludge was less than 60%. The sludge became solid and block-like. Before the modification process, the dehydrated sludge was crushed into powder form with a particle size not exceeding 20 mm. Based on preliminary testing of the types and dosages of chemicals, the chemicals were mixed thoroughly with the crushed sludge. Subsequently, the mixture was transferred to the sludge solidifying area, where it was shaped into piles, covered with tarpaulins, and subjected to solidification.

2.3.3. Sludge Leachate Treatment

In addition to the indicators related to carbon sources, the effluent water quality from the sludge leachate treatment process should meet the "Water Quality Standards for Discharging Wastewater into Urban Sewers" (DB31445-2009) in Shanghai [22]. Based on the primary pollutants in the leachate and the results of static tests, a combination of physical and chemical techniques was applied in the treatment. The technologies used for phosphorus removal included coagulation and sedimentation. The technologies used for ammonia nitrogen removal included flocculation, aeration, and oxidation. The specific process is detailed in Figure 3.

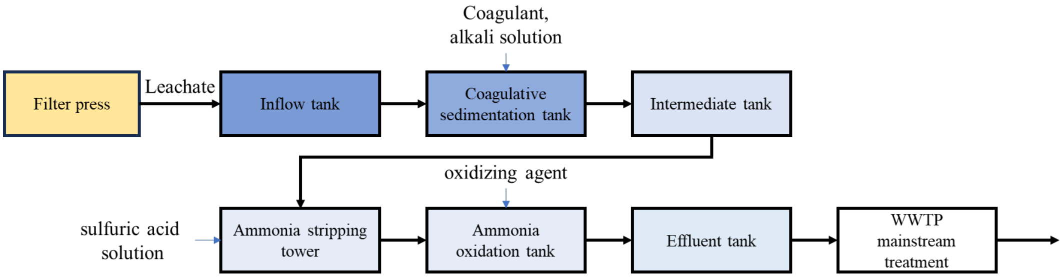

Figure 3. The experimental process flow for sludge leachate treatment.

The sludge leachate was directed from the outlet pipe of the plate-and-frame filter press into the continuous experimental influent tank. Subsequently, the leachate was pumped to the coagulation and precipitation tank. Following the application of coagulants for phosphorus removal and pH adjustment using an alkaline solution, the leachate flowed into an intermediate tank. From the intermediate tank, the leachate was pumped into the ammonia nitrogen stripping tower. After the stripping process, the treated leachate was pumped to an oxidation tank for ammonia nitrogen oxidation. Finally, the treated leachate was discharged into the effluent tank.

2.4. Analytical Method

2.4.1. pH, Organic Matter, Potassium (K), and Hygienic Indicators for Sludge

The pH, organic matter, potassium (K), and hygienic indicators in the sludge samples were determined by strictly following the Chinese standard method (CJ/T 221-2005) [23].

2.4.2. pH and COD (Chemical Oxygen Demand) for Leachate

The pH and COD in the water samples were determined by strictly following the Chinese standard methods (GB 6980-1986 [24] and GB 11914-89 [25]). The pH value was detected using an Eh-pH meter (PHS-25, Shanghai Precision and Scientific Instrument Co., Ltd., Shanghai, China) directly. The value of COD was detected using the dichromate method. Water quality detections were all accomplished on the sample collection day.

2.4.3. Heavy Metals and Heat Value of Sludge

The contents of heavy metals in the sludge were quantified by means of ICP-AES spectrometry (Agilent Corporation, Santa Clara, CA, USA). Heat value tests on sludge samples were performed according to GB/T213-2008 [26]. The sludge samples were dried for 24 h under 105 °C and then crushed to 2 mm particle size. The heat value of sludge samples (~0.6 g) was determined by employing an oxygen bomb typical calorimeter.

3. Results and Discussion

3.1. Sludge Conditioning and Dewatering

An experiment was conducted on the raw landfilled sludge with an average moisture content of 90.5% and an average organic matter content of 32.3%. The sludge was conditioned in a conditioning tank and then transported to a plate-and-frame filter press for dewatering, with the resulting sludge product being discharged into the lower sludge hopper. The properties of the dewatered sludge were analyzed and are presented in Table 3.

Table 3. Properties of dewatered sludge.

Item	Mean Value	Max. Value	Min. Value
Moisture content (%)	58.3	63.6	52.9
Organic matter (%)	32.2	35.7	28.9
Cl (mg/L)	240	354	157
Higher heating value (kcal/kg)	2005	2080	1950
Lower heating value (kcal/kg)	1800	1880	1740
Ni (mg/kg)	52.1	61.7	45.5
Cu (mg/kg)	483	521	414
Zn (mg/kg)	1074	1250	944
Cr (mg/kg)	191	200	176
Cd (mg/kg)	2.38	2.51	2.29
Pb (mg/kg)	59.6	64.8	53.7
Hg (mg/kg)	3.45	3.82	3.14
As (mg/kg)	20.0	21.8	18.6

The results indicated that the moisture content of the sludge product was controlled at around 60%. The dehydrated sludge exhibited high hardness, with most of it readily detaching automatically. The conventional chemicals used for sludge dewatering are usually PAC (polyaluminum chloride) and PFC (polymerization ferric chloride), typically containing large quantities of chlorine ions, causing severe corrosion in incineration facilities [27,28]. However, the average chloride ion concentration of the dewatered sludge was 240 mg/kg in this study. According to the Code for Investigation of Geotechnical Engineering (GB50021-2001) [29], indicating the corrosiveness of clayey soil to reinforcements in concrete structures above the groundwater level, the dewatered sludge product fell within the category of “weak corrosiveness”. The organic matter content was at an average value of 32.2%. The variation range of the HHV (higher heating value) and LHV (lower heating value) showed relatively small fluctuations of 2010 kcal/kg (HHV) and 1800 kcal/kg (LHV). Comparing the heavy metal indicators in the dewatered sludge with conventional sludge disposal standards, it could be concluded that the heavy metal indicators in the test dewatered sludge cake met the standards for conventional sludge disposal. Therefore, there was no need for further treatment or disposal of heavy metals in the sludge. In summary, the use of chemicals made from PFSS and PEA for sludge dewatering and conditioning resulted in favorable equipment operation and sludge properties.

3.2. Power Plant Co-Incineration

Power plant co-incineration refers to a relatively stable and controllable sludge treatment and disposal method where sludge is co-incinerated with powdered coal in power plants. The existing sludge dewatering facilities and transfer vehicles at the WWTP could support the co-incineration of sludge in a thermal power plant.

As previous results of sludge conditioning and dewatering experiments indicated, using PFSS and PEA emulsion coagulant as conditioning agents showed a good dewatering effect. However, during incineration, the chlorine and sulfur in the raw fuels typically led to corrosion damage to the equipment, as well as air pollution [30–33]. According to the latest requirements from power plants, the chlorine and sulfur element contents in the received sludge after conditioning and dewatering should both be less than 1.2% to prevent corrosive effects on equipment. The chlorine element content in the dewatered sludge met the requirement after conditioning with these agents, but the sulfur ion content reached 1.59%. Therefore, an experiment was conducted to optimize the dewatering agent formulation for co-incineration sludge by replacing PFSS with polyaluminum silicate (PAS), as shown in Table 4.

Table 4. Chlorine and sulfur element detection results for power plant co-incineration sludge.

Reagent	Main Component	Dosage (kg/t DS)	Dry Weight Gain Ratio (%)	Moisture Content (%)	Chlorine as Received Basis (%)	Sulfur as Received Basis (%)
Original reagent	PFSS PEA	550 9	5.20	59.6	0.24	1.59
Modified reagent	PAS PEA	100–600 10–30	2.7–20	58.7	0.12	0.79

The thickness of the dewatered sludge cake was approximately 3–4 cm. The sludge cake could be easily separated and then transported to the power plant for co-incineration. A total of 149.6 tons of dehydrated sludge with approximately 60% moisture content was co-incinerated in the experiment. The results are presented in Table 5. Overall, the co-incineration process proceeded smoothly, without significant issues. Some sludge with a moisture content exceeding 60% made the feeding system slightly sticky, but it showed a relatively minor impact on the overall combustion process. To prevent problems with the feeding system during long-term operation, the sludge moisture content of the deep dewatered sludge is recommended to be below 60%.

Table 5. Power plant co-incineration results.

Power Plant	Reagent	Moisture Content (%)	Co-Incineration Amount (t)
A	PFSS + PEA PAS + PEA	58.9 57.2	13.6 48.6
B	PFSS + PEA PAS + PEA	58.6 58.2	15.4 45.1
C	PFSS + PEA PAS + PEA	63.3 62.1	12.1 15.4

In the experiments conducted at three power plants, the different reagents and varying dosages had no obvious impact on the incineration flue gas. There was no difference in smoke indicators between co-incineration and conventional coal powder incineration. Based on the analysis of the co-incineration results and the chlorine and sulfur element concentrations in the received sludge, the combination of PAS and PEA was more suitable for application in actual sludge co-incineration than the combination of PFSS and PEA.

3.3. Sludge Modification

To address the problem of insufficient processing scale in existing sludge incineration facilities, a treatment has been implemented to blend the solidified sludge with the existing embankment soil within the landfill. This treatment provides a new approach to the resource utilization of excess landfill sludge, aiming to meet land use criteria in China, including heavy metal content, organic matter, compaction, etc., to comply with the standards required for construction site backfill soil. This approach facilitates the co-treatment of sludge within the landfill, reducing the need for external transportation and additional earthworks. Feasibility testing and optimization of the modified sludge were conducted, including the types and proportions of modification agents.

3.3.1. Heavy Metal

Heavy metals in sludge products pose a potential danger that limits the use of sludge for land applications [34–36]. The heavy metal results indicated that both before and after modification, the detected concentrations for all indicators were below the requirements of standards for various types of soil, including agricultural soil, land improvement soil, garden landscaping soil, forest soil, mixed landfill soil, etc. Therefore, after modification, the risk of heavy metal pollution in the sludge when used as construction backfill soil was relatively low, making it suitable for various end-uses. Table 6 shows the heavy metal content of dewatered sludge after modification experiments.

Table 6. Heavy metal content of dewatered sludge.

Item	**Dosage of Solidifying Agent**		
	0	**5%**	**7.5%**
Ni (mg/kg)	55	63	33
Cu (mg/kg)	417	370	365
Zn (mg/kg)	1192	1038	1022
Cr (mg/kg)	120	104	89
Cd (mg/kg)	1.8	1.6	1.6
Pb (mg/kg)	75	67	65
Hg (mg/kg)	1.7	1.6	1.5
As (mg/kg)	5.87	5.78	5.81

3.3.2. Soluble Salt

The soluble salt content results indicated no significant difference in the soluble salt index before and after modification. According to the Code for Geotechnical Investigation of Building Foundation (GB50021-2001) [29], the corrosion levels of sulfate ions, chloride ions, and magnesium ions were determined to be weak, very weak, and weak, respectively. The comprehensive evaluation suggested weak corrosion. This implies that when used as construction backfill soil, the sludge would have a relatively minor impact on building materials. Table 7 shows the soluble salt content and the corrosion level of dewatered sludge after modification experiments.

Table 7. The soluble salt content of dewatered sludge.

Item	**Batch 1**	**Batch 2**	**Corrosion Level**	**0% Addition**	**5% Addition**	**7.5% Addition**	**Corrosion Level**
CO_3^{2-} (%)	0	0	n.a.	0	0	0	n.a.
HCO_3^- (%)	0.13	0.02	n.a.	0.05	0.14	0.12	n.a.
SO_4^{2-} (%)	0.24	0.51	weak	0.21	0.19	0.18	weak
Cl^- (%)	0.03	0.05	very weak	0.03	0.03	0.01	very weak
Ca^{2-} (%)	0.13	0.36	n.a.	0.37	0.39	0.35	n.a.
Mg^{2-} (%)	0.06	0.06	very weak	0.14	0.21	0.18	very weak
Na^+ (mg/kg)	359.8	327.3	n.a.	40.23	46.83	50.37	n.a.
K^+ (mg/kg)	458.1	363.7	n.a.	42.37	53.99	57.99	n.a.

Notes: n.a. means not available.

3.3.3. Organic Matter, Bearing Ratio, Compressive Strength

After a 5% solidifying agent was added, the organic matter content decreased to 27.19%, which could not meet the requirements for organic matter content in standards such as Specification for Design of Urban Road Subgrades (CJJ194-2013) [37] and Code for Construction and Acceptance of Earthwork and Blasting Engineering (GB50201-2012) [38]. Therefore, the modified sludge was not suitable for direct application in compacted fill areas. As a solution to expand the range of suitable fill materials, the modified sludge could be mixed with inorganic materials, such as lime-treated soil, to reduce the organic matter content.

The bearing ratio is a typical indicator used to evaluate the strength of subgrade soil and pavement materials [39]. The unconfined compressive strength test measures the ultimate strength of a specimen under axial pressure without lateral confinement. The results of bearing ratio tests and unconfined compressive strength tests under different proportions of stabilizing agents are shown in Figure 4. Without a solidifying agent, the bearing ratio of the sludge product was 31%. The bearing ratio of the sludge increased to 53% after 5% solidifying agent was added and further to 57% with a 7.5% proportion. Sludge without a solidifying agent had a very low unconfined compressive strength. As the proportion of stabilizing agents increased, the 7-day unconfined compressive strength of the sludge specimens showed a significant increasing trend. This result indicates that the modification treatment significantly enhanced the strength of the sludge.

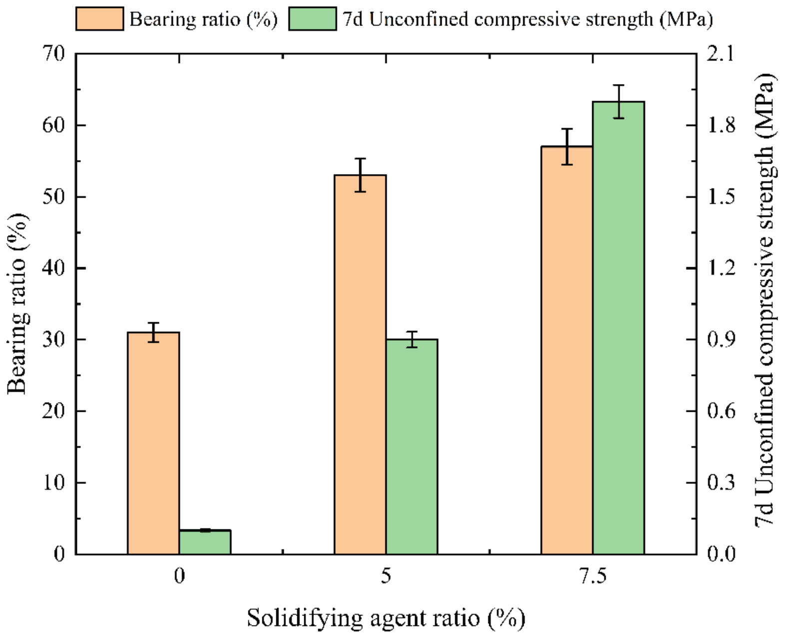

Figure 4. Dewatered sludge bearing ratio and unconfined compressive strength results.

3.3.4. Apparent Compaction Effect of Sludge

The visual appearance of the compacted sludge after rolling is depicted in Figure 5. When no solidifying agent was added, the sludge exhibited a loose texture with significant elasticity during the compaction process, making it challenging to compact. Additionally, the sludge tended to adhere to the compactor roller, resulting in a rough and cracked surface after compaction. However, after adding 5% and 7.5% solidifying agent, the compressive strength of the sludge significantly improved. This improvement alleviated the issue of adhesion to the roller during compaction, leading to denser and smoother compacted sludge with a more even surface. The apparent quality after compaction improved with a higher dosage of the chemical agent.

Figure 5. Visual appearance after compaction of dewatered sludge: (**a**) solidifying agent addition ratio of 0%; (**b**) solidifying agent addition ratio of 5%; (**c**) solidifying agent addition ratio of 7.5%.

3.3.5. Compaction Test Results

The compaction degree, also known as the compaction density, refers to the percentage represented by the ratio of the dry density of soil or other road construction materials after compaction to the standard maximum dry density [40]. Proper compaction is essential to ensure the strength, stiffness, stability, and smoothness of roadbed and pavement layers, thus extending the service life of the roadbed and pavement. The results for the compaction degree are illustrated in Figure 6.

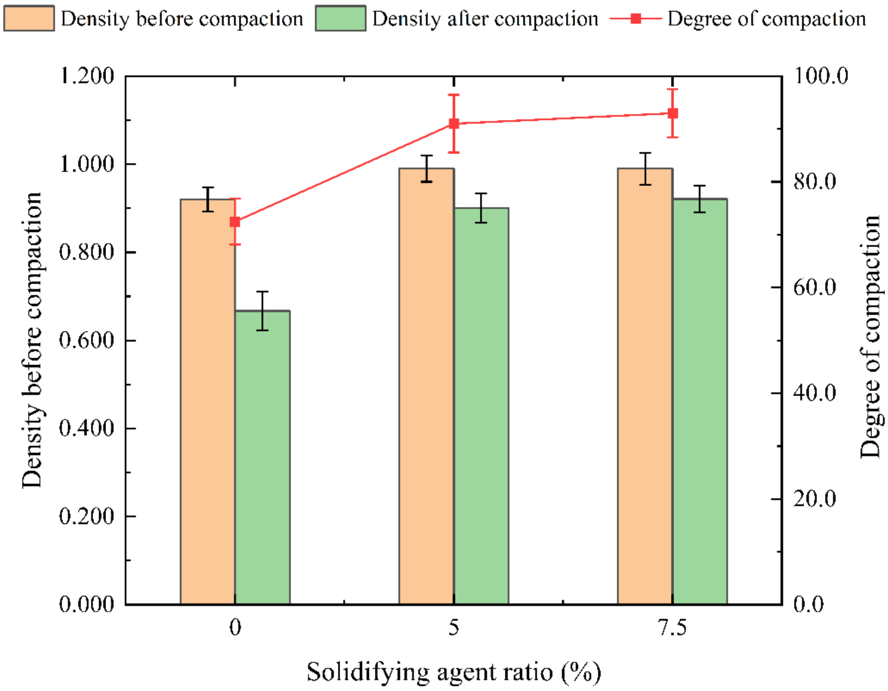

Figure 6. Sludge compaction test results.

When no solidifying agent was added, the compaction degree of the sludge was 72.5%. After adding 5% and 7.5% solidifying agent, the compaction degree of the sludge increased by more than 90%, meeting the compaction requirements for backfill soil above pipelines according to the Code for Construction and Acceptance of Water and Sewerage Pipeline Works (GB 50268-2008) [41].

In summary, the detected concentrations of heavy metals and soluble salts in the sludge before and after modification both met the requirements for construction backfill soil. After adding 5% and 7.5% solidifying agent, the organic matter content in the sludge remained relatively high, but the bearing ratio and 7-day unconfined compressive strength were significantly improved. The modified sludge is generally suitable for use as backfill soil above pipelines.

3.4. Leachate Treatment

The coagulation and precipitation unit, as a pretreatment processor before ammonia nitrogen stripping, primarily adjusted the pH value and reduced the total phosphorus and suspended solids in the sludge leachate. The total phosphorus concentration of the sludge leachate influent was relatively low, and after dosing with the phosphorus removal agent, it generally met the treatment target requirements.

The stripping unit was mainly used to remove ammonia nitrogen. By adjusting the pH value and adding sulfuric acid solution, ammonia nitrogen was removed by blowing air at room temperature. More than 60% of the ammonia nitrogen in the sludge leachate was removed through stripping. The variations of pH value and the concentration of ammonia nitrogen during stripping and oxidation processes are depicted in Figure 7.

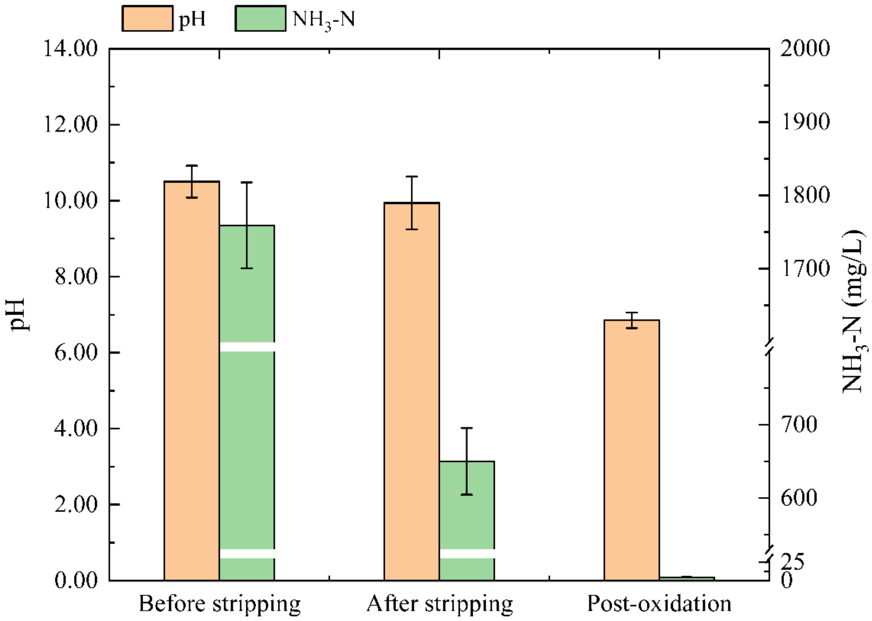

Figure 7. The ammonia nitrogen stripping and oxidation effect on the sludge press leachate.

The oxidation unit was applied to treat the remaining ammonia nitrogen. Sodium hypochlorite was added to oxidize and remove ammonia nitrogen, ensuring that the effluent's ammonia nitrogen remained consistently within treatment standards. The results indicated that the oxidation unit effectively removed the remaining ammonia nitrogen from the stripping tower's effluent, and the effluent's ammonia nitrogen consistently met treatment requirements. The actual chlorine dosage was higher than the theoretical dosage, primarily due to the presence of organic nitrogen and reducible substances in the sludge filter liquor. Additionally, the continuous unit showed some removal of COD in the effluent, suggesting that the oxidation unit cooperatively removed some of the COD.

Additionally, due to the acidic nature of the solid sodium hypochlorite used in the experiments, different amounts of sodium hydroxide were added into the oxidation unit to ensure that the effluent pH value met treatment requirements. In practical applications, a ready-made 10% sodium hypochlorite solution was used, which might have varying levels of free chlorine and is highly alkaline. When oxidizing with the ready-made 10% sodium hypochlorite solution, the pH value might remain unchanged or increase. Therefore, the pH value of the effluent after oxidation might exceed a value of 9. To meet treatment requirements, the pH value of the sludge leachate after stripping and oxidation should be kept within the desired range by using an acidic solution. Finally, the treated leachate was recycled back to the mainstream treatment of the WWTP. The pH of the effluent was controlled between 7 and 9, as it could serve as an alkalinity supplement for wastewater treatment.

4. Conclusions and Prospects

Due to the historical "emphasize wastewater and underestimate sludge" approach in the construction of wastewater treatment plants in China, the development of sludge treatment and disposal has been slow. Sludge landfilling thus used to be the priority method for sludge management. This research on the treatment of landfill sludge, conducted at a WWTP, suggests the feasibility of the overall technical route of sludge extraction, conditioning and dewatering, co-incineration at power plants, and solidification for backfilling. Both the combination of PFSS and PEA and the combination of PAS and PEA as coagulant aids were able to reduce the sludge moisture content to below 60%. The use of conditioning agents such as PAS and PEA in the dewatering and co-incineration process did not reveal any significant problems regarding the equipment. The contents of various heavy metals in the modified sludge met the relevant standards for various types of construction land. However, practical implications are rarely seen in China because the organic matter content of the final modification sludge exceeds the standard of 8%. The soluble salt contents of sludge before and after solidification and modification were not much different; the corrosion grade was low; and the corrosion of concrete, steel, and other building materials was weak. The results of the modification experiment illustrated that the modified sludge could be used as a backfill material in construction areas without requirements for organic matter. This process provides a new approach to sludge resource utilization.

All technologies for landfill sludge and the associated leachate treatment were feasible for meeting the wastewater discharge standards. These research findings provide valuable engineering experience and solutions for the reprocessing and resource utilization of existing landfill sludge. Nevertheless, these processes are associated with high energy consumption and costs, and they result in the wastage of nitrogen and phosphorus resources in the wastewater. It is recommended that in future research, emphasis should be placed on analyzing the possibility of nitrogen and phosphorus recovery and utilization from percolate. Simultaneously, from the perspective of energy conservation, an investigation into carbon neutralization technology for high-concentration ammonia-containing wastewater is suggested.

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Abbreviations

WWTP, wastewater treatment plant; HDPE, High-Density Polyethylene; PFSS, polyferric silicate sulfate; PEA, polyetheramine; COD, Chemical Oxygen Demand; PAC, polyaluminum chloride; PFC, polymerization ferric chloride; HHV, higher heating value; LHV, lower heating value; PAS, polyaluminum silicate.

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