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Engineering Properties of Controlled Low-Strength Materials Containing Bottom Ash of Municipal Solid Waste Incinerator and Water Filter Silt

Wen-Ten Kuo * and Zhen-Chang Gao

Department of Civil Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 807, Taiwan; ken1098102204@gmail.com

* Correspondence: wtkuo@cc.kuas.edu.tw; Tel.: +886-7-3814526 (ext. 15233)

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Abstract: The bottom ash of a municipal solid waste incinerator (MSWI) and water filter silt (WFS) were applied to a controlled low-strength material (CLSM) in the present study. The CLSM of the control group was composed of cement, water, and fine aggregates. WFS was first used as a fill material to replace 10% of the volume of natural fine aggregates in the CLSM. MSWI bottom ash was used to replace 0%, 25%, 50%, 75%, and 100% of the volume of the remaining natural fine aggregates with a water-cement ratio of 1.6. The engineering properties of freshness, hardening, and durability were examined. The results revealed that the slump flows of all of the mixture proportions ranged between 50 and 70 cm. The tube flow ranged between 20 and 30 cm, conforming to ASTM D6103 and construction regulations regarding CLSMs stipulated by the Water Resources Agency of the Ministry of Economic Affairs in Taiwan. Increases in the replacement amount of MSWI bottom ash prolonged the time required to achieve a resistance to penetration of 2.74 MPa. The diameter of the drop test ball was less than 7.6 cm, indicating that the mixture proportions had sufficient bearing capacity for successive construction. At an age of 28 d, the compressive strength did not exceed the 8.4 MPa prescribed in ASTM D4832. The ultrasonic pulse velocity and water absorption exhibited identical growth tendencies. In summary, using MSWI bottom ash to create CLSMs is feasible on the condition that the appropriate amount of WFS should be added.

Keywords: municipal solid waste incineration (MSWI) bottom ash; water filter silt (WFS); controlled low-strength material (CLSM)

1. Introduction

Municipal solid waste (MSW) is causing ecological problems worldwide. To fight increasing municipal waste, the development of waste-to-energy technology has drawn widespread attention in various countries. Incineration is the quickest solution. In addition to reducing the volume of MSW [1], it also decreases the demand for landfills [2]. Furthermore, the heat generated through burning waste can be converted into electrical energy and thus generate power [3].

The incineration of MSW produces a large amount of fly ash and bottom ash [4], which leach high levels of heavy metals. They are classified as hazardous waste [5] and are prone to affect the environment. However, in recent years, the technology used to recycle incinerator bottom ash has become more developed. After undergoing pretreatments such as magnetic separation, crushing and sieving, or screening, the incinerator ash is subject to treatment processes such as stabilization, maturation, or washing, depending on the classification, use, and demand for the recycled resource. Maturation effectively reduces the water content of bottom ash, whereas washing removes all heavy metal content such as Cl^- and $SO_4{}^{2-}$ in bottom ash as well as its foul odor. X. G. Li et al. [6]

application of municipal solid waste incineration (MSWI) bottom ash as a substitute of quartz sand. Leaching toxicity was also determined to ensure the environmental safety. The incorporation of MSWI bottom ash can reduce the gas-foaming time, compressive strength, density and thermal conductivity. Byproducts such as bottom ash generated by waste combustion can be considered a type of typical aggregate material, which can be useful in civil engineering and as a substitute for conventional natural aggregate [4,7].

Developed countries have researched and developed a new type of concrete material-controlled low-strength material (CLSM) for use as an alternative to conventional backfill material. It can be obtained from local or alternative materials and can shorten work duration and reduce cost so that the impact on traffic is reduced and the quality of filling work is improved. The American Concrete Institute (ACI) [8] defined CLSM as self-compacting, and it is mainly used as a substitute material for compacted backfill. CLSM causes little subsidence and is nonseparating, excavating, and ecofriendly. It is widely used for backfilling after pipe excavation and road repairs in Taiwan and abroad. There is no limitation on the use of aggregate for CLSM. Following the Taiwanese government's promotion of sustainable development and green building public policies, countless studies on the use of recycled aggregate have been conducted in recent years. The ACI recommended that recycled aggregates that passed tests can be used as a substitute aggregate for CLSM. Nonconventional materials such as boiler ash, recycled glass, cement kiln dust (CKD), incinerator bottom ash, crushed stones, rubber granules from waste tires, fluidized bed combustion ash, recycled concrete aggregates, and other similar industrial byproducts have been used in the past decade in CLSM as a substitute material for fine aggregates [9–20].

For many years, studies have employed various types of industrial byproducts in CLSM and have achieved significant results in the actual engineering application of CLSM. For example, Kuo et al. [21] used waste oyster shells in their CLSM. Sheen et al. [22,23] replaced the Portland cement in CLSM with soil-based stainless steel-reducing slag and investigated the CLSM's engineering properties. Lee et al. [24] mixed fly ash, boiler ash, and bottom ash in a CLSM in their alkali-activation research. Miren et al. [25] used recycled fine aggregates in CLSM in their feasibility study. In another study, CKD and hearthstone were employed to replace the cement in CLSM.

Zhen et al. [9] reported as feasible the use of MSW incineration bottom ash as a starting material for producing CLSM. The addition of bottom ash to a CLSM was favorable for a pozzolanic reaction forming a highly crystalline AFt phase, reducing the material's porosity and enhancing its compressive strength. Using bottom ash in CLSM is very promising; providing the heavy metal content is within an appropriate limit, the bottom ash is stable and not corrosive after mixing and it enhances the stability, strength, and load-bearing value of the CLSM following its use [16,17]. Dickson et al. [19] added bottom ash and dredged sediment to CLSM, discovering that the compressive strength obtained with the bottom ash was higher than that obtained with the dredged sediment. Currently, washed soil and washed bottom ash generated by MSW incineration are yet to be widely employed in CLSMs. This study confirmed the stability of the two types of bottom ash and analyzed their effect on the environment. The application potential of the developed CLSM as a building material component was also evaluated.

2. Testing Methods

2.1. Materials

In the current study, Type I Portland cement, the quality of which conformed to the regulations of ASTM C150 [26], was used. Natural sand and MSWI bottom ash were passed through a No. 4 sieve. The particle size distribution is shown in Figure 1. WFS was a powder material produced from sieving MSWI bottom ash through a No. 200 sieve to obtain particles with a size of 75 μm or smaller. The powder material was dried before use. The physical and chemical properties of the materials are shown in Tables 1 and 2.

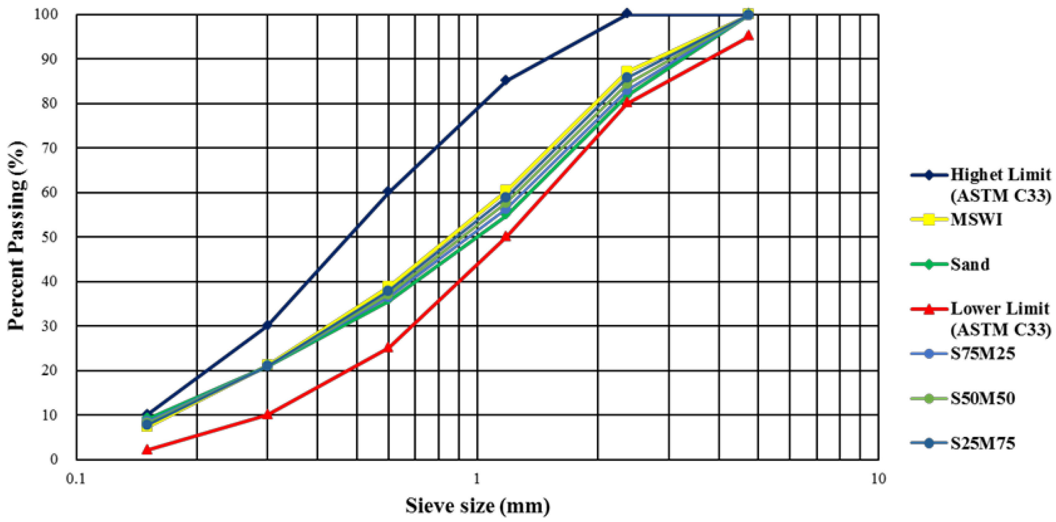


Figure 1. Particle size distribution of municipal solid waste incinerator (MSWI) and sand materials.

Table 1. Sand, municipal solid waste incinerator (MSWI), and water filter silt (WFS) physical properties.

Properties	Sand	MSWI	WFS
Specific gravity (OD)	2.573	2.002	2.561
Water absorption (%)	2.564	11.179	-
Moisture content (%)	2.05	4.25	44.5
Fineness modulus (FM)	2.979	2.86	-

Table 2. Chemical compositions of Portland cement type I, MSWI, and WFS.

Chemical Compositions (%)	Cement	MSWI	WFS
SiO_2	20.87	24.84	23.49
Al_2O_3	4.56	8.42	8.19
Fe_2O_3	3.44	30.63	18.18
CaO	63.14	27.8	38.8
MgO	2.82	1.5	1.7

2.2. Mixture Proportion Design and Tests

Because there are no standard designs for CLSM mixture proportions thus far, the current study used WFS as a fill material to replace 10% of the natural fine aggregates in the CLSM on the basis of a literature review. MSWI bottom ash was used to replace 0%, 25%, 50%, 75%, and 100% of the remaining natural fine aggregates. The design used a water-cement ratio of 1.6 and ages of 3 d, 7 d, 28 d, and 56 d. The mixture proportions are shown in Table 3.

Table 3. Mixture proportions of controlled low-strength material (CLSM) (unit: kg/m^3).

W/C	NO.		Cement	Sand	Water	MSWI	WFS
1.6	WFS10	M0	218.9	1378.9	350.2	-	148.6
		M25		1034.1		292.1	
		M50		689.4		584.2	
		M75		344.7		876.3	
		M100		-		1168.4	

According to ASTM C143 [27] and ASTM D6103 [28], the slump should exceed 19 cm, with a slump flow of 40 cm and a tube flow ranging between 20 and 30 cm. As specified in ASTM C403 [29], the initial setting time of a CLSM is when the resistance to penetration exceeds 2.74 MPa. The ball drop value was obtained from ASTM D6024 [30]. A free-fall heavy ball was used to impact the specimen; this process was repeated five times. The diameter of the indent area on the specimen surface was measured; the indent diameter D should be less than 7.6 cm. According to ASTM D4832 [31], the compressive strength on Day 28 of curing should not exceed 8.4 MPa. Ultrasonic pulse velocity was tested using the approach described in ASTM C597 [32] to measure the internal density of the specimen and to ascertain the effect of age on the specimen. Water absorption was examined according to the procedures of ASTM C642 [33]. Specifically, a specimen cured for 28 d was soaked in water for a day, removed, and dried with a dry cloth before it was weighed. Subsequently, the specimen was dried in an oven for 24 h before being removed and weighed again. Following the ASTM C373 [34], the porosity of the CLSM specimen was calculated by determining the volume of the specimen, which is based on its weight in water and its wet weight in the atmosphere after being in water for 24 h on Day 28 of the curing process. Regarding sulfate attack, procedures described in ASTM C1012 [35] were adopted; specifically, on Day 28 of the curing process, the specimen was dried in an oven for a day and then immersed in sulfate for another day (both steps constituted a cycle); this process was repeated for five cycles, after which weight loss and changes in appearance were examined.

3. Results and Discussion

3.1. Slump, Slump Flow, and Tube Flow

In order to investigate the workability of this MSWI, the experiment of Slump, slump flow, and tube flow was carried out at the same time after the sample was mixed, and the results are shown in Figure 2, when the water-cement ratio was 1.6, the slump measured 26.8–26.5 cm, slump flow was 65.3–56.9 cm, and tube flow registered values of 23.5–21.7 cm, all of which conform to the requirements for ordinary fluidity levels specified in ASTM C143 and ASTM D6103. The replacement of MSWI bottom ash did not cause an increase in slump flow. When the replacement of WFS and MSWI bottom ash was increased, the slump, slump flow, and fluidity diminished gradually, thereby increasing construction difficulty. Two possible causes of this phenomenon were determined.

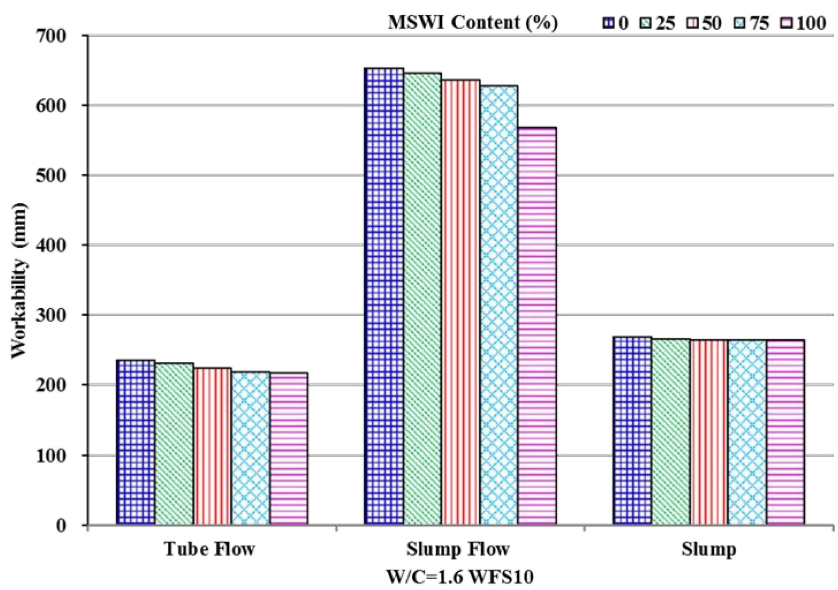


Figure 2. Effect of MSWI content on flowability.

(1) The workability of the CLSM decreased with increase in MSWI bottom ash content because the bottom ash possessed a high water absorption rate. The increase in the replacement of MSWI bottom ash increased the water absorption during the mixing. The loss of mixing water decreased the fluidity,

thereby causing the slurry to thicken and become sticky when the CLSM was mixed. Under mixing conditions that used the same water amount, increasing the replacement of MSWI bottom ash likely incurs a high loss of workability. Because WFS is a type of clay soil, which represents high water absorption, an increase in the WFS replacement reduces the workability of the CLSM, the result is similar to that of Kuo et al. [21] using high water absorption oyster shell (WOS).

(2) The fineness modulus (FM) of the MSWI bottom ash was 2.86, lower than that (2.98) of fine aggregates. Smaller particles represent a higher specific surface area. After the MSWI bottom ash was used to replace cement in the CLSM, the surface water absorption increased, reducing the fluidity of the CLSM and severely decreasing the self-consolidating property. The increase in the proportion of the MSWI bottom ash considerably affected the workability of the CLSM.

3.2. Penetration

According to ASTM C403, a CLSM can be used in construction works only when it has a penetration value of 2.75 MPa. Figure 3 presents the penetration result. When the WFS replacement was 10% and the replacement of MSWI bottom ash was 25%, 50%, 75%, and 100%, a penetration value of 2.75 MPa was achieved in 14.33–16.87 h, satisfying the time requirement of 12–36 h for ordinary CLSMs.

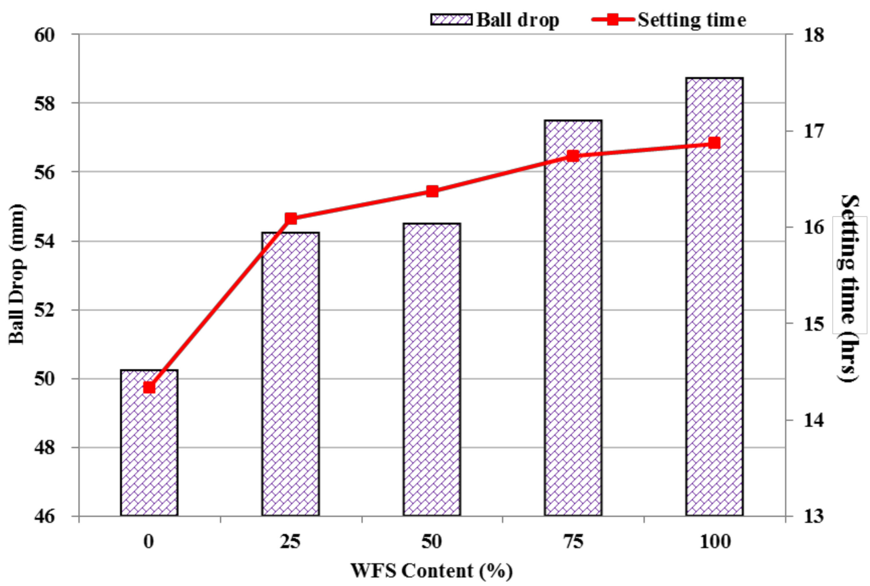


Figure 3. Effect of MSWI content on ball drop and setting time.

In the present study, the time required to achieve a penetration value of 2.75 MPa extended as the replacement of MSWI bottom ash was increased, because the bottom ash had large structure pores, which facilitated water absorption and delayed the hydration effects, thereby prolonging the initial setting time. The uneven combustion of the incinerator bottom ash also resulted in excess organic matter in the bottom ash, thereby delaying the setting of the CLSM.

3.3. Ball Drop

According to ASTM D6024, the ball drop test is a destructive test for assessing whether to continue the successive work. The indentation diameter of the ball drop test must be less than 7.6 cm to confirm whether the mixture proportion exhibits sufficient bearing capacity. The specimen undergoes a ball drop test in a day, as shown in Figure 3. The ball drop test revealed increasing indentation diameters as the replacement proportion increased. The values of the ball drop test ranged between 5 and 5.9 cm, which were lower than 7.6 cm. These results indicated that the mixture proportion exhibited sufficient bearing capacity for successive construction. These results were only a preliminary assessment of the material bearing capacity.

3.4. Compressive Strength

CLSM is mainly used in the application of trench backfilling, and it must have self-filling, excavation and low subsidence requirements. As specified in ASTM D4832, the uniaxial compressive strength on Day 28 should not exceed 8.4 MPa. The compressive strength values of CLSMs in the current study are shown in Figure 4. Compressive strength increased with age for all mixture proportions. The compressive strength was 3.02–2.71 MPa on Day 3, 4.59–4.34 MPa on Day 7, and 6.25–5.87 MPa on Day 28. These values conformed to the strength requirement of excavatability. After the cement hydration was completed through the gradual aging of the CLSM, the increase in the later-stage compressive strength gradually plateaued.

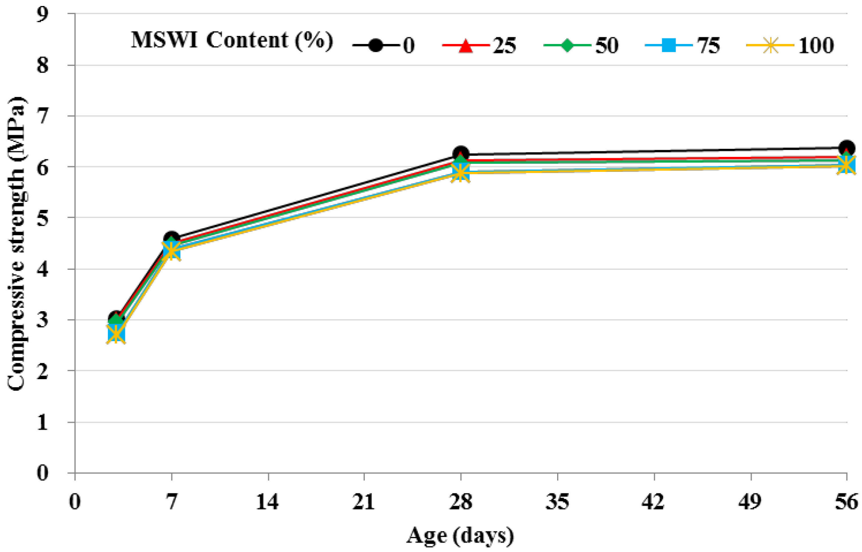


Figure 4. Effect of MSWI content on compressive strength.

When the replacement of the MSWI bottom ash was increased, the compressive strength decreased, which was possibly attributed to the porous structure and water absorption characteristics of MSWI bottom ash, this result is the same as the compressive strength of the application of pulp ash to CLSM by Wu et al. [36], the use of materials with high water absorption reduces the compressive strength. In addition, the FM of MSWI bottom ash is lower than that of fine aggregates. Thus, when an identical water-binder ratio is used, an increase in the replacement of MSWI bottom ash increased the FM of the fine aggregate, reducing the compressive strength of the CLSM.

3.5. Ultrasonic Pulse Velocity

Ultrasonic pulse velocity is used to monitor the densification of the sample. It is mainly to measure the density change inside the CLSM. The result of the value is similar to the trend of compressive strength, but it cannot clearly represent the test result of compressive strength. The ultrasonic pulse velocity of the CLSM is shown in Figure 5. The ultrasonic pulse velocity of various mixture proportions increased with age (Day 3: 2692–2150 m/s; Day 7: 2992–2333 m/s; and Day 28: 3081–2610 m/s).

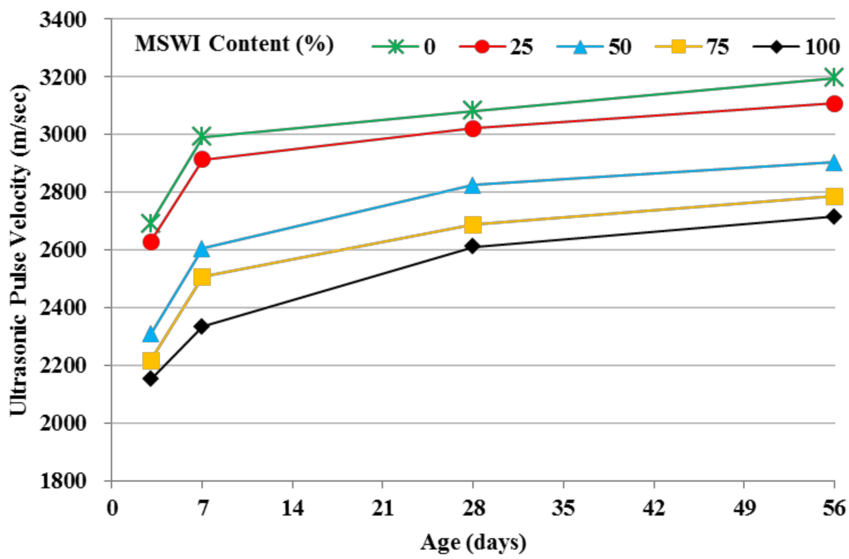


Figure 5. Effect of MSWI content on ultrasonic pulse velocity.

Increasing the WFS content fills the pores in the interfaces between the slurry and the aggregates, thereby hindering the pulse transfer pathways and reducing the pulse velocity. This phenomenon explains why the WFS content clearly affected the ultrasonic pulse velocity. Increasing the replacement of the MFWI bottom ash reduced the ultrasonic pulse velocity because the porous bottom ash had a high water absorption rate. The pores enlarged when the CLSM lost moisture after curing, thereby reducing the ultrasonic pulse velocity.

3.6. Water Absorption

To assess the ability of external moisture to enter a specimen, the water absorption rate is used to determine the size distribution of the internal pores of the CLSM specimen. If concrete slurry contains increased amount of free water that is not involved in hydration reaction, additional capillary pores form, increasing the water absorption rate. As shown in Figure 6, the water absorption ranged between 16% and 22%, showing an increasing trend as the replacement of MSWI bottom ash and WFS content was increased.

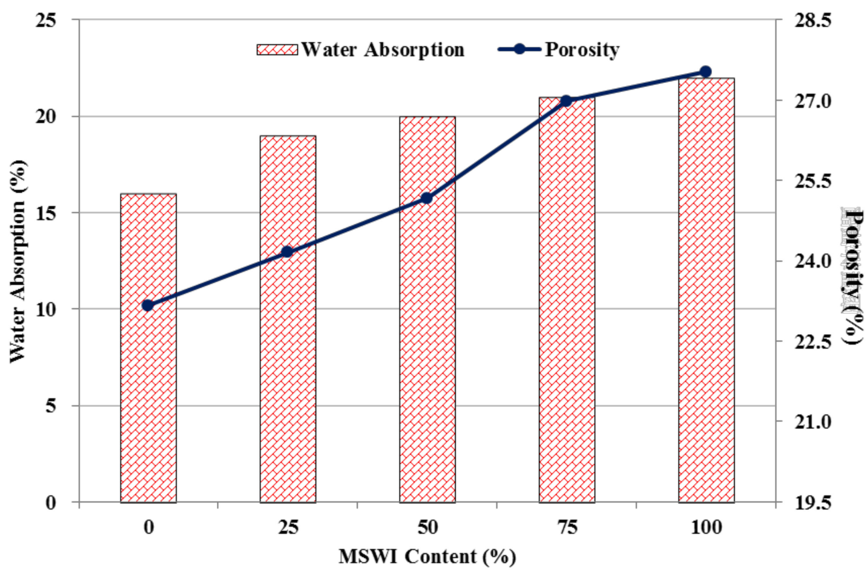


Figure 6. Effect of MSWI content on water absorption and porosity.

3.7. Porosity

Porosity is mainly used to measure the density of a CLSM specimen containing MSWI bottom ash. Generally, when the porosity of a material is low, the material contains few interconnecting pores, and therefore features low water absorption and high strength, and is resistant to freezing and penetration. Concrete pores are highly related to freezing resistance. Figure 6 shows that the porosity ranged between 23.2% and 27.5%. As the MSWI bottom ash replacement was increased, the density of the CLSM specimen decreased. MSWI bottom ash itself is characterized by high water absorption and porosity; therefore, under a high water-cement ratio, the slurry and aggregates are loosely distributed and thus cannot effectively fill the internal pores of the specimen. Consequently, the porosity of the CLSM increased.

3.8. Sulfate Attack

In the present study, the CLSM specimen prepared with MSWI was cured. After aging for 28 d, the specimen was dried for 24 h in an oven at 100 °C ± 5 °C before being immersed in a saturated sulfate solution for 24 h. Subsequently, the specimen was dried again for 24 h before it was weighed. These steps were repeated to evaluate the effect of sulfate attack on the CLSM containing MSWI bottom ash. Figure 7 shows that the weight loss rate ranged between 5.991% and 6.824%. When the MSWI bottom ash replacement was increased, the weight loss resulting from sulfate attack increased. Because the CLSM is a porous and low-strength cementitious material, water acts as a medium for introducing sulfuric ions into the specimen. In addition, MSWI bottom ash is a material characterized by high water absorption and porosity; therefore, the aggregate strength and robustness of the studied CLSM were low. Consequently, as the replacement of MSWI bottom ash was increased, the CLSM became susceptible to sulfate attack.

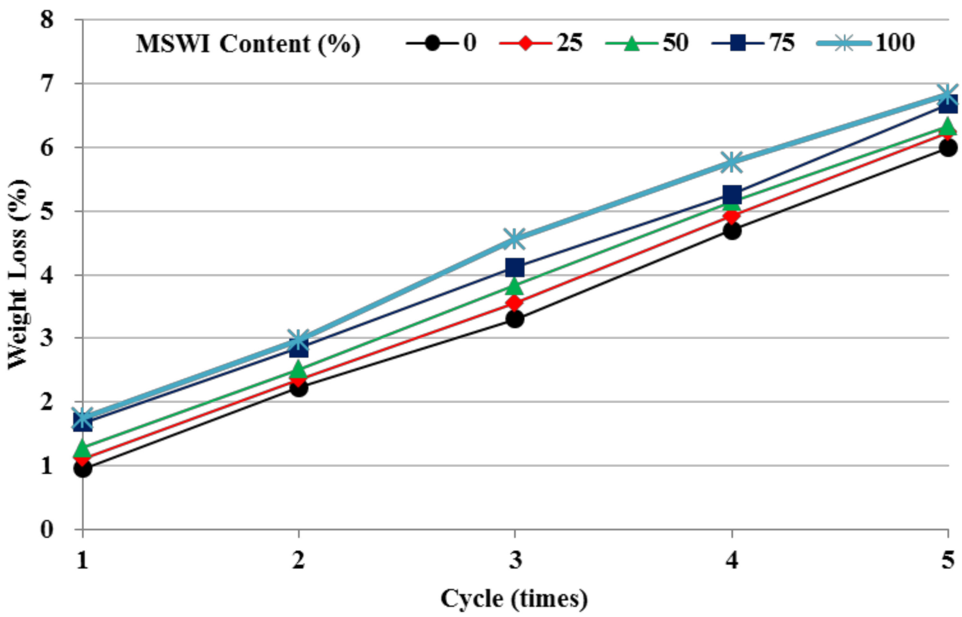
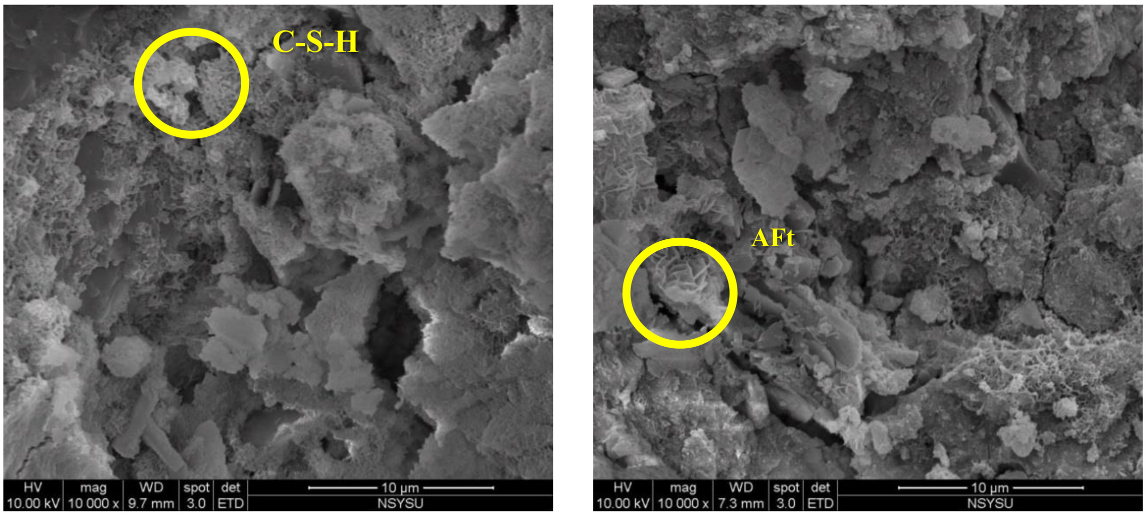


Figure 7. Effect of MSWI content on sulfate attack weight loss.

3.9. Microscopic Interfacial Properties

Figure 8 presents the SEM images of the specimens at a curing age of 28 d, revealing the microscopic interfacial properties of the control group (10% WFS, water-cement ratio of 1.6) and the specimen with 100% of its natural fine aggregate being replaced by MSWI bottom ash. The observed results revealed that the WFS and C-S-H gel stacked to form a pile. Because the WFS has a large specific surface area, the slurry structure was slightly compact when the WFS content was 10%. This result verified that the WFS effectively bonded with the slurry, thus increasing the compressive strength of the specimen. Observing the SEM image of the specimen containing 10% WFS and 100% MSWI bottom ash revealed that irregular, rose crystalline phase AFm, flaky CH crystal, and irregular, spike-shaped C-S-H gel were dispersed throughout the specimen. Hydration products were abundant. However, the C-S-H gel was not as intact as that in the control group.



(**a**) MSWI 0%, 28 days (**b**) MSWI 100%, 28 days

Figure 8. Scanning electron microscopy (SEM) image of MSWI CLSM (WFS10%).

4. Conclusions

1. The slump, slump flow, and tube flow of the CLSM in the current study were 26.8–26.5 cm, 65.3–56.9 cm, and 23.5–21.7 cm, respectively. The slump flow and tube flow values of all of the mixture proportions were within the regulated range, indicating the favorable workability of CLSM.
2. The control group reached the penetration value of 2.75 MPa the fastest (14.33 h). However, the time required to reach this value prolonged as the MSWI bottom ash replacement was increased.
3. The value of the ball drop test was 5–5.9 cm, satisfying the regulation of ASTM D6024.
4. To facilitate the subsequent excavation works in a construction process, the later-stage compressive strength of CLSM must be specified. The results of the current study showed that the compressive strength on Day 28 of curing was 6.25–5.87 MPa, satisfying the ASTM D4832 regulation of not exceeding 8.4 MPa. This result demonstrated that using recycled MSWI bottom ash in CLSMs is feasible.
5. In the future, waste incineration bottom slag can be expanded and applied to ready-mixed soil materials for feasibility evaluation of related experiments.

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