

Experimental Study on Solidification of Leachate Sludge with High Salt Content by Waste Incineration Bottom Slag

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Abstract. This paper takes the leachate sludge produced from the Guangzhou refuse landfill as the research object and selects sulfoaluminate cement as the fixation to solidify/stabilize the sludge. Meanwhile, bottom-slag is selected as the supplementary fixation. Through unconfined compressive strength test and Scanning electron microscope (SEM), the effect of the mixing amount of cement and bottom-slag on the sludge's strength is systematically studied. Results show that sulfoaluminate cement can improve the strength of solidified sludge. Sulfoaluminate cement can increase the strength of samples by promoting the hydration reaction, but the effect is better when the content exceeds 40%. When the cement content is fixed, the strength of the sample increases with the bottom slag content. When the bottom slag content exceeds 10%, the proportion of cement in the hydration reaction will decrease, and then the strength of the sample will increase first and then decrease. In addition, under different cement contents, the sample will reach the peak value when the bottom slag content is 10%. Thus, 40% cement + 10% bottom slag is the relative optimal content.

Key words: Leachate sludge; Solidification/Stabilization; Sulfoaluminate cement; Unconfined compressive strength.

1. Introduction

Landfill is the main centralized method of solid waste disposal[1-2]. The leachate generated by the compaction and fermentation of waste in landfills and piles has a polluting effect on soil, resulting in leachate sludge containing many heavy metals and organic matter. Its high water and organic matter contents make leachate sludge less strong than normal sludge [3]. Leachate sludge also tends to destabilize the foundation of the sludge disposal site [4]. Thus, the treatment of leachate sludge is an urgent issue that must be addressed.

Currently, the treatment of sludge is mainly based on solidification and stabilization. The curing agent is mainly based on ordinary silicate cement, and a few have lime[5,6], fly ash[7-8], bentonite[9-10], and gangue[11] as auxiliary curing agents. Given the extremely high water content and the high soluble salt content of leachate sludge, the soluble salts are mostly chlorine salts, which have a hindering effect on the hydration reaction of cement. Consequently, the involvement of cement in solidification and stabilization unsatisfactory. Although the addition of an auxiliary curing agent can improve the solidification and stabilization, it cannot be used on a large scale to treat pollutants from waste incineration from an environmental and economic point of view, and the use of composite cements[12] has been rarely studied.

In addition, the residue produced by the incineration of waste (80% of the bottom residue after incineration) and the high percentage of CaO in the bottom residue composition present a certain volcanic ash characteristic. Adding ground waste incineration substrate to concrete improves the dry shrinkage characteristics of the concrete, significantly reducing the permeability of chloride ions and improving the carbonation resistance of concrete[13]. The bottom slag is used in stabilizing the pavement properties of gravel and improving the dry shrinkage and frost resistance of cement stabilized aggregates to a certain extent[20].

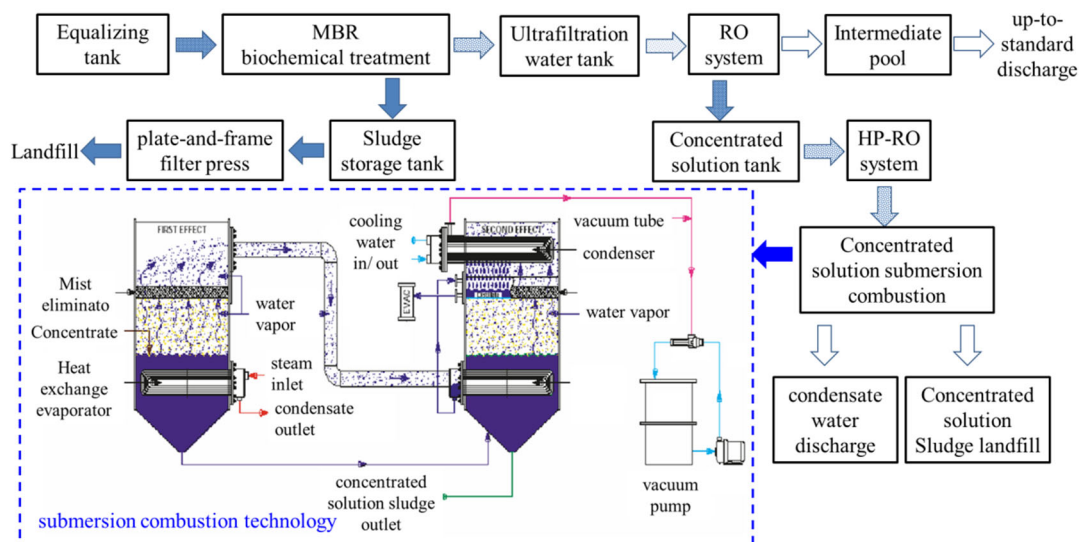


Fig. 1 Leachate treatment technology in a municipal solid waste landfill in Guangzhou

In this paper, the leachate sludge from a landfill in Guangzhou is the object of study. The leachate sludge was cured and stabilized with sulfate cement and bottom slag as curing agents, and the curing effect and mechanism were investigated through unconfined compressive strength tests and microscopic analysis tests. The purpose of treating waste pollutants through waste is achieved by aiding the solidification of pollutants through the incineration of bottom slag waste.

2. Experimental section

2.1. Basic physicochemical properties of leachate sludge

The leachate sludge is dark black, flows with a smooth surface, has no obvious holes and a low odor, and will flow out after a period of resting. The leachate has a very high water content, high proportion, density, and alkaline PH, and a low organic matter content. Three soluble salts, namely, NaCl, K₂CO₃, and Na₂SO₄, are predominant and have a high salt content. The physical indicators of the sludge and its elemental composition are shown in Tables 1–3.

Table 1 Basic physical properties of leachate sludge

Physical properties	
Environmental moisture content (water quality/total mass)/%	21.11
Geotechnical moisture content (water quality/dry soil quality)/%	26.76
Specific gravity	2.31
PH	9.31
Density (g/cm ³)	1.88
Plastic limit/%	9.62
Liquid limits/%	19.18
Organic matter content/%	5.87

Table 2 Elemental composition of leachate sludge

Element type	Element composition(XRF)/%
Na ₂ O	35.51
Cl	28.14
K ₂ O	17.05
SO ₃	14.14
MgO	2.44
CaO	2.07
SiO ₂	0.40
Fe ₂ O ₃	0.13
P ₂ O ₅	0.07
Al ₂ O ₃	0.48

Table 3 Elemental composition of admixture

Element type	Element composition (XRF)/%	
	Aluminum sulfate cement	Waste incinerates the bottom residue
CaO	47.07	57.7
SiO ₂	10.07	9.63
SO ₃	11.54	5.19
Al ₂ O ₃	24.37	4.95
Fe ₂ O ₃	2.7	5.47
MgO	1.13	3.65
P ₂ O ₅	0.096	2.89
Na ₂ O	0.49	2.25
K ₂ O	0.99	1.25
Cl	0.25	3.80
Other	1.30	3.22

2.2. Cement and bottom slag

SAC42.5 sulfo-aluminate cement was used in this test, and the waste incineration by-product slag was taken from a waste incineration power plant in Guangzhou. Dried and sieved waste incineration slag with a bulk density of 1.14 g/cm³ after drying and sieving was selected as an auxiliary curing agent, while sulfo-aluminate cement contained more S and Al elements; the slag had a lower Cl element content because it was pretreated by drenching in the incineration plant.

2.3. Test methods

The specific test methods for leachate sludge curing and stabilization are summarized in Table 4.

Table 4 –Specific test methods for leachate sludge

Experiment name	Unconfined compressive strength test	Micro Analysis Test
Test equipment	Strain Controlled Triaxial Gauge	SEM/XRD
Number of test groups	The content of bottom slag is 5%, 10%, and 15% of wet soil, and the content of sulfoaluminate cement is 10%, 20%, 30%, 40% of wet soil and three groups of different mixing ratios.	Take 28d old samples with bottom slag content of 10% and cement content of 40%

2.4. Specimen preparation

The sludge, cement, and admixture required for this test are mixed and placed into a three-flap mold. Then, the mold is removed after 3–5 days in a constant temperature and humidity curing oven to reach the demolding strength. After demolding, the specimens remain in the conditioning chamber until the set age (7, 14, and 28 days) for the subsequent tests.

3. Results and discussion

3.1. Mechanical properties of cured sludge

The unconfined compressive strength of the cured sludge is shown in Table 5.

Table 5 Test results of unconfined compressive strength of solidified sludge samples

Unconfined compression strength (kPa)		Cement content (kPa)				
		10	20	30	40	
Curing age (days)	7	0	151.841	131.387	88.245	123.543
		5	-	152.958	181.196	254.93
		10	-	237.281	339.253	427.498
		15	-	229.437	298.072	349.058
	14	0	162.763	152.958	131.387	417.693
		5	-	358.863	402.005	598.105
		10	-	347.097	464.757	709.882
		15	-	262.774	382.395	525.548
	28	0	174.529	274.54	511.821	1483.8
		5	-	531.431	1072.667	2144.4
		10	-	435.342	788.322	2431.2
		15	-	284.345	676.545	837

The unconfined compressive strength of the cured sludge specimens under the condition of curing age of 7d showed a trend of decreasing and then increasing with the increase of cement content, and the strength reached the lowest value at 30% cement content and the highest value at 10% cement content. The pattern of strength development indicates that the soluble salt ions in leachate sludge do affect the curing/stabilization effect of cement, and as a clear constraining effect, sulfo-aluminate cement has the effect of increasing early strength, but from the 7d strength results, it was not found that the cured sludge specimens with high cement content exhibited a significant increase in strength.

By combining the graphs, we can obtain the pattern of the unconfined compressive strength (UCS) of the sludge cured bodies for three variables, namely, cement content, age, and substrate content, as shown in Fig. 2. (1) The UCS of all 7-d specimens was greater than 50 kPa, which is the strength requirement for a temporary cover in landfill according to the Disposal of Sludge from Municipal Wastewater Treatment Plant—Quality of Sludge for Co-landfilling (GB/T 23485–2009)[14]. (2) The peak strength of the specimen increases with the cement admixture at the same age and substrate content. The peak strength increases even more to 5.6 times the original strength at 28 days of curing and 10% bottom slag dosage. (3) The strength of the specimens increases with the age at a certain admixture of cement and slag, reaching 71% at 20% cement and 5% slag. (4) The amount of slag required to reach the peak of the specimen varies. At 7 days of curing, all three doses of cement reach the peak at the slag dose of 10%. At 14 days of curing, the required amount of slag to reach the peak for a specimen with 20% cement content is 5%. The amount of substrate required to reach the peak of the cured sludge specimens with 20% and 30% cement contents at 28 days of curing is 5% in both cases. This phenomenon can be attributed to the relatively long maintenance (> 7 days) after the bottom sludge has been incorporated into the leachate cured sludge. Increasing the slag content requires more cement to stimulate the hydration reaction optimally because of the volcanic ash properties of the slag. However, when the amount of bottom slag is high (>10%), the substitution of some particles can weaken the hydration of the cement and thus affect the proportion of cement in the overall curing system because of their large size and high density[15-18]. Therefore, the tendency

for the strength to decrease at high amounts of bottom slag (>10%) is explained by the fact that at low cement contents, the peak occurs at low bottom slag contents. The graph also shows that the UCS values at 40% cement admixture are greater than those at 20% and 30% cement admixtures at all ages and bottom slag admixtures. This finding shows that the increase of the cement mixture can effectively increase the strength of the specimens. In addition, the strength of the specimens with 10% slag + 40% cement mixture is always greater than that of the specimens with the rest of the mixture at different curing ages. Therefore, 10% of bottom slag and 40% of cement mix are relatively optimal values.

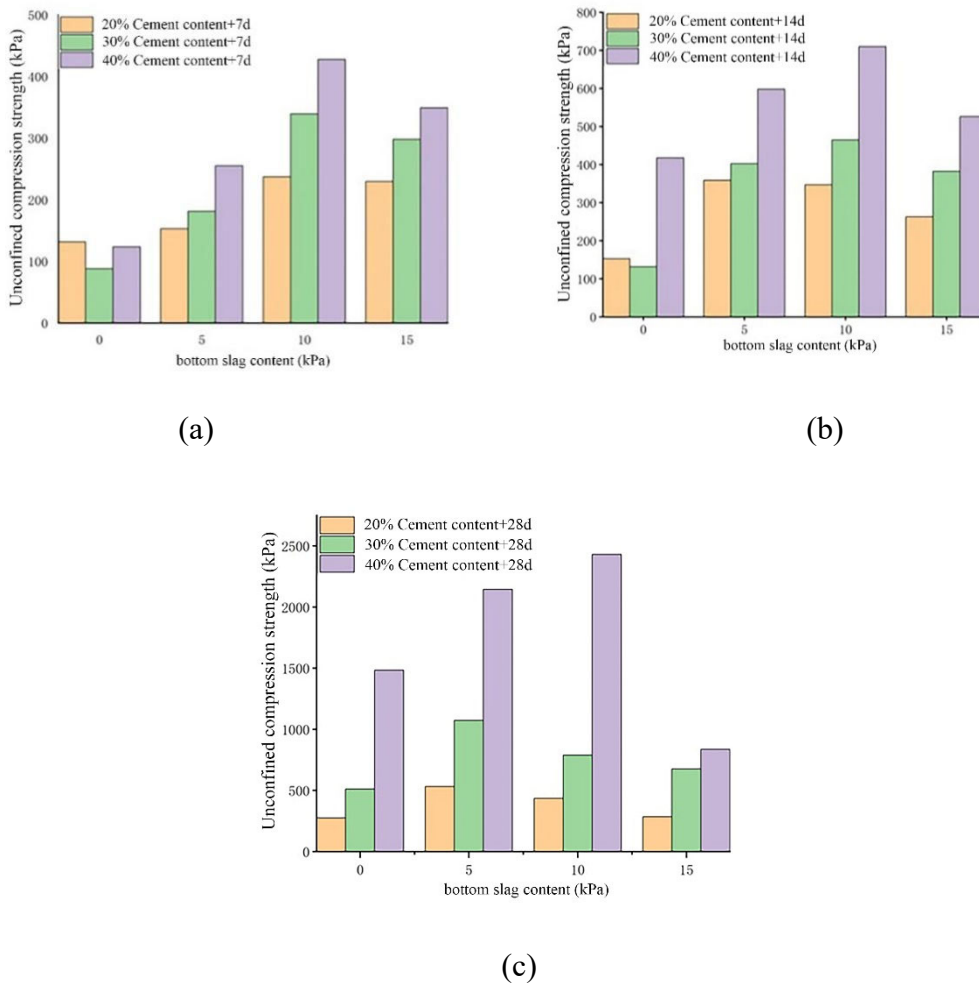


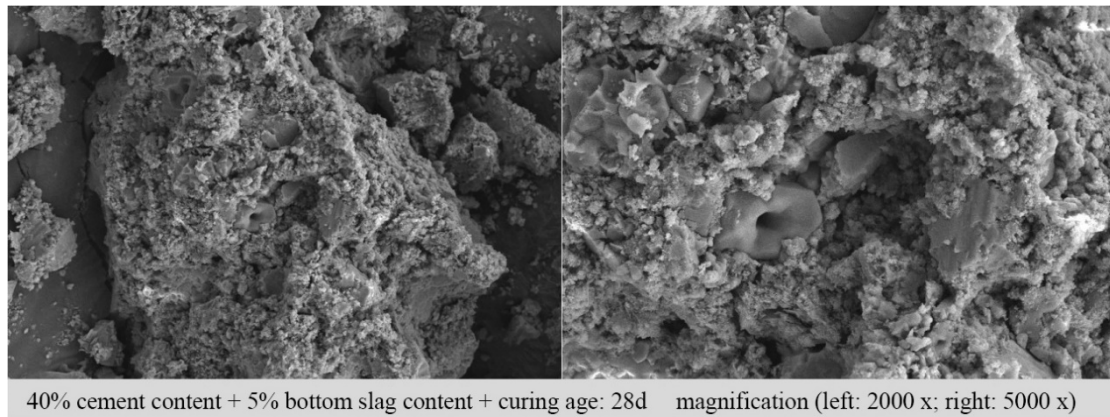
Fig. 2 Unconfined compressive strength of sludge solidified body under different cement and bottom slag content: (a) 7 days, (b) 14 days, and (c) 28 days

3.2. Microscopic analysis of cured sludge

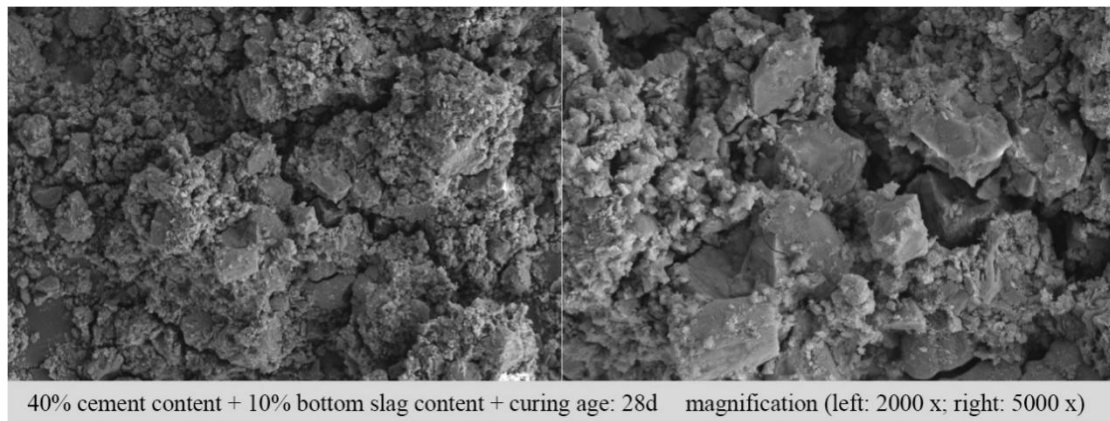
SEM microstructure analysis

The microstructure of the sludge curing body after the incorporation of waste incineration substrate is shown in Fig. 3. The figure shows that when the cured sludge specimen is mixed with the substrate, the specimen body, which originally had large voids, is filled with the large substrate particles, accompanied by the hydration reaction and the products of the hydration reaction by wrapping and bonding, making the specimen form a tighter and more complete block, thus increasing the strength. However, at the 15% admixture level, the high content of slag reduces the proportion of cement, indicating no significant production of hydration products. With the increase of curing age, the hydration products on the surface of the C-CSS specimen with 40% cement content at 28 d were continuously generated and interwoven, which continuously cemented and filled the pores with sludge particles, resulting in the internal microstructure of the specimen gradually transformed from

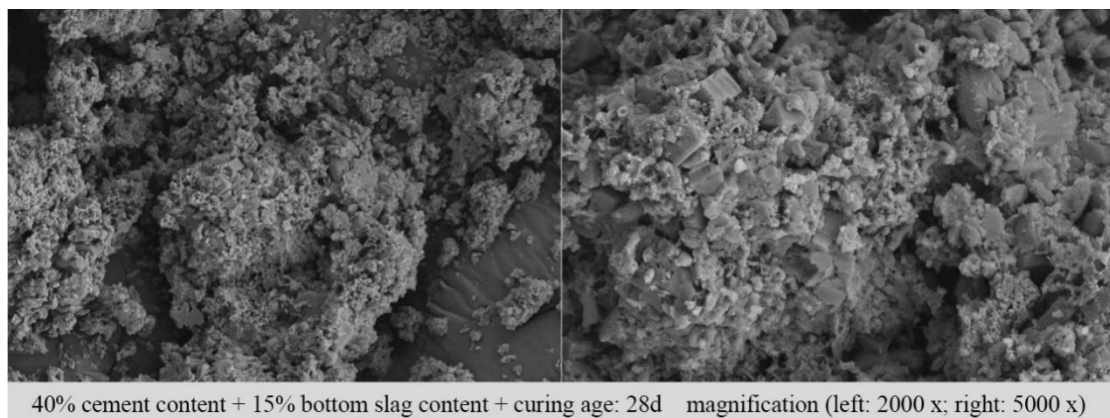
the original disperse particle accumulation morphology to the cemented agglomerate mosaic morphology. The skeletal structure system was essentially changed, and the strength was significantly improved. Furthermore, the fragmented hydration products do not make the specimen a complete whole, which is consistent with the conclusions obtained from the previous strengths.



(a)



(b)



(c)

Fig. 3 SEM pictures of sludge solidified body: (a) 7d; (b) 14d and (c) 28d

XRD mineral composition analysis

Using the same method, the specimens were selected for the study under the 28-day maintenance age, and XRD mineral composition analysis was carried out as shown in Fig. 4.

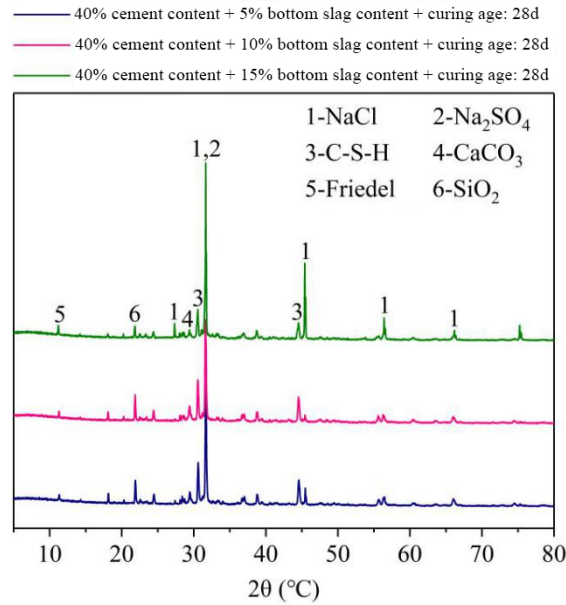


Fig.4 Mineral composition of solidified sludge

The figure shows that the intensity of the diffraction peaks of the C-S-H gel ($\text{Ca}_5\text{Si}_6\text{O}_{16}(\text{OH})\cdot 4\text{H}_2\text{O}$) and the Friedel salt ($3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{CaCl}_2\cdot 10\text{H}_2\text{O}$) in the mineral composition of the sludge curing body increases and then slightly decreases with the addition of bottom slag. This phenomenon can be attributed to the fact that Friedel salts are formed by consuming the chloride in the pore fluid of the cement^[19]. The strength of the chloride ions increases as they combine with the continuously generated hydration products to form Friedel salts. As the amount of slag increases (10%–15%), the particle substitution of the slag weakens the hydration reaction and therefore stops producing hydration products, resulting in a reduction in strength.

4. Conclusions

In this paper, aluminum sulfate cement is the main curing agent, and the bottom residue of the waste incineration product is used as the auxiliary curing agent. The sludge of leachate was cured and stabilized, and the strength change law and reasons of the subleacher sample were explored through the unconventional compressive strength test and microscopic analysis test of the cured specimen. The following conclusions were drawn.

- (1) After the bottom slag is incorporated, the strength of the sample shows a tendency to increase first and then decrease under different cement dosages at different ages. When the bottom slag dosage is high ($> 10\%$), the strength will decrease accordingly with the increase of the bottom slag.
- (2) At a short maintenance age (< 7 days), when the bottom slag dosage is 10%, the strength reaches the peak. With the increase of age, when the cement content is low ($\leq 30\%$), the peak appears when the bottom slag dosage is 5%. The strength of the specimen under the 10% bottom slag + 40% cement dosage is always greater than the strength of the sample under the remaining proportions. Therefore, the 10% bottom slag + 40% cement dosage is the relative optimal value.

5. Data Availability Statement

The Data that support the findings of this study are available from the corresponding author upon reasonable request.

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