Experimental research on the Strength Characteristics of Leachate Sludge with Different Incorporation Ratios of MSWI Bottom Ash

Xueli Xiao[1], Yongjian Liu[1*], Lan Luo[1], Yongmei Chen[1], Dongxia Zhu[2]

[1]Guangzhou Institute of Science and Technology, Guangzhou 510540, China
[2]Shenzhen Building Safety and Construction Quality Testing and Appraisal Center, Guangdong, Shenzhen 518052, China

*Corresponding author's e-mail: liu-yongjian@163.com

Abstract. This study employs sulphoaluminate cement as the primary solidifying agent and municipal solid waste incineration bottom ash as the auxiliary solidifying agent to conduct solidification treatment on leachate sludge from domestic waste landfills. The results indicate that: (1) Sulphoaluminate cement demonstrates superior solidification effects compared to ordinary Portland cement in treating leachate sludge; (2) The unconfined compressive strength of the solidified leachate sludge increases with the rise in cement content; (3) Municipal solid waste incineration bottom ash can serve as a skeleton-building material; (4) The synergistic use of waste incineration by-products with sulphoaluminate cement in solidifying leachate sludge for landfill disposal exhibits a certain volume reduction effect.

Keywords: MSWI bottom ash; Strength characteristics; Leachate sludge

1 Introduction

In China, with rapid economic development and urbanization, municipal solid waste (MSW) production grows steadily, causing severe environmental problems. The proper disposal of MSW is crucial[1, 2]. By 2023, according to the "China Statistical Yearbook 2024", China's harmless treatment volume was 254.017 million tons, and the treatment rate was 100%. The daily treatment capacity reached 1.14 million tons, including 170,000 tons for landfill and 860,000 tons for incineration. As shown in Figure 1, landfill and incineration are the main MSW disposal methods. In 2023, incineration and landfill accounted for 75.44% and 14.91% of total harmless treatment respectively, with the incineration proportion rising yearly while the landfill method remaining essential[3]. In 2023, there were 366 landfill sites. Waste incineration gets more attention as it reduces waste volume by 85% - 90% and mass by 60% - 90% and enables energy recovery. By the end of 2023, in addition to the 366 landfill sites mentioned above, there were another 330 domestic waste landfills (a total of 696) with an annual capacity of 210 million tons. Incineration produces by - products like MSWI fly ash and MSWI

G. Zhao et al. (eds.), *Proceedings of the 2025 8th International Conference on Traffic Transportation and Civil Architecture (ICTTCA 2025)*, Atlantis Highlights in Engineering 39,
https://doi.org/10.2991/978-94-6463-793-9_81

bottom ash. MSWI bottom ash, which accounts for about 85% - 95% of the by - product mass and 20% - 25% of the waste mass, is the main by - product. Classified as general waste due to its low hazard, it can be recycled in construction materials, etc[4–7]. With the increase in MSW incineration, bottom ash production will increase, and its proper disposal becomes urgent[8]. Currently, landfill is the main way to deal with landfill leachate sludge, but the high - moisture, low - strength traditional sludge causes instability of the waste pile. Leachate sludge needs to be solidified before landfill to meet China's requirements of <60% moisture, ≥50 kPa unconfined compressive strength, and leaching toxicity standards[9, 10]. The growing MSW by - products also need proper disposal, leading to the "waste - treats - waste" concept of co - processing incineration by - products and landfill leachate sludge.

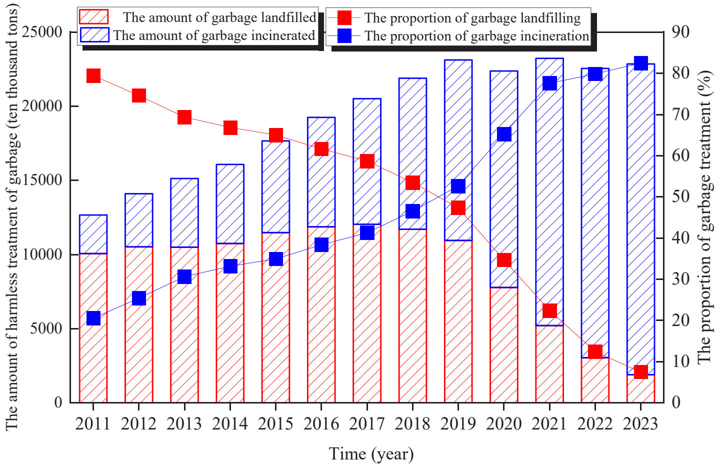

Fig. 1. Domestic Waste Treatment Methods and Proportions in China, 2011-2023

2 Experimental Materials and Methods

2.1 Experimental Materials

2.1.1 Leachate Sludge. The landfill leachate sludge used in the experiment was collected from a landfill site in Guangzhou City. It appeared as a dark brown, jelly-like substance with a pungent odor, as shown in Figure 2. The particle size distribution curve of the leachate sludge is illustrated in Figure 3, and its fundamental physical properties are summarized in Table 1. As can be observed from the particle size distribution curve in Figure 3, the particle sizes of the leachate sludge are predominantly concentrated within the range of 10 μm to 300 μm, which is similar to the particle sizes of soft soil. Additionally, Table 1 reveals that the leachate sludge exhibits an extremely high moisture content, demonstrating a phenomenon of "high water content and low solid content." This is primarily attributed to the physical and biochemical characteristics of the sludge, which inherently result in its high moisture content.

The SEM pictures of leachate sludge is illustrated in Figure 4. The mineral composition of the leachate sludge is illustrated in Figure 5. Based on the analysis of their elemental composition (Table 2), it is evident that the mineral components of the leachate sludge are predominantly calcium and magnesium salts. The XRF analysis reveals a notably high proportion of calcium, accounting for 27.24%. Table 3 presents the heavy metal content of the leachate sludge, with the limit standards referenced from the "Specifications for Sludge Quality in Co-landfill of Sludge from Municipal Wastewater Treatment Plants" (GB/T 23485-2009). It is observed that the concentration of zinc (Zn) in the leachate sludge exceeds the stipulated limit, necessitating solidification treatment prior to landfill disposal.

Table 1. Basic physical properties of leachate sludge

Water content /%	Specific weight	pH	Natural density /g/cm^3	Plastic limit /%	Liquid limit /%	Organic matter content /%
761.13	1.59	7.1	1.01	144.53	414.21	71

Fig. 2. Leachate sludge characterize

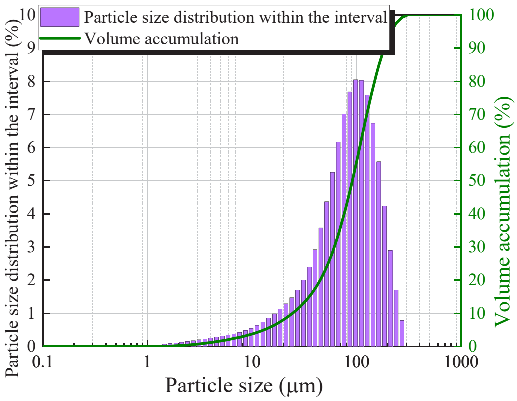

Fig. 3. Particle gradation curve of leachate sludge

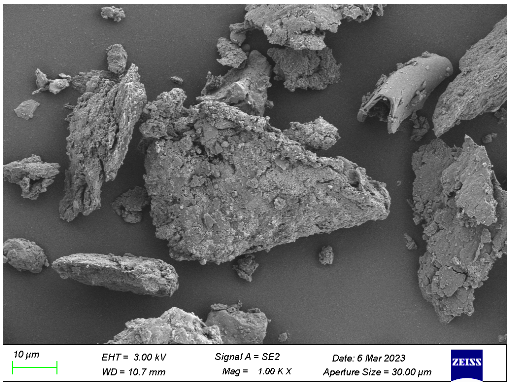

Fig. 4. SEM pictures of leachate sludge

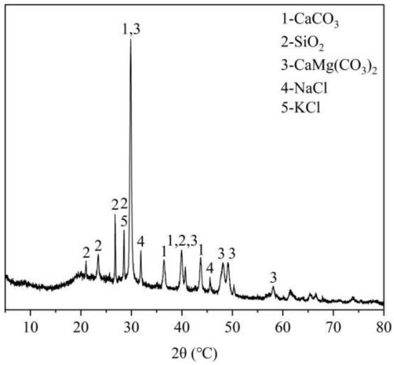

Fig. 5. Mineral composition of leachate sludge

Table 2. Elemental composition of leachate sludge

Elemental composition(XRF) /%										
CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	MgO	P_2O_5	Na_2O	K_2O	Cl	Oth-ers
27.24	3.06	11.19	2.78	3.28	2.30	7.61	10.36	12.10	17.46	2.02

Table 3. Heavy metal content in leachate sludge

Materials	Heavy metal content(mg/kg)								
	Ag	Ba	Be	Cd	Cr	Cu	Ni	Pb	Zn
Leachate sludge	2	N.D. [a]	N.D. [a]	N.D. [a]	440	46	40	6	4200
Limit value	-	-	-	20	1000	1500	200	1000	4000

[a] This element was not detected

2.1.2. Cement. The cement utilized in this experiment comprises ordinary Portland cement of grade PO42.5R from the Shijing brand and calcium sulfoaluminate cement of grade P.SAC42.5 produced by Wuxi Golden Eagle Building Materials Co., Ltd. The primary chemical constituents of these cements are detailed in Table 4.

Table 4. Elemental composition of cement

Materials	Elemental composition(XRF) /%										
	CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	MgO	P_2O_5	Na_2O	K_2O	Cl	Others
OPC	59.74	20.89	4.66	6.88	3.33	3.13	-	0.14	0.92	-	0.32
SAC	50.09	9.02	16.75	17.26	2.31	2.10	0.12	0.31	0.81	0.25	0.80

2.1.3. Bottom Ash from Waste Incineration. The bottom ash used in the experiment was collected from a waste incineration plant in Guangzhou. As shown in Figure 6, the experimental bottom ash primarily consists of glass fragments, metal residues, and clinker, presenting as gray granular particles with a rough surface. The particle size distribution is extremely wide, as illustrated in Figure 7. The elemental composition of MSWI bottom ash are detailed in Table 5.Therefore, prior to use in the experiment, the bottom ash was dried in an oven at 105°C ± 2°C until a constant weight was achieved. Subsequently, it was mechanically ground, and the bottom ash passing through a 2 mm sieve was selected as the supplementary curing agent for this experiment.

Fig. 6. Morphology of MSWI bottom ash passing 2 mm sieve

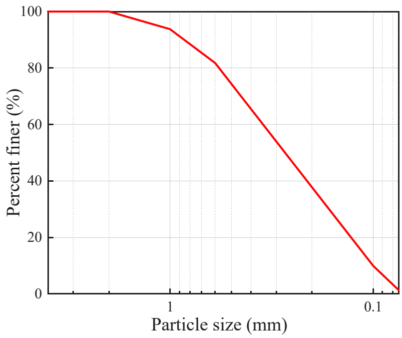

Fig. 7. Gradation curve of MSWI bottom ash passing 2 mm sieve

Table 5. Elemental composition of MSWI bottom ash

Materials	Elemental composition(XRF) /%										
	CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	MgO	P_2O_5	Na_2O	K_2O	Cl	Others
MSWI bottom ash	29.20	33.92	1.93	7.94	8.94	2.11	6.08	3.71	1.49	2.12	2.55

Table 6. Heavy metal content of MSWI bottom ash

Materials	Heavy metal content(mg/kg)								
	Ag	Ba	Be	Cd	Cr	Cu	Ni	Pb	Zn
MSWI bottom ash	3	1900	N.D.[a]	N.D.[a]	790	640	350	230	3400
Limit value	-	-	-	20	1000	1500	200	1000	4000

[a] This element was not detected

As can be seen from Table 6, the heavy metal leaching toxicity of bottom ash from waste incineration is significantly lower than the limits specified in the sludge disposal and mixed landfill quality standards, classifying it as general solid waste.

2.2 Specimen Scheme

To investigate the optimal dosage of stabilizing agents for leachate sludge, solidified samples were prepared with varying proportions of cement and bottom ash, as well as different curing periods. A series of unconfined compression tests were conducted. Each group of tests included three parallel experiments, and the results were averaged from these three replicates. The experimental design is detailed in Table 7.

Table 7. Test plan

Cement content /%	Bottom ash content /%	days /d
10, 30, 50	0, 5, 10, 15, 20	7, 14, 28

3 Experimental Results and Analysis

3.1 Optimization of Cement Curing Effectiveness

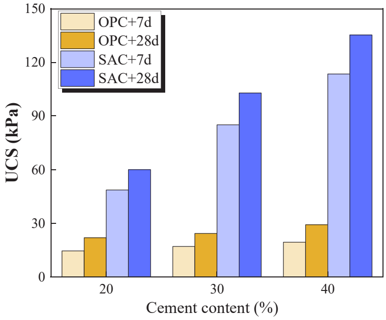

Fig. 8. The relationship between unconfined compressive strength of solidified leachate sludge and cement type

As can be seen from Figure 8, ordinary Portland cement, commonly used as a modifier for sludge solidification, does not perform ideally when used alone to solidify leachate sludge. Although the unconfined compressive strength of the solidified leachate sludge increases gradually with the addition of cement, the rate of increase is quite limited. When the cement content reaches 40%, the strength of the solidified body is only 19 kPa, which is far below the required landfill strength for dewatered sludge (≥50 kPa). In contrast, calcium sulfoaluminate cement demonstrates a superior solidification effect on leachate sludge. With a cement content of 30%, the 7-day unconfined compressive strength of the sample reaches 85 kPa, meeting the landfill strength requirements. Therefore, this study selects calcium sulfoaluminate cement as the primary solidifying agent.

3.2 The Influence of Bottom Ash Content from Waste Incineration on the Strength Characteristics of Landfill Leachate Sludge.

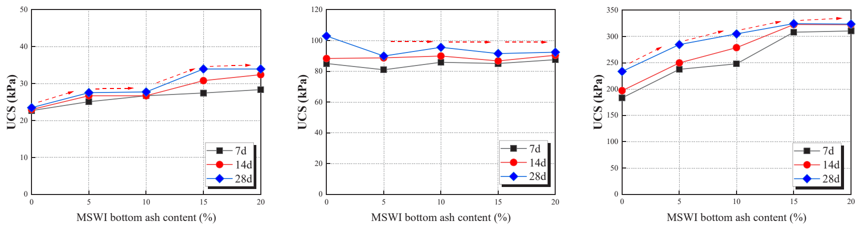

Fig. 9. Relationship between unconfined compressive strength of sludge solidified body and MSWI bottom ash content

The unconfined compressive strength test was conducted on solidified leachate sludge samples with varying cement contents and different proportions of bottom ash. The relationship between strength and the incorporation of bottom ash from waste incineration is illustrated in Figure 9. As shown in the figure, the unconfined compressive strength of the solidified leachate sludge samples increases with the rise in cement content. When the sulfate cement content reaches 30%, the strength of the solidified leachate sludge sample at a curing age of 28 days attains 103 kPa, meeting the mechanical strength requirement for landfill (≥50 kPa). This is primarily attributed to the cementitious and water-reducing effects of sulfoaluminate cement. During the hydration process, the cement consumes a significant amount of free water in the leachate sludge and generates hydration products such as C-S-H gel and ettringite, which possess binding properties. These hydration products form a stronger internal framework within the leachate sludge, thereby enhancing the overall strength of the sludge. As the cement content increases, more reactive substances participate in the hydration reaction, and more free water is consumed, leading to a reduction in the water content of the sludge solidification body and an increase in hydration products.

From the relationship between the unconfined compressive strength of the sludge solidification bodies and the bottom ash content shown in Figures (a) and (b), it can be observed that for sludge solidification bodies with low cement content (≤30%), the addition of municipal solid waste incineration bottom ash does not significantly enhance the strength of the specimens. This is because when the strength of the solidified specimens is low, the bonding force between the bottom ash particles and the sludge particles is weak, and the particles do not effectively act as a skeleton, making it difficult to form a stable spatial skeleton structure, thus contributing little to the strength. As shown in Figure 9 (c), when the cement content is 50%, the unconfined compressive strength of the specimens increases with the increase in the bottom ash content, indicating that the bottom ash can synergistically enhance the solidification of sludge.

3.3 The Impact of MWSI Bottom Ash Dosage from Waste Incineration on the Volume Increase Ratio of Solidified Leachate Sludge

With the continuous expansion of urban areas, land resources are becoming increasingly scarce. The challenge of safely disposing of a greater volume of leachate sludge and waste incineration by-products within limited space is becoming more pronounced. If the volume of leachate sludge treated through solidification/stabilization is too large, it not only increases disposal costs but also occupies more space. Therefore, when evaluating the effectiveness of leachate sludge solidification, it is essential to consider the volume change of the solidified product. The volume increase ratio is a critical metric for assessing this issue. The calculation method for the volume increase ratio is based on the following formula.

$$\lambda = \frac{V_{\text{Cement}}}{V_{\text{Leachate sludge}}} = \frac{m_{\text{Leachate sludge}} + m_{\text{MSWI bottom ash}}}{m_{\text{Leachate sludge}}} \times \frac{\rho_{\text{Leachate sludge}}}{\rho_{\text{Cement}}} \tag{1}$$

$$\lambda_0 = \frac{V_{\text{MSWI bottom ash}} + V_{\text{cement}} + V_{\text{Leachate sludge}}}{V_{\text{Leachate sludge}}} = \frac{\frac{m_{\text{MSWI bottom ash}}}{\rho_{\text{MSWI bottom ash}}} + \frac{m_{\text{cement}}}{\rho_{\text{cement}}} + \frac{m_{\text{Leachate sludge}}}{\rho_{\text{Leachate sludge}}}}{\frac{m_{\text{Leachate sludge}}}{\rho_{\text{Leachate sludge}}}} \quad (2)$$

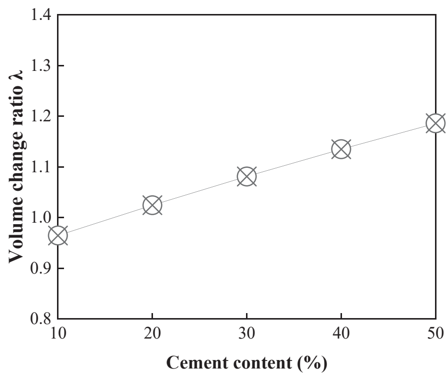

Fig. 10. Relation curve between volume change ratio of solidified leachate sludge and sulphate aluminium cement content

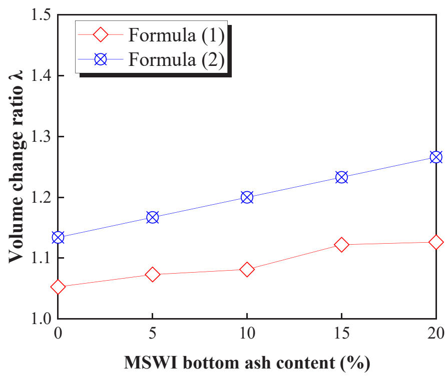

Fig. 11. Volume change ratio of solidified leachate sludge with different content of MSWI bottom ash

Figure 10 illustrates the relationship curve between the volume increase ratio of solidified leachate sludge and the dosage of sulphoaluminate cement. As depicted in the figure, the volume increase ratio of the solidified leachate sludge samples continuously rises with the increasing content of sulphoaluminate cement, which consequently leads to additional consumption of landfill capacity. However, the strength of the solidified leachate sludge is closely related to the dosage of sulphoaluminate cement. An increase in the strength of the solidified sludge can appropriately enhance the landfill height. Therefore, when determining the dosage of sulphoaluminate cement, it is essential to consider both the strength and the volume increase ratio as influencing factors, in order to select the most reasonable dosage of sulphoaluminate cement.

when the cement dosage reaches 30%, the strength of the solidified leachate sludge samples meets the landfill strength requirements. Hence, the volume increase of the solidified leachate sludge corresponding to different dosages of waste incineration by-products at this cement dosage can be compared. The ratio of the pre-solidification material volume to the sludge volume is calculated according to the following formula (2), and the results are shown in Figure 11.

As illustrated in Figure 11, the volume of the solidified leachate sludge with the addition of incineration by-products is significantly reduced compared to the sum of the volumes of the incineration by-products, solidifying agents, and leachate sludge. Moreover, the greater the amount of incineration by-products added, the larger the difference between the volume of the solidified body and the sum of the volumes of the materials before solidification. This indicates that the incineration by-products, in conjunction with sulfoaluminate cement, have a certain volume-reducing effect on the landfill solidification of leachate sludge.

4 Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) Calcium sulfoaluminate cement demonstrated superior solidification performance compared to ordinary Portland cement in the solidification of landfill leachate sludge.

(2) The unconfined compressive strength of the solidified landfill leachate sludge increased with the higher content of cement.

(3) Municipal solid waste incineration bottom ash, acting as a skeletal construction material, gradually exhibited its skeletal role in the solidified landfill leachate sludge as the strength of the solidified sludge increased.

(4) The co-utilization of municipal solid waste incineration by-products with calcium sulfoaluminate cement for the solidification of landfill leachate sludge demonstrated a certain volume reduction effect.

Acknowledgments

Guangdong Higher Education Association's 14th Five-Year Plan 2023 Higher Education Research Project (23GZD14), Guangdong Province Education and Teaching Reform Engineering Construction Project (Guangdong Education Gaohan[2023]No.4), Scientific Research Project of Guangdong Private Higher Education Institutions (GMG2024091).

References

1. Bansal D, Gupta G, Datta RM (2024) Environmentally responsible disposal and reuse of MSW incineration bottom ash: assessment from two Indian plants. Clean technologies and environmental policy 26:1439–1454.
2. Lei Z, Zhuoyu T, Jing D (2024) Spatial–temporal redundancy evaluation of the municipal solid waste incineration treatment capacity: the case study of China. Environmental Science and Pollution Research 31:9948–9963.
3. Wei Y, Liu S, Yao R, et al (2022) Removal of harmful components from MSWI fly ash as a pretreatment approach to enhance waste recycling. Waste Management,150,110-121
4. Liu J, Wu Y, Cheng L, et al (2024) Recycling of municipal solid waste incineration bottom ash (MSWIBA) particles into natural fine sands for sustainable engineering cementitious composites. Construction and Building Materials 418:21.
5. Zhang S, Poon CS (2025) Utilize municipal solid waste incineration (MSWI) bottom ash in cementing materials. High-Volume Mineral Admixtures in Cementitious Binders 215–233
6. Khatib J, Jahami A, El Kordi A, et al (2023) Effect of municipal solid waste incineration bottom ash (MSWI-BA) on the structural performance of reinforced concrete (RC) beams. Journal of Engineering, Design and Technology 21.
7. Liu F, Liu J, Wang B, Yuan X (2023) Analysis of Mechanical Properties and Pore Structure of Mortar Prepared from Municipal Solid Waste Incineration Slag. Journal of Testing and Evaluation,51(5):2780-2800.
8. (2024) Use of municipal solid waste incineration (MSWI) bottom ash as a permeable subgrade material: An experimental and mechanism study. Journal of the Air And Waste Management Association 74:291–303
9. Feng D, Wang J, Chen D, Liang S (2024) Experimental study on solidification/stabilization of leachate sludge by sulfoaluminate cement and MSWI by-products. Environmental Science & Pollution Research 31:
10. Feng D, Wang J, Wang Y, et al (2023) Alkali-activated geopolymer materials prepared from coal gangue and municipal solid waste incineration byproducts. Journal of Building Engineering, 80:108074.