Geomechanics and Engineering, *Vol. 38, No. 6 (2024) 541-551*
https://doi.org/10.12989/gae.2024.38.6.541

Optimal mixing proportion of bottom-ash-based controlled low strength material for high fillability

Youngsu Lee[1a§], Taeyeon Kim[2b§], Bongjik Lee[3c] and Seongwon Hong[*4]

[1]Taeyoung E&C, 111 Yeouigongwon-ro, Seoul 07241, Korea
[2]Department of Civil and Environmental Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, USA
[3]Department of Civil Engineering, Korea National University of Transportation,
50 Daehak-ro, Chungju-si, Chungbuk 27469, Republic of Korea
[4]Department of Safety Engineering, Korea National University of Transportation,
50 Daehak-ro, Chungju-si, Chungbuk 27469, Republic of Korea

(*Received November 23, 2023, Revised February 2, 2024, Accepted February 6, 2024*)

Abstract. Bottom ash classifies as a hazardous industrial-waste material that adversely affects human health. This study proposes its mixing with controlled low strength materials (CLSM) as a probable recycling approach. To this end, experiments have been performed to investigate the applicability of bottom-ash-based CLSM that comprises eco-friendly soil binders, water, fly ash, and a combination of bottom ash and weathered granite soil. The physical and chemical properties of the weathered granite soil, bottom ash, fly ash, and soil binders are analyzed via laboratory tests, including X-ray diffraction and scanning electron microscopy. To determine an appropriate CLSM mixing proportion, the flowability test is first performed on three mixture types having three replacement ratios of fly ash each. Subsequently, compressive-strength tests are performed. Based on the results of these tests, four mixtures are selected for the freeze-and-thaw test to determine the appropriate mixing proportion. Finally, the ground model and soil-contamination tests are performed to examine the field applicability of the mixture. This study confirms that bottom-ash-based CLSM causes negligible soil contamination, and it satisfies the prescribed performance requirements and contamination standards in Korea.

Keywords: environmentally friendly soil binder; field applicability; freezing and thawing; ground model test

1. Introduction

With the recent expansion of urban areas and congestion caused by the proliferation of high-rise urban buildings, buried utility pipelines are preferred for water and sewage, natural gas, oil, electricity, and communication. However, the development of urban areas results in serious problems such as difficulty in compaction of soil around the underground facilities and reduced compaction efficiency. To avoid traffic disruption, most excavation activities in downtown regions are performed at night, thereby reducing construction quality. Furthermore, the overlapping of underground pipes during backfilling or reduction of the gap between pipe joints and lower portions of the pipes causes a drastic reduction in the compaction efficiency, thereby ultimately resulting in road subsidence. This phenomenon also occurs owing to backfilling of structures, such as box structures, retaining walls, and bridge abutments, which demonstrate poor compaction efficiency.

Coal ash is an industrial byproduct of a boiler, furnace, or thermal power plant. It is formed through the process of combustion and is called coal combustion residual (Rekha *et al.* 2016). Generally, two types of coal ash—fly ash and bottom ash—are produced. The recycling of fly ash has been extensively researched and the process is used in construction industries (Mohanty *et al.* 2017, Chenari *et al.* 2018). However, bottom ash cannot be recycled in most cases and is disposed at ash ponds. Considering the detrimental effect of bottom-ash accumulation on the environment, the global demand for its recycling has increased recently (Gullu and Fedakar 2017, Kim *et al.* 2018, Kumar and Rai 2022, Tran *et al.* 2023).

To solve the abovementioned issues, controlled low strength material (CLSM) is considered one of the most suitable options in the field. CLSM is a self-compacted and self-leveling cementitious composite, as defined by the American Concrete Institute (ACI) committee 229 (ACI. 229R-2, 2013). It offers the advantages of (1) self-leveling and self-compacting properties that reduce the time and cost of machine usage, thereby resulting in faster construction. (2) It is easy to excavate owing to the low strength of CLSM. (3) It can be mixed with industrial byproducts, which makes it possible to meet the increasing demand for recycling the latter. Typically, CLSM comprises cement, fine and coarse aggregates, water, and fly ash. Refined byproducts or recycled composites such as coal ash, bottom ash, slag, cement kiln dust, asphalt dust, and quarry waste have been mixed with the CLSM to satisfy the global

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*Corresponding author, Associate Professor
E-mail: shong@ut.ac.kr
[a] Project manager
[b] Research Associate
[c] Professor
[§] Both authors contributed equally to this manuscript

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

recycling demand (Naganathan *et al*. 2010, 2012a, b, Ling *et al*. 2018, Xia *et al*. 2021). Green *et al*. (1998) examined the applicability of a CLSM mixture consisting of Class C fly ash, portland cement, bentonite, and water to a tunnel excavation. The CLSM mixture successfully supported the tunnel excavation and there was no surface settlement on the ground (Ahmad *et al*. 2023). Gassman *et al*. (2001) investigated the quality of CLSM because quality control of CLSM is difficult in a construction site owing to construction delays and inappropriate water supply by truck operators. Gabr and Bowders (2000) conducted an experiment on a CLSM mix composed of AMD sludge, portland cement, Class F fly ash, and water to analyze its workability, excavatability, hardening time, and stability. Naik *et al*. (2003) used combined fuel ash (CFA) to produce the CLSM, and the test results indicated that the CFA based CLSM satisfied the ACI 229R-2 (2013) criteria. CLSM with cement kiln dust was tested by Pierce *et al*. (2003) to identify the engineering properties, including the 28-day unconfined compressive strength, volume stability (bleeding), setting time, mass density, and flowability. Katz and Kovler (2004) conducted experiments on CLSM added with cement kiln dust, asphalt dust, coal fly ash, coal bottom ash, or quarry waste to investigate the possibility of producing CLSM with those wastes. In 2009, Siddique used coal combustion products, spent foundry sand, cement kiln dust, wood ash, and rubber from scrap tire to produce the CLSM, and investigated the properties of the byproducts after their addition to the CLSM. Razak *et al*. (2009) examined a CLSM prepared with industrial-waste incineration bottom ash and found that incinerator bottom ash was a suitable industrial waste for producing CLSM. In a study by Lee *et al*. (2013), industrial byproducts were added to the CLSM to examine the fresh and hardened characteristics of an alkali-activated, cementless CLSM mixture. Kim *et al*. (2016) produced a CLSM combined with wastes such as ponded ash, fly ash, and excavated soil, and conducted tests to examine the bleeding, flowability, and initial setting time of the fresh mixtures and the compressive strength, water absorption, and corrosivity of the hardened CLSM. Park *et al*. (2017) reported the test results of circulating fluidized bed combustion (CFBC) based CLSM; CFBC can be utilized as a material source for producing the CLSM. Ahadzadeh Ghanad *et al*. (2020) mixed fine black spruce residual with CLSM and thoroughly examined the properties of the fresh and hardened mixture.

Because of the self-compacting properties of the CLSM, it may be possible to use it in places where it is impossible to compress the structural fill or backfill, e.g., a very narrow trench. Because the range of compressive strength of the CLSM is between 0.7 and 8.3 MPa, it can be employed as a bedding substance in a shallow foundation by providing a uniform surface. In addition to self-leveling and compacting, flowability is an important property of CLSMs. Old tunnels and sewers comprise numerous voids around underground structures. A flowable CLSM can easily penetrate the soil and fill such voids (Green *et al*. 1998). Despite numerous investigations being undertaken on CLSMs, no prior study has reported the use of laboratory tests to identify the compressive strength of bottom-ash-based CLSM mixtures comprising eco-friendly soil binders. Moreover, the degree of soil contamination after a significant aging period—as per Korean standards—caused by the use of such a mixture has not been reported in prior studies. This study addresses these gaps in existing literature. To investigate the field applicability of the bottom-ash-based CLSM, the flow characteristics and change in strength of the CLSM were identified experimentally. Subsequently, based on the test results obtained in this study, the optimum mixing proportion has been determined in this study. Furthermore, the field applicability of the bottom-ash-based CLSM mixture has been examined in the light of the ground-model and soil-contamination tests. The findings of this study confirm that the bottom-ash-based CLSM has no harmful effects on soil.

2. CLSM Design Criteria

2.1 Background of CLSM design criteria

According to the ACI committee 229 (ACI 229R-2, 2013), CLSM is defined as a self-leveling and self-compacted cementitious composite, which is also known as flowable, unshrinkable, or controlled density fill (it is sometimes called flowable mortar, plastic soil cement, soil–cement slurry, flowable fly ash, or fly ash slurry). It is mainly employed as a backfill geomaterial in place of general fills. To be categorized as CLSM, the unconfined compressive strength of the material should be 8.3 MPa or less at 28 days and the uniaxial compressive strength is required to be below 2.1 MPa in consideration of future re-excavation. However, several strength criteria have been proposed recently. The typical strength range for CLSM applied in the field is 0.35 to 0.70 MPa (ASTM D4832, 2016; ASTM D6103, 2004), and ACI committee 229 (ACI 229R-2, 2013) mentions that a compressive strength of CLSM ranging from 0.3 to 0.7 MPa corresponds to the allowable bearing capacity of well-compacted soil. The Transportation Research Board (2008) specified that the compressive strength of the CLSM should be between 0.35 and 1.0 MPa, and some researchers suggest uniaxial compressive strength in the range of 0.3 to 1.1 MPa, considering future excavation ease and sufficient strength(Trejo *et al*. 2004, Ling *et al*. 2018). ASTM D6103 (2004) specifies the typical value of the flowability of an open-end flow cylinder of 150 mm length and 75 mm diameter as 150–200 mm. In Japan, the CLSM called "liquefied stabilized soil" is commonly used; it is generally manufactured in the form of slurry by mixing water and hardening agent in the soil in situ. The strength of the liquefied stabilized soil used in Japan varies widely between 0.1 and 0.6 MPa; backfilling of buried pipes under roadways requires strength of 0.14 MPa or more immediately after traffic resumption and 0.6 MPa or less at 28 days. The strength requirement for a filler used for filling a small-scale cavity is 0.3 MPa or higher, and for that used for filling an underground cavity is 0.1 MPa or higher(Mizuguchi *et al*. 2004). JHS A 313 (1992) requires flowability of 110–200 mm or higher, and

Table 1 Physical properties of weathered granite soil and bottom ash

Description	Symbol	Unit	Weathered granite soil	Bottom ash	fly ash
Specific gravity	G_s	-	2.68	2.07	2.63
Effective particle size	D_{10}	mm	0.03645	0.112012	0.00972
D_{30} particle size	D_{30}	mm	0.09958	0.204833	0.022
D_{60} particle size	D_{60}	mm	0.19389	0.395106	0.0487
Uniformity coefficient	C_u	-	5.31	3.53	5.01
Coefficient of curvature	C_c	-	1.40	0.95	1.02
Soil classification	USCS		SM	SP	ML
Liquid limit	LL	%	21.33	-	48.00
Plastic limit	PL	%	20.44	-	-
Plasticity index	PI	%	0.89	-	-
OMC	w_{OMC}	%	10.78	-	-
Max. dry density	$\gamma_{d\,\max}$	kN/m^3	19.0	-	-

applications such as underground spaces and small-scale cavities require a filling material with high flowability of 200 mm or higher (Lee *et al*. 2018).

2.2 Application criteria

Recently, many researchers have proposed various criteria for the strength of CLSM, and related content has been added to Section 2.1 Background of CLSM Design Criteria. In this study, we referred to various CLSM strength standards. The uniaxial compressive strength of CLSM after curing for 28 days was set to 0.7 MPa or less, which is the maximum strength commonly applied, allowing for various CLSM applications and future excavation. In addition, to shorten construction due to rapid curing, we've set a criterion for the uniaxial compressive strength after 7 days of curing, setting it to a minimum of 0.3 MPa. This value falls within the commonly applied strength range for on-site applications, allowing the use of CLSM from the 7th day after curing. The strength criterion after 1 day of curing was established at 0.14 MPa or higher, based on the Japanese CLSM design standard, representing the minimum strength required for vehicle traffic.

3. Experimental procedure

In this study, the optimum mixing proportions of the bottom-ash-based CLSM and eco-friendly soil binder were determined by performing the flowability and compressive-strength tests. Subsequently, the field applicability of CLSM was analyzed based on the results of the repeated freeze-and-thaw, ground-model, and soil-contamination tests.

3.1 Materials

Weathered granite soil was selected to investigate the field applicability of bottom-ash-based CLSM; the soil was sampled at depths of 0.8–1.0 m at Chungju-si, Chungcheongbuk-do, South Korea. The particle size distribution curves and physical properties of weathered granite soil, bottom ash and fly ash are presented in Fig. 1 and summarized in Table 1. Fig. 2(a) shows the x-ray diffractometer (XRD, SCINTAG model XDS 2000) analysis results of weathered granite soil, which had SiO2 and AI2O3 contents of 64.9% and 16.5%, respectively.

The bottom ash used in this study was an industrial by-product from Yeongheung power station. It was processed into a particle diameter of 2 mm or less with a grinder and added to the CLSM mixture as a powder. The particle distribution curve and XRD results of bottom ash are depicted in Figs. 1 and 2(b), respectively, where the SiO2 and AI2O3 contents are 54.6% and 23.4%, respectively. The fly ash used in this study is a commercially available product produced in Korea for use as a concrete admixture. The particle size distribution curves and XRD results of the fly ash used in this study are shown in Figs. 1 and 2(c), respectively, where the SiO2 and AI2O3 contents are 37.3% and 23.9%.

Ultra-high-resolution field emission scanning electron microscope (SEM, JEOL model JSM-7610F) was employed for further investigation of the properties of bottom ash and fly ash, as presented in Fig. 3. The porous structures with angular and rough surface of bottom ash and smooth spherical shape of fly ash were clearly observed. Tables 1 and 2 list the physical and chemical properties of bottom ash, respectively. The chemical properties of fly ash, which is added to the mixture, are also summarized in Table 2. The specific gravity of fly ash equals 2.21.

The eco-friendly soil binder used in this study was prepared by mixing porous silica (SiO2) and calcium carbonate (CaCO3) to replace portland cement. The physical and chemical characteristics of the binder are summarized in Table 3. The eco-friendly binder has a composition similar to that of general low-heat cement and has excellent initial strength. Furthermore, harmful substances such as lead and cyanide contained in the soil binder were not measured in the dissolution test. The binder has the advantage of low pH when compared with cement.

To study the optimal mixing proportion of bottom-ash-based CLSM, nine cases (three mixtures types with three

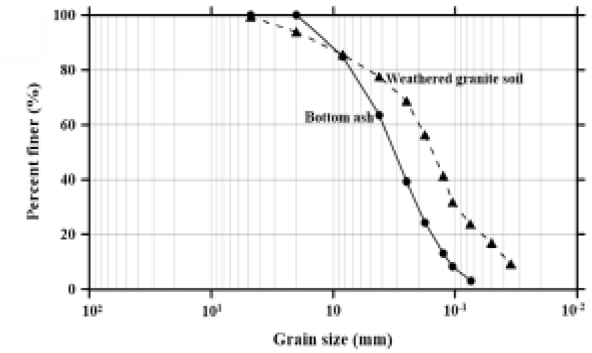
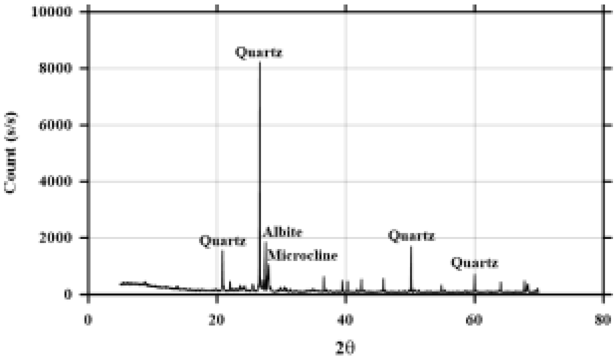
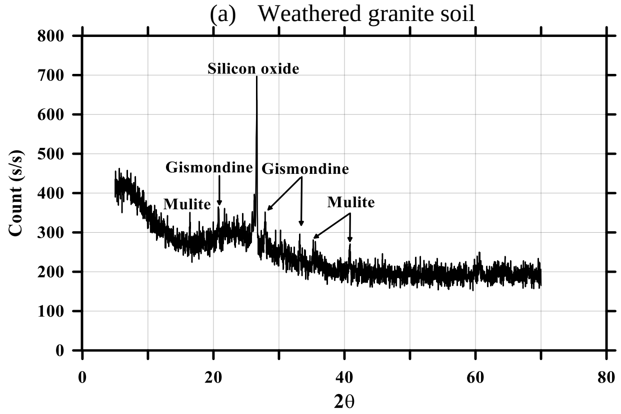


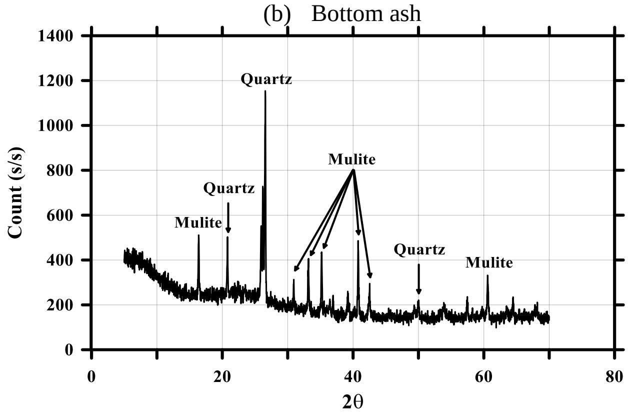
Fig. 1 Particle size distribution curves of weathered granite soil and bottom ash



(a) Weathered granite soil



(b) Bottom ash



(c) Fly ash

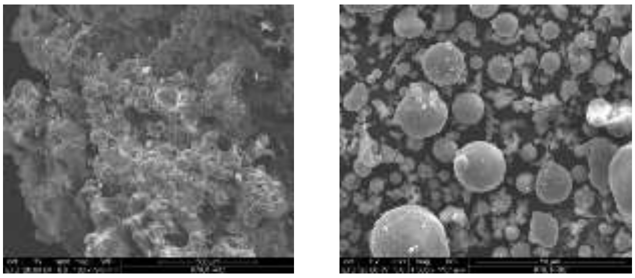
Fig. 2. XRD analysis results: (a) weathered granite soil and (b) bottom ash (c) fly ash

Table 2 Chemical properties of bottom ash and fly ash

Chemical component	Bottom ash (%)	Fly ash (%)
SiO_2	54.6	37.3
Al_2O_3	23.4	23.9
Fe_2O_3	8.6	3.38
MgO	4.97	0.533
CaO	1.5	1.95

Table 3 Physical and chemical characteristics of eco-friendly soil binder [7]

Chemical composition (%)		Physical properties		
SiO_2	20.07	Specific gravity		3.08
Al_2O_3	5.21	Blaine (cm^2 / g)		120
Fe_2O_3	2.96	Hydration heat(cal / g)		14
MgO	2.67	pH		11
CaO	63.08	Setting time (min)	Initial	50
SO_3	2.98		Final	75
IG-LOSS	2.67			



(a) Bottom ash (b) Fly ash

Fig. 3 SEM images of (a) bottom ash and (b) fly ash

replacement ratios of fly ash) of mixture proportions were prepared, as summarized in Table 4. Once the proper amount of water content was determined through flowability tests, 27 cases (three mixtures types with three replacement ratios of fly ash and three dosages of the eco-friendly binder) of uniaxial compressive strength tests were conducted to investigate theappropriate mixture proportion for field application. The samples was cured in the environmental chamber at temperature of 21 ± 1℃, humidity of 95±2%.

3.2 Mixture proportions for field application

The flowability test was conducted in accordance with ASTM D6103 (2004) to determine the appropriate water content to satisfy the high flowability criterion of CLSM. During the test, a flow cylinder with diameter of 76 mm and height of 150 mm was placed on a non-absorbent square plate with dimensions of 600 × 600 mm and filled with the mixed CLSM sample without any compaction, as shown in Fig. 4. Subsequently, the round mold was raised vertically for two–four seconds, and the largest flow diameter of the sample and its perpendicular diameter were measured; the average of the two diameters was calculated for the flow value, and the water content of the sample was then determined. The

Table 4 Mixture proportions of CLSM (mass fraction)

Mixture type	Aggregate		Replacement ratio of fly ash (%)	Eco-friendly soil binder (%)[†]
	Bottom ash(%)	Weathered granite soil(%)		
B25W75F00SB3	25	75	0	3
B25W75F00SB5	25	75	0	5
B25W75F00SB7	25	75	0	7
B25W75F10SB3	25	75	10	3
B25W75F10SB5	25	75	10	5
B25W75F10SB7	25	75	10	7
B25W75F20SB3	25	75	20	3
B25W75F20SB5	25	75	20	5
B25W75F20SB7	25	75	20	7
B50W50F00SB3	50	50	0	3
B50W50F00SB5	50	50	0	5
B50W50F00SB7	50	50	0	7
B50W50F10SB3	50	50	10	3
B50W50F10SB5	50	50	10	5
B50W50F10SB7	50	50	10	7
B50W50F20SB3	50	50	20	3
B50W50F20SB5	50	50	20	5
B50W50F20SB7	50	50	20	7
B75W25F00SB3	75	25	0	3
B75W25F00SB5	75	25	0	5
B75W25F00SB7	75	25	0	7
B75W25F10SB3	75	25	10	3
B75W25F10SB5	75	25	10	5
B75W25F10SB7	75	25	10	7
B75W25F20SB3	75	25	20	3
B75W25F20SB5	75	25	20	5
B75W25F20SB7	75	25	20	7

* Curing period (days) : 1 day, 7day, 28day

[†] Mixture proportion only for uniaxial compression test

(a) Cylindrical mold with square plate

(b) Cylindrical mold filled with CLSM

(c) Spread CLSM

Fig. 4 Flowability tests: (a) Cylindrical mold with square plate, (b) cylindrical mold filled with CLSM, and (c) spread CLSM

(a) Outside environmental chamber (b) Inside environmental chamber

(c) Spread CLSM

Fig. 5 Compressive strength tests: (a) outside the environmental chamber, (b) inside the environmental chamber, and (c) specimen after test completion

abovementioned steps were repeated by increasing the water content and three flow values were measured for each value of the water content. When the flow values were more than 10%, a retest was performed for reliability.

Cylindrical specimens with height of 200 mm and diameter of 100 mm were fabricated in accordance with ASTM D4832 (2016). After mixing, demolding was performed at one day of curing, and the specimens were stored and cured in a computer controlled environmental chamber (DONG AH TESTING MACHINE, DA-355-02) at constant temperature of 20±1 °C and constant relative humidity of 100±5% until the target age (see Fig. 5). Strain-controlled compression tests were conducted at the strain rate of 2 mm/min.

3.3 Evaluation of field applicability

Freezing and thawing, ground model, and soil contamination tests were performed to evaluate the field applicability of the CLSM. First, to assess the change in strength of the CLSM due to the repeated freeze–thaw cycles, a mixing ratio suitable for the CLSM criteria was selected, and the specimen was prepared using the same mold as that used for the uniaxial compressive strength test. It was cured in water maintained at 20±1°C for seven days, after which the test was conducted in an environmental chamber (SAM HUNG MACHINERY CORP., SH-CNT-3) in accordance with ASTM D560-03 (2003). One cycle of freezing–thawing was repeated 12 times by freezing at −21°C for 24 h and then thawing at 21°C for 24 h, and three uniaxial compressive strength tests were performed for each cycle to evaluate the strength. Second, ground model tests were performed to evaluate the capability of the CLSM prepared at the optimal mixing ratio as the backfill material to fill empty underground spaces between and/or around the buried pipes appropriately. Fig. 6 depicts the schematic diagram, panoramic view, and detailed dimension of the container box and locations of the paper molds. The container box was made from a transparent acrylic plate with 8 mm thickness to observe the filling capability of the CLSM. Two boxes were prepared for testing the CLSM condition at 1 day and 28 days. After placing the bottom-ash-based CLSM in the box, the paper molds were inserted at each location by pushing them with constant loads. The unit weight of the CLSM in the slurry state and the weight of the CLSM filling in the ground model test were compared. In addition, to measure the strength of the CLSM at different depths, twelve paper molds with diameter of 50 mm and height of 100 mm were inserted in the model ground at depths of 100 mm, 250 mm, and 400 mm from the top of the box (see Figs. 6(f)-6(h)), and the uniaxial compressive strength was measured at 1 day and 28 days of age. Finally, to evaluate the environmental contamination that can occur when bottom-ash-based CLSM is employed as the backfilling material, soil contamination test of the CLSM with the optimal mixing ratio was carried out at 28 days according to the Soil Environment Conservation Act of South Korea (2017).

4. Results and discussion

4.1 Flowability

Flowability tests were performed to investigate the flow characteristics of the CLSM and to determine the optimal

(a) Schematic diagram (b) Panoramic view

(c) Front view of container box (d) Side view of container box

(e) Plan view of container box (f) Front view of paper mold location

(g) Side view of paper mold location (h) Plan view of paper mold location

Fig. 6 Model test: (a) schematic diagram, (b) panoramic view, (c) front view of container box, (d) side view of container box, (e) plan view of container box, (f) front view of paper mold location, (g) side view of paper mold location, and (h) plan view of paper mold location

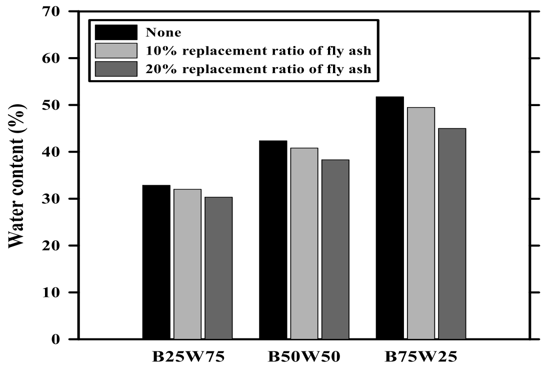
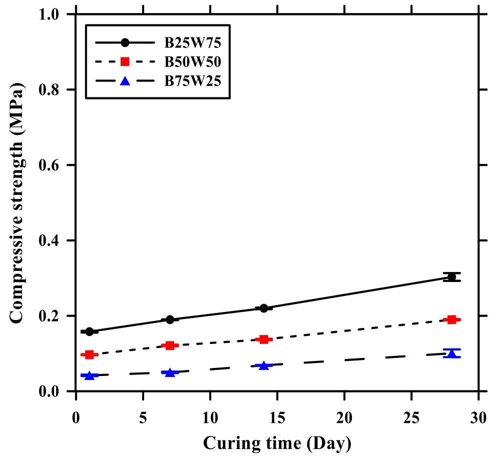


Fig. 7 Variation in flow-test results based on different concentrations of bottom-ash addition

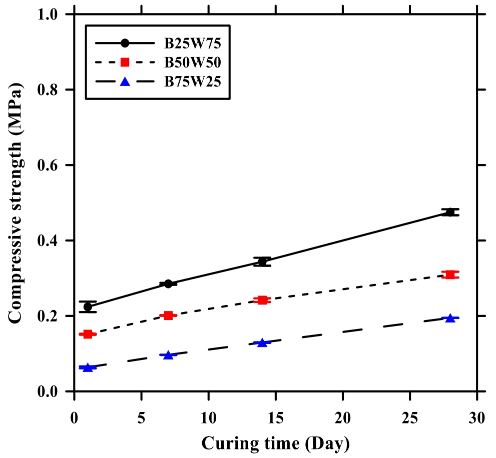
water content for each mixture type with different replacement ratios of fly ash. Fig. 7 demonstrates the water content required for the flowability criterion [flow value of 200 mm (ASTM D6103, 2004)]. The water contents of BA25WGS75, BA50WGS50, and BA75WGS50, which satisfied the flowability criterion without replacement of fly ash, were measured to be 32.86%, 42.36%, and 51.75%, respectively. It was observed that the water content increased with increasing quantity of bottom ash. The main reason for this phenomenon is that the bottom ash used as the aggregate has a porous structure with a large specific surface area due to unburned carbon and contains calcium oxide components with good water absorption. Furthermore, the water content required for the minimum flowability criterion decreased as the replacement ratio of fly ash increased. This is because the quantity of bottom ash is reduced, as it is partially replaced with fly ash, which has smaller particles with a more spherical formation. In contrast, the bottom ash can absorb water to fill the porous structures and impede the water flow due to its angular and rough shape.

4.2 Compressive strength

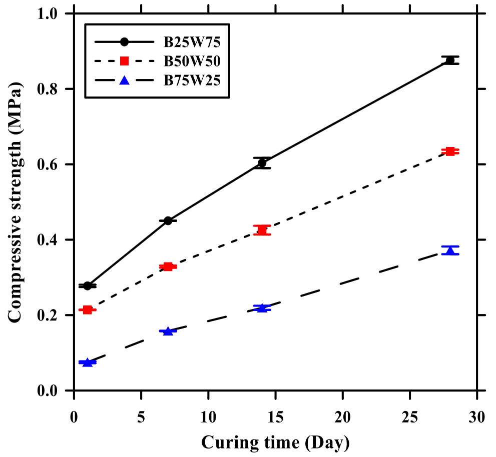
Fig. 8 presents the compressive strength of the CLSM according to the curing time. It was found that the compressive



(a) Addition of 3% soil binder

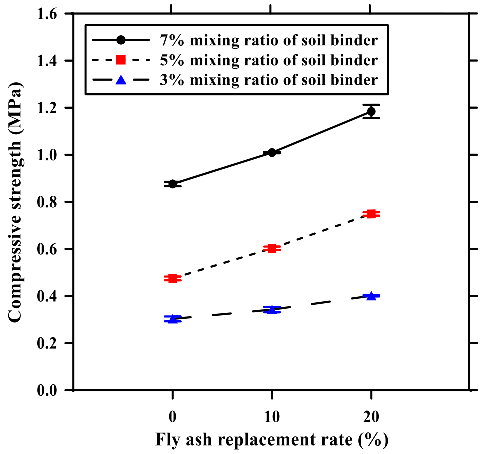


(b) Addition of 5% soil binder

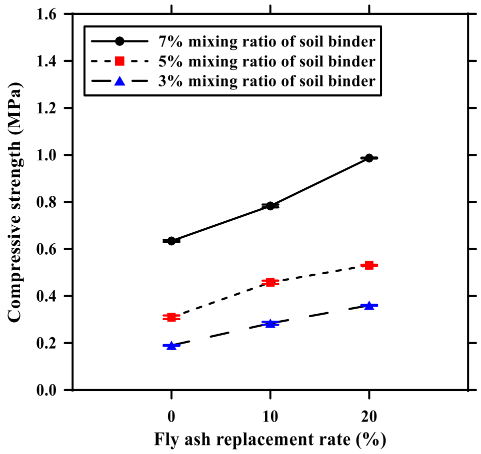


(c) Addition of 7% soil binder

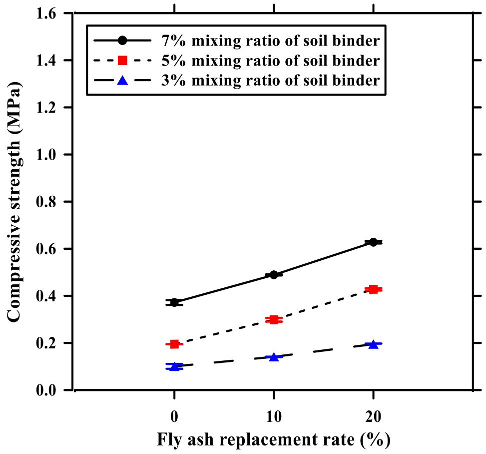
Fig. 8 Compressive strength variation with curing time



(a) B25W75



(b) B50W50



(c) B75W25

Fig. 9 Compressive strength variation based on fly-ash replacement ratio

strength increased as the ratio of the environmentally friendly soil binder increased, whereas the strength decreased when the bottom-ash mixing ratio increased. Moreover, the rate of increase of strength according to the age of the specimen also decreased with increasing mixing ratio of bottom ash. This tendency was clearly observed when the addition ratio of the environmentally friendly soil binder was increased. This is because the sulfate produced by sulfur trioxide in the bottom ash hinders the hydration reaction (Irassar *et al*. 2005). Fig. 9 shows the compressive strength at 28 days of aging according to the replacement ratio of fly ash for the same mixing ratio of bottom ash. As the mixing ratio of the bottom ash and addition ratio of the environmentally friendly soil binder were the same, the increase in compressive strength was attributed to the increase in the fly ash replacement ratio. This tendency became more prominent when the addition ratio of the environmentally friendly soil binder and bottom ash aggregate ratio were increased. The primary reason for this trend was that the production of sulfate, which hinders the hydration reaction, was reduced due to the substitution of bottom ash with fly ash,

Table 5 Four mixture proportions for repeated freezing and thawing test (mass fraction)

Mixture type	Aggregate		Replacement ratio of fly ash (%)	Eco-friendly soil binder (%)	Water content (%)
	Bottom ash (%)	Weathered granite soil (%)			
B25W75F10SB5	25	75	10	5	32.00
B50W50F20SB5	50	50	20	5	38.29
B50W50F00SB7	50	50	0	7	42.36
B75W25F20SB7	75	25	20	7	45.00

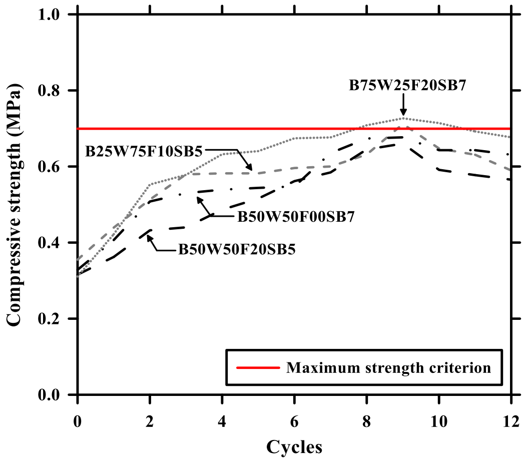


Fig. 10 Change in strength due to repeated freeze–thawing

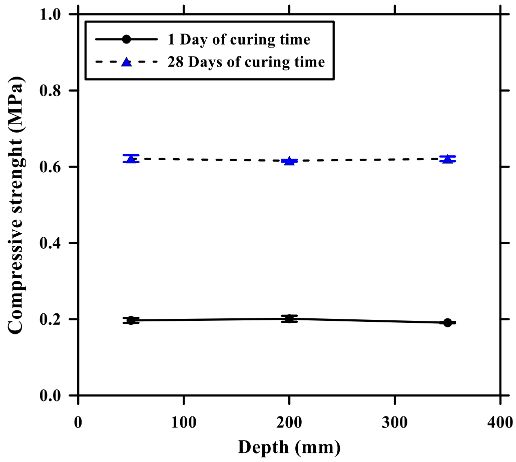


Fig. 11 Compressive strength variation of CLSM with soil depth

and the hydration reaction and polymerization reaction were further activated by the addition of fly ash (Lim *et al.* 2016). Based on the test results of uniaxial compressive strength to determine a suitable soil binder addition ratio and mixing ratio for the CLSM criteria, four mixture proportions of the bottom-ash-based CLSM were selected for the repeated freezing and thawing tests, as summarized in Table 5.

4.3 Changes in compressive strength due to repeated freezing–thawing

To investigate the changes induced by the repeated freeze¬–thaw cycles in the compressive strength of the bottom-ash-based CLSM, the test specimens were prepared using the same mold used during the compressive-strength test. Fig. 10 displays the changes in the compressive strength, induced by repeated freeze–thaw loadings. It can be clearly observed that the strength of the CLSM increased up to nine cycles and then decreased until the 12th cycle. In addition, the maximum strength of all four specimens applied with repeated freeze–thaw loadings was slightly higher than that of the specimens produced under the same mixing conditions with wet curing for 28 days, indicating that there was no influence of the repeated freezing–thawing of the bottom-ash- based CLSM. In particular, the maximum strength of B25W75F10SB5 and B75W25F20SB7 slightly exceeded the standard maximum strength (0.7 MPa), suggesting that it would be difficult to utilize them in this study. Therefore, B50W50F20SB5 and B50W50F00SB7 were used for the ground model test. However, B50W50F20SB5 requires additional processing to replace the bottom ash partially with fly ash. Accordingly, considering the range of the compressive strength and the utilization of bottom ash among the four mixing ratios that meet the CLSM criteria, the mixing ratio of B50W50F00SB7, in which the addition ratio of the environmentally friendly soil binder is 7% and the appropriate mixing ratio of bottom ash and weathered granite soil is 50:50, is optimal.

4.4 Results of ground model test

Ground model tests were performed to assess the fillability and changes in strength according to the depth after casting of B50W50F00SB7. Through the ground model test, almost 100% fillability was observed and the changes in strength according to depth were negligible, as exhibited in Fig. 11. The coefficient of variation for the compressive strength tests was calculated to be less than 3%, indicating the reliability of the test results. Furthermore, compared to the uniaxial compressive strength assessed using the mold, the mixture demonstrated corresponding strength values of 91.8% and 97.65% after 1 and 28 days of aging, respectively, thereby indicating that the application of bottom-ash-based CLSM would not lead to problems related to fillability and strength. The unit weight of the bottom-ash- based CLSM in the slurry state was measured to be 16.16 kN/m3. The amount of CLSM used in the ground model test was 1.73 kN and its volume was 1066.26 m3; thus, the unit weight was determined to be 16.19 kN/m3, which signified that there was no difference between the two states.

4.5 Soil contamination test

Soil contamination test of the bottom-ash-based CLSM

Table 6 Results of soil contamination test of CLSM with B50W50F00SB7

Elements	Criteria (mg/kg)			Detected contaminant (mg/kg)
	Zone 1	Zone 2	Zone 3	
Copper	150	500	2,000	15.6
Lead	200	400	700	6.2
Zinc	300	600	2,000	41.2
Nickel	100	200	500	11.2
Fluorine	400	400	800	276

Note: Zone 1 represents agricultural land, school zone, and residential zone; Zone 2 represents sports ground and amusement parks; Zone 3 represents road, railroads, parking lots, and plant sites

prepared with the optimal mixing proportion (B50W50F00SB7) was conducted and the results were compared with the soil contamination standard stipulated in the Soil Environment Conservation Act of South Korea. Totally, 22 types of contaminants were examined and 17 of them were not detected at all. (The 17 contaminants were cadmium, arsenic, mercury, hexavalent chrome, organophosphorous compound, polychlorinatedbiphenyls, cyanogen, phenol, benzene, toluene, ethylbenzene, xylene, total petroleum hydrocarbons, trichloroethylene, tetrachloroethylene, benzo(a)pyrene, and 1,2-dichloroethane.) Table 6 shows the detected contaminants and their quantities. The results were obviously within the soil contamination standard.

5. Conclusions

This study proposes the use of a mixture of bottom ash and CLSM as an appropriate means to recycle the former, which classifies as a hazardous industrial waste. Accordingly, laboratory tests have been conducted to investigate the feasibility and field applicability of bottom-ash-based CLSM mixture. Based on the experimental results and extensive analysis of the CLSM according to different mixing ratios, the following conclusions can be drawn;

- The test results for the flowability of CLSM of different mixing ratios indicate that the water content that satisfies the minimum flowability criterion increases with increase in the bottom-ash mixing ratio. Moreover, at constant bottom-ash mixing ratio, the flowability decreases with increase in the fly-ash replacement ratio.
- According to the experimental data for the uniaxial compressive strength, increasing the amount of bottom ash decreases the mixture strength. Moreover, when the bottom-ash mixing ratio remains constant, the strength increases with increase in the concentration of the environment-friendly soil binder and fly ash replacement ratio.
- The compressive-strength results obtained via the freeze–thaw tests reveal that the maximum strength of the specimens slightly exceeds the strength of those produced under the same mixing conditions and wet cured for 28 days. This indicates no effect on the change in compressive strength due to the freeze–thaw cycles
- As regards the range of strength development and bottom-ash content in the CLSM mixture, the suitable mixing proportion comprises equal quantities of bottom ash and weathered granite soil, no fly ash replacement, and 7% additional ratio of the environment-friendly soil binder (mixture type: B50W50F00SB7).
- The ground model tests reveal that the optimal mixing proportion (B50W50F00SB7) of the CLSM demonstrates full fillability along with strength development of up to 91.8% and 97.65% of the equivalent uniaxial strength after 1 and 28 days of aging, respectively. Moreover, no changes are observed in the strength with soil depth. Furthermore, the results of the soil-contamination tests reveal the detected contaminants to remain within their respective acceptable limits.

Acknowledgments

This research was supported the Mid-Career Researcher and Young Researcher Program through the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT; Ministry of Science and ICT) (2023R1A2C2006400, 2021R1C1C1010087) and Basic Science Research Program through the NRF funded by the Ministry of Education (2021R1A4A2001964). We greatly appreciate the support.

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