Beneficial Reuse of Municipal Solid Waste Incineration Bottom Slag in Civil Engineering

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Abstract-Rapid economic development has caused many disturbing problems in many countries. Waste disposal is a prominent one of those problems. Waste incineration has gradually become the most popular treatment method. Waste incineration has many advantages, such as processing capacity, short period, recycling and utilization of resources, etc., but it also produces a lot of incineration bottom slag. Landfilling is one of the methods for waste incineration bottom slag treatment. However, many domestic waste landfill sites no longer accept incineration bottom slag. Therefore, finding sufficient ways to deal with the incineration bottom slag has become an urgent problem. With the increase of environmental pressure and the development of technology, the beneficial use of incineration bottom slag has been gradually considered. Municipal solid waste incineration bottom slag is an atypical particulate material, similar to some construction materials of civil engineering. For a construction material, basic physical properties and engineering properties are important factors in its performance. However, there is limited research about the engineering performance of incineration bottom slag. The purpose of this paper is to investigate the basic physical and mechanical properties of the incineration bottom slag from one incineration plant in Wuhan and provide a theoretical basis for its application in civil engineering. Through laboratory tests, we found that the incineration slag completely meets the engineering requirements and is harmless to the environment. The incineration bottom slag can be used for road embankment filling, sludge dewatering treatment improvement, landfill site covering, it can substitute aggregates in concrete, etc.

Keywords-municipal solid waste incineration bottom slag; beneficial reuse; civil engineering; engineering properties; laboratory test

I. INTRODUCTION

With the rapid economic development, people's living standards have improved significantly while the population density has increased along with the output of domestic waste. Approximately 2 billion tons of domestic waste are produced globally each year [1]. In 2016, the production of waste was about 200 million tons in China, as shown in Figure 1, with a yearly increase of 5.99%. Traditional domestic waste treatment methods mainly include composting and centralized sanitary landfills. However, composting treatment has problems such as long cycles, sanitary conditions, and secondary pollution. Sanitary landfill is often limited by the landfill site resources. However, compared with compost treatment and sanitary landfills, the waste incineration treatment technology has the advantages of short treatment cycle, high treatment efficiency, small footprint, and high degree of harmlessness [2-6]. With its unique technical advantages, waste incineration treatment has gradually become a popular waste treatment technology. During the recent years the proportion of domestic waste treated by incineration has increased. The residue produced by the incinerator is called incineration ash. China generally divides garbage ash into two categories: incineration bottom slag and fly ash. The incineration bottom slag content is about 80% of the ash slag, and the fly ash is accounted for the 20%.

The research on the incineration bottom slag of domestic waste incineration has a long history, and the domestic research on the bottom slag of waste incineration started relatively late. Authors in [8] comprehensively introduced the main components of waste incineration ash and did related research on basic inorganic chemical properties, organic chemical properties, and heavy metal leaching toxicity. Authors in [9] studied the compaction properties of cohesive soil coarse-grained soil through experiments. The test results showed that the coarse-grain content greatly affects the compaction properties of the soil. When the coarse-grain content is 50%-70%, the compaction effect is ideal. Authors in [10] conducted an experimental study on the improvement of the bottom slag and clay mixed soil and found that when the content of coarse particles in the coarse-grained soil is small, the maximum dry density changes little with the increase of its content. When the content of coarse particles further increases, the density

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gradually increases, and the dry density reaches its maximum at 60%. Authors in [11, 12] conducted compaction tests on a mixture of bottom slag and clay of a certain incineration power plant and found that the waste incineration bottom slag belongs to coarse-grained soil, it is poorly graded, but its particle gradation is easy to modify, and the bottom slag soil mixed with a certain amount of clay shows good compaction characteristics. In addition, the tests also showed that the clay-bottom slag mixed soil has good shear resistance.

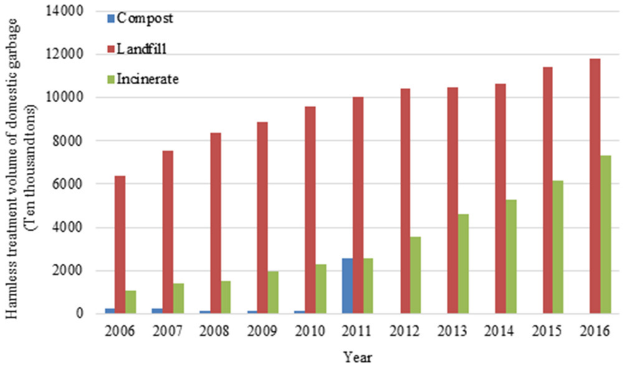

Fig. 1. Harmless treatment of domestic garbage in China during 2006-2016.

Authors in [13] analyzed the material properties of the incineration bottom slag and explored the influence of water content on the strength of the incineration bottom slag through ultrasonic tests, saturated triaxial tests, and unconfined compressive strength tests. Authors in [14] studied the strength of the incineration bottom slag through triaxial tests and reported that the organic matter content greatly affects its elastic deformability. Authors in [15] analyzed the element composition and microstructure of the incineration bottom slag. Authors in [16] conducted a solidification experiment on the bottom slag-sludge mixture. Authors in [17] analyzed the potential thoroughfare of incineration bottom slag in road construction through direct shear tests and three-axis analysis. Regarding the resource utilization of incineration bottom slag, foreign research started earlier and is relatively systematic. At present, the resource utilization of incineration bottom slag has not been systematically analyzed in China.

This paper aims to conduct a systematic study on the basic physical properties and engineering characteristics of incineration bottom slag and provide a theoretical basis for its utilization in civil engineering. The article will mainly analyze the basic physical property tests (screening test, density test, water content test, limit water content test, and specific gravity test), mechanical properties (compaction test, direct shear test, and load-bearing ratio test), and the environmental impact. Based on the research findings, further analysis of the direction in which the incineration bottom slag can be used as a resource is conducted.

II. BASIC PHYSICAL PROPERTIES OF INCINERATION BOTTOM SLAG

Due to the regional differences in waste classification and waste composition, the composition of waste incineration bottom slag varies greatly. The composition of the incineration bottom slag largely determines its performance and affects its engineering applications.

First, the basic physical properties of the incineration bottom slag were analyzed. The sample was taken from a garbage incineration plant in Wuhan, China. The bottom slag was off-white and light brown when the water content was high. The incineration bottom slag contained a lot of ceramic and glass fragments. The basic physical properties of the measured incineration bottom slag include specific gravity, water content, particle gradation, and limited water content. The measured parameters were compared with natural gravel and other building materials. The test operation rules and procedures were carried out following the standard soil test method (GB/T 50123-2019) [18] and highway soil test regulation (JTGE40-2007) [19].

A. Specific Gravity Test

The specific gravity of a solid refers to the ratio of the density of the substance in a fully compacted state to the density of pure water at 4°C under standard atmospheric pressure. It is a dimensionless value and is generally affected by temperature and pressure. The specific gravity can represent the relative density of the soil, which is often used in engineering to calculate its compactness.

TABLE I. SPECIFIC GRAVITY OF INCINERATION BOTTOM SLAG

Temperature (°C)	Specific gravity of water	Mass of solid (g)	Mass of equal volume of water (g)	Gs	Average Gs
22.2	0.997724	30.12	11.02	2.72	2.71
22.2	0.997724	30.06	11.04	2.71	
22.0	0.997769	29.89	11.00	2.71	

The results show that the average specific gravity of the waste incineration bottom slag is 2.71. The detailed results are shown in Table I. In general, the specific gravity of sandy soil lies in the range of 2.65-2.69, the specific gravity of silt is in the range of 2.70-2.71, the specific gravity of silty clay is in the range of 2.72-2.73, and the specific gravity of clay is in the range of 2.74-2.76. It can be seen that the specific gravity of the bottom dross is close to that of the silty clay.

B. Particle Analysis Test

Particle gradation refers to the relative content of each particle group. The particle size gradation of the soil affects its strength, permeability, and frost resistance. A well-graded soil can achieve a higher degree of compaction and has better mechanical properties. Poorly graded soil has many larger pores and good permeability. It can be used in drainage structures and filter layers in engineering. The particle gradation analysis result of the bottom slag is shown in Figure 2. The average particle size of the bottom slag (i.e. D50) is 2.0mm, and the particles in the sample with a particle size in the range of 1-60mm account for 52.97% of the total mass of the incineration bottom slag sample. The content of particles with a particle size of less than 0.1mm is 3.47%. It can be seen that the bottom slag is sandy soil, so it belongs to coarse-grained soil.

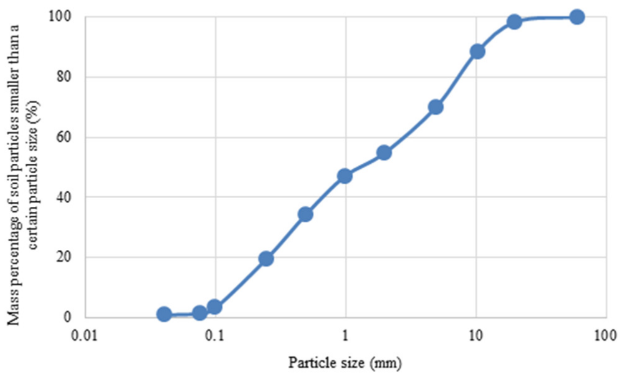

Fig. 2. Gradation curve of bottom slag particles.

The uneven coefficient of the bottom slag was calculated as Cu > 5 and belongs to the inhomogeneous category. The curvature coefficient was Cc < 1, the bottom slag particle size is discontinuous, and it also can be seen from Figure 2 that two-particle groups, i.e. 0.075-0.1mm and 1-2mm are missing. In summary, the incineration bottom slag belongs to poor gradation.

C. Water Content Test

Water content refers to the ratio of the mass of solids to the mass of water in the sample. It can be seen from the test results that the natural air-dried water content of the incineration bottom slag is 6.3%. Considering that the water content of the incineration bottom slag is greatly affected by the stacking time and location, the impact of the water content in engineering applications is negligible.

D. Atterberg Limits Test

The water content between the two consistencies of cohesive soil is called the Atterberg limit content of the soil. The Atterberg limit water content from the plastic state to the liquid state of the soil is called the liquid limit, and the Atterberg limit water content between the plastic state and the semi-solid state is the plasticity limit. Through the Atterberg limits water content test, the liquid limit and plastic limit of the soil can be determined, the state of the soil can be evaluated, and the classification of the soil can be clarified. The test results show that the liquid limit of the incineration bottom slag is 26.5%, and the plastic limit is 3.6%. The plasticity index is 22.9%, and the liquid limit index is 0.11. The incineration bottom slag is in a hard plastic state under the sampling state, and its plasticity is not strong.

III. ENGINEERING CHARACTERISTICS OF THE INCINERATION BOTTOM SLAG

A. Proctor Compaction Test

Seven different sets of compaction tests were carried out to analyze the compaction characteristics of the incineration bottom slag. By applying different compaction works to soil samples with different water content, they can reach different degrees of compaction. The corresponding dry density was determined, in order to obtain the optimal moisture content and maximum dry density through analysis, which can be used for the design and construction of backfill projects.

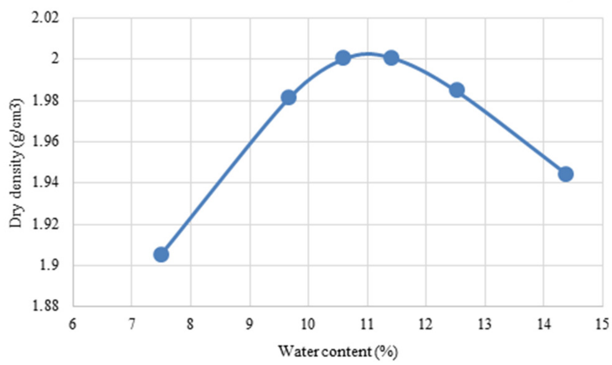

Fig. 3. Curves of water content and maximum dry density.

The relationship between the water content of the incineration bottom slag and the maximum dry density curve is shown in Figure 3. The best water content of the incineration bottom slag under heavy compaction test conditions is 11%, and the maximum dry density is 2.05g/cm^3. It can be seen that when the water content of the incineration bottom slag is lower than 11%, the soil quality is relatively uniform, the strength is high, so it is not suitable for compaction, and additional settlement is likely to occur when the soil samples are immersed in water. When the incineration bottom slag is in a state where the water content is greater than 11%, the soil structure is dispersed, has strong plasticity, and a strong ability to adapt to deformation, but it has low strength and strong anisotropy. In summary, when the incineration bottom slag is at a suitable water content, it can show good compaction, strong plasticity, and high strength.

B. Direct Shear Test

The direct shear test is a simple and effective method to determine the shear strength of the soil. The maximum shear stress of the soil under different vertical loads and pressures was determined, and finally two important shear strength indexes of soil were obtained, cohesion c and friction angle φ, which can be used as an important theoretical basis for evaluating soil bearing capacity. The relationship curve between the shear strength of the bottom slag and the vertical pressure is shown in Figure 4. According to the analytical test results, the friction angle of the bottom slag is 31.8°, and the cohesion is 41.2kPa.

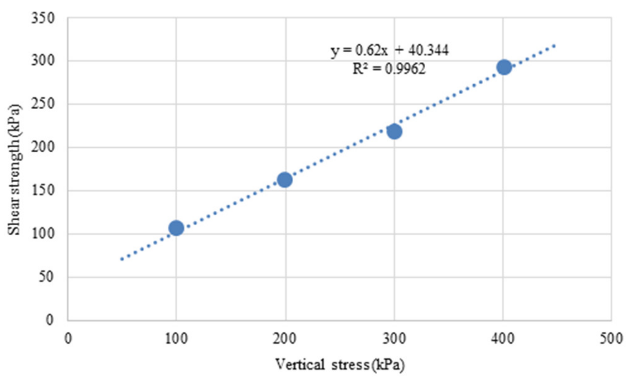

Fig. 4. Relationship between shear strength and vertical pressure.

C. CBR Test

The California Bearing Ratio (CBR) test evaluates the load-bearing capacity of the soil material through the use of a probe of a specific size to penetrate the soil sample. The bearing ratio is a value that characterizes the ability of a material to resist local deformation. It refers to the ratio of the unit pressure when the penetration amount reaches 2.5mm or 5mm to the load strength when the standard crushed stone sample is pressed into the same penetration amount.

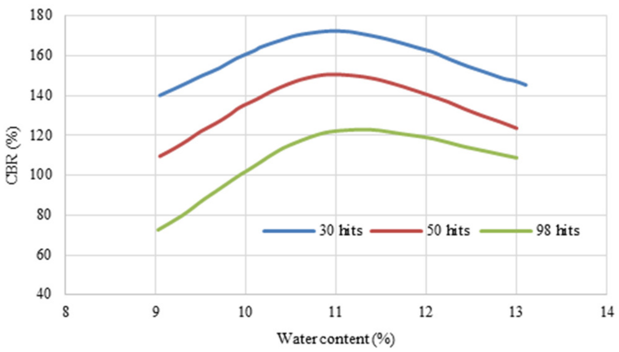

Fig. 5. Relationship between water content and penetration.

The relationship between water content and penetration is shown in Figure 5. From the relationship between water content and the CBR value, it can be seen that the CBR value changes parabolically with the change of water content. The parabola reaches the highest point at the optimal water content, and the maximum CBR value is obtained. For bottom slag samples with the same water content, the higher the compaction times, the greater the CBR value. When the water content is the same, the more compaction times, the greater the unit compaction work received by the sample, the higher the degree of compaction, and the stronger the bearing capacity, which is manifested by the gradual increase in the CBR value.

IV. ENGINEERING APPLICATION ANALYSIS

A. Embankment Backfill

In highway construction, a large amount of earthwork is needed to fill the roadbed and the pavement. From the aforementioned screening and compaction tests, it can be seen that the bottom slag has good framework and compaction performance. According to the relevant standards of highway quality acceptance, the maximum compaction degree of the first-class expressway is required to reach 96% under heavy compaction conditions, and 95% for the second-class highway. It can be seen from the compaction test that the compaction of the incineration bottom slag can reach 97% under the conditions of the heavy compaction test, which means it meets the highway quality acceptance standard.

B. Binder Admixture

In many silt treatment projects, due to the characteristics of high water content, weak permeability, and low strength of silt, its processing efficiency is greatly hindered. The bottom slag of waste incineration is different from sludge. It has a porous surface, strong water absorption, high strength, and a certain amount of pozzolanic activity. If the aggregate properties of the incineration bottom slag, higher water absorption, and pozzolanic activity are considered, the waste incineration bottom slag can be mixed into the sludge and improve its mechanical properties and increase its volume. Therefore, the treatment efficiency can be improved significantly. From the results of particle size analysis, it can be seen that the content in particles larger than 5mm in the bottom slag is 70.15%, while the content of particles smaller than 5mm is only 29.85%. Therefore, the size of the incineration bottom slag is above 4.75mm, which meets the requirements of GB/T14685-2011 [23]. It can be used as a gravel-like aggregate in the solidification of sludge, playing a good skeleton function. In the mixed soil material, the bottom slag plays the role of the coarse-grained framework, and the fine particles in the sludge fill the pores between the particles.

C. Use in Concrete and Asphalt instead of Aggregates

Through the analysis of the bearing ratio and the test results, the incineration bottom slag has good local compressive strength. The content of particles within the range of 2-60mm in the bottom slag is 52.97%, and the content of particles smaller than 0.1mm is 3.47%. High content of large particles can play a very good skeleton effect. According to GB/T14684-2001 [24], the thickness and particle gradation are evaluated, and the fine-grain modulus is calculated to be 2.5, and the particle gradation is within a reasonable range, indicating that the bottom slag can be used as gravel aggregates in concrete.

V. DISCUSSION

In most developed countries, the comprehensive utilization rate of incineration bottom slag is very high, and in some reaches 100% [20, 21]. However, the characteristics of the solid waste incineration bottom slag are significantly affected by the region, and its economic development level. This paper studies the physical and mechanical properties of the solid waste incineration bottom slag in central China, represented by Wuhan, and analyzes the feasibility of recycling the incineration bottom slag in civil engineering. For example, the Cu and Cc of incineration bottom slag in Suzhou area reported in [22] are 0.05 and 44, respectively, and the optimal moisture content is around 17%, which diverge greatly from the values obtained in this paper. Therefore, the comprehensive reuse of incineration bottom slag needs to consider many factors, and it is necessary to take measures according to local conditions, and take the optimal resource recycling method according to the characteristics of incineration bottom slag in different regions.

VI. CONCLUSIONS

This paper conducted a series of experimental studies on the bottom slag of waste incineration, analyzed its basic physical and mechanical properties, and conducted a feasibility analysis of its resource utilization in civil engineering. The following conclusions were drawn:

- The incineration bottom slag has similar properties to sandy soil. The content of coarse particles is relatively high, the surface is loose and porous, and the water absorption rate is relatively high. The specific gravity is about 2.71. Under heavy compaction conditions, it can reach a compaction degree more than 95%, and the effective CBR is not less than 72.96% at the optimal water content.

- The specific gravity of the incineration bottom slag is close to that of sand, with good compaction performance, high compressive strength and low shear strength. The incineration bottom slag has good framework supportability, strong water absorption, and easy to improve gradation.
- When the incineration bottom slag is matched with different materials, it can show better engineering properties. The incineration bottom slag can be combined with fine-grained soil and be used to road embankment filling. Due to the good compatibility of the incineration bottom slag, the improved particle size gradation is better, and the compaction effect is significantly improved. In addition, the bottom slag can be used as sludge solidified aggregates to replace aggregates of cement concrete and asphalt materials.

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