The Study of the Environmental Characteristics and Engineering Behavior of Basic Oxygen Furnace Slag Mixed with Dredged Sediment of Land Reclamation

TSAI-YING CHU*, CHUN-HUNG LIN and HUNG-CHU HSU****

**Environmental Protection Department, China Steel Corporation*
*** Marine Environment and Engineering Department, National Sun Yat-sen University*

This study investigated the swelling behavior of Basic Oxygen Furnace (BOF) slag mixed with dredged sediment. A mixture of BOF slag with various proportions of dredged sediment (hereafter "the Mixture") was subjected to a heated swelling test to examine its impact on the swelling behavior of BOF slag. The test results showed that the swelling at 80ºC decreased with the increased proportion of dredged sediment, and the mixing ratio was the main factor, while the mixing method was secondary. To understand the environmental characteristics of the Mixture, the pH value, the Toxicity Characteristics Leaching Procedure (TCLP), and the Environmental Use Leaching Procedure were conducted separately. The results showed that the pH values were below the standards for hazardous industrial waste, and the leaching concentrations of heavy metals were lower than all applicable standards, while most of them were not detected. The experimental results showed that the Mixture can effectively reduce the swelling of BOF slag and has no impact on environmental quality, which provided a useful reference for future application of the Mixture for land reclamation.

Keywords: Basic oxygen furnace (BOF) slag, Dredged sediment, Environmental characteristics, Swelling test, Land reclamation

1. INTRODUCTION

BOF slag is a by-product inevitably produced in the steelmaking process, with a total annual output of approximately 1.6 million metric tons from China Steel Corporation and Dragon Steel Corporation. BOF slag is one of the recycled aggregates, which is an important aspect of the government's promotion of the circular economy. It has characteristics of abrasion resistance, high hardness, and high skid resistance, making it a good engineering material. Moreover, it has been tested by the American multiple toxicity characteristic leaching procedure (MTCLP), the Dutch Building Material Decree (BMD), and the Japanese leaching test, all showing that the leaching concentrations are below the standards, indicating the long-term stability of heavy metals in BOF slag. On the other hand, Taiwan's ports need to dispose of approximately 1 million cubic meters of dredged sediment each year, which has low strength and poor load-carrying capacity, making it less suitable as an engineering material.

BOF slag and dredged sediment are both important materials for the circular economy. Taiwan, being an island nation, is actively promoting the use of recycled aggregates and vigorously promoting the development of oceans and ports, seeking economic benefit and environmentally friendly treatment is an important issue nowadays. Using BOF slag as fill material for land reclamation can accelerate the overall development rate of ports and achieve the basic principles of resource-efficient use in the circular economy. Therefore, this study conducts relevant experiments to investigate the swelling behavior and environmental safety after mixing BOF slag with dredged sediment.

2. EXPERIMENTAL METHOD

2.1 Materials

BOF slag is produced by China Steel Corporation, and processed by CHC Resources Corporation to obtain the graded BOF slag aggregates. Dredged sediment is obtained from the dredging of Kaohsiung Port.

2.2 Environmental Safety Test of BOF Slag, Dredged Sediment, and the Mixture

The testing method for the toxicity characteristic is the Toxicity Characteristic Leaching Procedure (TCLP) of waste[1]. The resulting leachate is analyzed for various components of heavy metals, including Hg, As, Cu, Cd, Pb, Cr, Cr^{6+}, Ba, and Se.

The other testing method is the environmental use leaching procedure for recycled aggregates[2]. The procedure involves a liquid-to-solid ratio (L/kg) of 10:1, mixing and stirring for 6 hours, followed by solid-liquid separation using a 0.45 μm membrane filter paper. The resulting leachate is analyzed for various components of heavy metals, including As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, Se, B, Cr^{6+}, and F.

2.3 Swelling Test of BOF Slag Mixed with Dredged Sediment

The mold dimensions for the indoor swelling strain test are an inner diameter of 15.2 cm and a height of 12.7 cm. Considering the effectiveness of the specimen size and particle size, both the BOF slag and dredged sediment samples are sieved through a 3/8-inch sieve before being filled into the mold.

Two mixing methods, double-layer and multiple-layer mixing, are conducted to understand the influence of mixing methods on the swelling behavior. In the double-layer mixing test, the BOF slag is first placed at the bottom of the mold, and then the dredged sediment is filled in the upper part. In the multiple-layer mixing test, the BOF slag and dredged sediment to be mixed are divided into two layers of volume and filled into the mold, with the BOF slag as the bottom layer, progressively stacked up to the predetermined amount. Subsequently, the specimens are immersed in a heated water tank filled with saturated artificial seawater, and their strain is measured at different ratios at 80°C listed in Table 1.

3. RESULTS AND DISCUSSION

3.1 Environmental Safety Test of BOF Slag, Dredged Sediment, and the Mixture

The pH values of BOF slag and dredged sediment were measured separately (at 25°C), resulting in 12.43 and 7.15, respectively. Both pH values are below the specified standard for hazardous waste identification (12.5).

After testing with the TCLP, the leaching concentrations of various heavy metals from BOF slag and dredged sediment were below the standard values for TCLP, with several heavy metals not detected listed in Table 2.

The leaching concentrations of heavy metals from the BOF slag were all below the quality standards for BOF slag land reclamation specified in the BOF Slag Maritime Engineering Manual, and several heavy metals were not detected. As for the dredged sediment, there are currently no specific leaching standards for environmental use in Taiwan. However, all tested heavy metals were not detected. The test results are summarized in Table 3.

Table 1 Swelling test plan for BOF slag mixed with dredged sediment.

Test number	BOF slag ratio (%)	Dredged sediment ratio (%)	Mixing method
1	100	0	-
2	80	20	double-layer, multiple-layer
3	60	40	multiple-layer
4	40	60	double-layer, multiple-layer
5	20	80	multiple-layer
6	0	100	-

Table 2 Results of TCLP testing of BOF slag and dredged sediment.

Material	Leaching concentration in leachate (mg/L								
	Hg	As	Cu	Cd	Pb	Cr	Cr^{6+}	Ba	Se
BOF slag	ND	ND	ND	ND	ND	ND	ND	0.119	ND
Dredged sediment	ND	ND	0.072	ND	ND	<0.010 (0.003)	ND	0.095	ND
TCLP standard	≦0.2	≦5.0	≦15.0	≦1.0	≦5.0	≦5.0	≦2.5	≦100.0	≦1.0
MDL	0.0001	0.022	0.004	0.001	0.020	0.002	0.01	0.001	0.029

Note: "ND" indicates values below the method detection limit (MDL) and the MDL is noted in the remarks column. Values below the quantitation detection limit (QDL) but above the MDL are indicated as "<QDL value" and the actual value is provided in parentheses, but these values are for reference only.

Table 3 Results of environmental use leaching procedure for recycled aggregates testing of BOF slag and dredged sediment.

Material	Leaching concentration in leachate (mg/L)											
	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Se	B	Cr^{6+}	F
BOF Slag	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.022	ND	0.11
Dredged Sediment	ND	ND	ND	<0.020 (0.006)	ND	ND	ND	ND	ND	0.171	ND	0.18
Land Reclamation Standard for BOF Slag	≦0.03	≦0.009	-	-	≦0.0015	-	≦0.03	-	≦0.03	≦20	≦0.15	≦15
MDL	0.005	0.001	0.005	0.005	0.0001	0.005	0.002	0.011	0.006	0.006	0.001	-

The pH values of the Mixture were tested after mixing BOF slag and dredged sediment at ratios of 1:1 and 7:3. The pH values were measured at 25°C and were found to be 12.43 for both mixtures. These pH values are below the specified limit of 12.5 for hazardous waste. After testing with the TCLP, the leaching concentrations of various heavy metals from the Mixture were below the standard values for TCLP, with several heavy metals not detected. Besides, the leaching concentration of Cu was lower in the Mixture compared to the leaching concentration from a single material. The test results are summarized in Table 4.

After mixing BOF slag and dredged sediment at ratios of 1:1 and 7:3, and testing with the environmental use leaching procedure, the leaching concentrations of various heavy metals from the Mixture were below the quality standards for BOF slag land reclamation specified in the manuals of BOF slag utilization in marine engineering(3), with several heavy metals not detected. Besides, the leaching concentration of B was lower in the Mixture compared to the leaching concentration from a single material. The test results are summarized in Table 5.

Table 4 Results of TCLP Testing of the Mixture.

Material	Leaching concentration in leachate (mg/L)								
	Hg	As	Cu	Cd	Pb	Cr	Cr^{6+}	Ba	Se
the Mixture at a ratio of 1:1	ND	ND	ND	ND	ND	<0.010 (0.002)	ND	0.064	<0.100 (0.029)
the Mixture at a ratio of 7:3	ND	ND	ND	ND	ND	ND	ND	0.184	ND
TCLP Standard	≦0.2	≦5.0	≦15.0	≦1.0	≦5.0	≦5.0	≦2.5	≦100.0	≦1.0
MDL	0.0001	0.022	0.004	0.001	0.020	0.002	0.01	0.001	0.029

Table 5 Results of environmental use leaching procedure for recycled aggregates testing of the Mixture

Material	Leaching concentration in leachate (mg/L)											
	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Se	B	Cr^{6+}	F
the Mixture at a ratio of 1:1	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.067	ND	0.10
the Mixture at a ratio of 7:3	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.045	ND	0.13
Land Reclamation Standard for BOF Slag	≦0.03	≦0.009	-	-	≦0.0015	-	≦0.03	-	≦0.03	≦20	≦0.15	≦15
MDL	0.005	0.001	0.005	0.005	0.0001	0.005	0.002	0.011	0.006	0.006	0.001	-

After mixing BOF slag and dredged sediment at a ratio of 7:3 and extracting with seawater, the pH value at 25°C was 9.30, which was lower than the pH value of 12.43 obtained by using pure water extraction. This difference was attributed to the buffering capacity of seawater ions, which inhibit the leaching of $Ca(OH)_2$ from BOF slag immersing into the water. Additionally, the leaching concentrations of heavy metals in the extract were not significantly different from the seawater background values, and several heavy metals were not detected. The test results are summarized in Table 6.

BOF slag mixed with dredged sediment at a ratio of 7:3 and immersed in seawater showed that the concentrations of heavy metals in seawater were mostly below the quantitation detection limit and even below the method detection limit for various immersion times. The test results are summarized in Table 7.

3.2 Swelling Test of BOF Slag Mixed with Dredged Sediment

The swelling test was conducted on the Mixture at different ratios under heating. The swelling strain at 80°C decreased as the proportion of dredged sediment increased. There was only a slight difference in swelling behavior between the double-layer and multi-layer mixing methods shown in Figure 1.

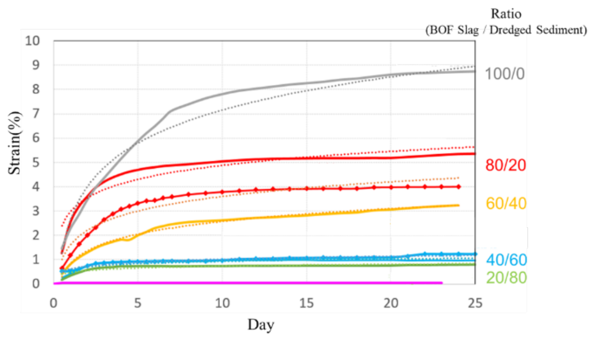

Fig.1. Swelling Strain of the Mixture with Different Ratios at 80°C.

Table 6 Results of seawater extraction leaching test of the Mixture.

Material	Leaching concentration in leachate (mg/L)										
	As	Cd	Cu	Hg	Ni	Pb	Zn	Se	Cr^{6+}	Mn	Ag
seawater background value	ND	ND	<0.0010 (0.00069)	ND	ND	<0.0010 (0.00097)	<0.0050 (0.00226)	ND	ND	ND	ND
the Mixture at a ratio of 7:3	ND	ND	0.0047	ND	0.0013	ND	ND	ND	ND	ND	ND
MDL	0.0003	0.0002	0.0005	0.00015	0.0005	0.0005	0.0016	0.0007	0.0019	0.0005	0.006

Table 7 Results of long-term leaching test of the Mixture immersed in seawater.

Immersion time (day)	Leaching concentration in leachate (mg/L)										
	As	Cd	Cu	Hg	Ni	Pb	Zn	Se	Cr^{6+}	Mn	Ag
0	ND	ND	<0.0010 (0.00069)	ND	ND	<0.0010 (0.00097)	<0.0050 (0.00226)	ND	ND	ND	ND
45	<0.0020 (0.0010)	ND	0.0032	ND	ND	ND	ND	ND	ND	ND	ND
60	<0.0020 (0.0004)	ND	0.0030	ND	<0.0010 (0.00074)	ND	ND	ND	ND	ND	ND
90	<0.0020 (0.0007)	ND	0.0028	ND	<0.0010 (0.00081)	ND	ND	ND	ND	ND	ND
120	<0.0020 (0.0005)	ND	0.0028	ND	ND	ND	ND	ND	ND	ND	ND
180	<0.0020 (0.0005)	ND	0.0011	ND	ND	ND	ND	ND	ND	ND	ND
240	<0.0020 (0.0010)	ND	<0.0010 (0.0005)	ND	ND	ND	ND	ND	ND	ND	ND
MDL	0.0003	0.0002	0.0005	0.00015	0.0005	0.0005	0.0016	0.0007	0.0019	0.0005	0.006

To quantify the swelling absorption capacity of the Mixture with different ratios, the swelling strain of the pure BOF slag specimen at 80°C on the 25th day of heating was taken as the baseline H. Based on the percentage of dredged sediment mixed in, a reduction factor was applied. For example, a specimen mixed with 20% dredged sediment would hypothetically have a BOF slag swelling strain of 0.8H. The actual measured swelling strain was then subtracted from this estimated swelling strain to obtain the difference, which represented the swelling absorption. The relationship between the swelling absorption and the mixing ratio derived from this analysis is shown in Figure 2. As depicted, the swelling strain decreased as the proportion of dredged sediment increased. The optimum swelling absorption capacity was observed when the dredged sediment was mixed at a ratio of 52%. Further increasing the proportion of dredged sediment beyond this point resulted in a decline in the swelling absorption capacity.

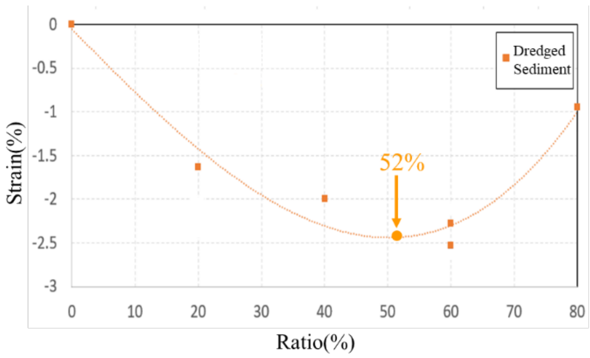

Fig.2. Long-term swelling absorption of BOF slag mixed with different ratios of dredged sediment at 80°C.

4. CONCLUSIONS

The pH values of the BOF slag dredged sediment, and the Mixture, as well as the TCLP and Environmental Use Leaching Procedure testing results, complied with relevant regulations. Furthermore, the pH values and leaching concentrations of heavy metals of BOF slag mixed with dredged sediment at different ratios (1:1 and 7:3), using different extracting media (pure water and seawater), and at different immersion times also complied with relevant regulations. BOF slag mixed with dredged sediment effectively reduced the swelling strain of BOF slag. The swelling behavior of the Mixture is primarily controlled by the mixing ratio, with the mixing method being a secondary factor. The swelling strain decreased as the proportion of dredged sediment in the mixture increased.

The experimental results demonstrated that mixing BOF slag with dredged sediment effectively overcomes the swelling issue without adverse effects on environmental quality. In future applications for land reclamation, adjustments may be made regarding the characteristics of the reclaiming materials, the production volume, and the reclaimed land use subsequently.

REFERENCES

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