Title

Development of High-Performance Fly-Ash-Based Controlled Low-Strength Materials for Backfilling in Metropolitan Cities

Journal
Applied Sciences, 13(16)

ISSN
2076-3417

Authors
Han, Jingyu
Jo, Youngseok
Kim, Yunhee
et al.

Publication Date
2023

DOI
10.3390/app13169377

Peer reviewed

applied sciences

MDPI

Article

Development of High-Performance Fly-Ash-Based Controlled Low-Strength Materials for Backfilling in Metropolitan Cities

Jingyu Han [1], Youngseok Jo [2], Yunhee Kim [3] and Bumjoo Kim [3,*]

[1] Department of R&D, Chemius Korea Co., Ltd., Suncheon 57942, Republic of Korea
[2] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720, USA
[3] Department of Civil and Environmental Engineering, Dongguk University, Seoul 04620, Republic of Korea
* Correspondence: bkim1@dongguk.edu

Abstract: Controlled low-strength materials (CLSMs) have been developed using various byproducts for backfilling or void-filling around pipelines or culvert boxes. However, these CLSMs have encountered issues related to their inadequate placement around underground facilities, despite satisfying the performance requirements, especially flowability, recommended by the American Concrete Institute (ACI) 229 committee. In this study, a new CLSM is developed to ensure a significantly higher flowability, lower segregation, and faster installation compared with previously developed CLSMs. This is achieved through a series of laboratory tests. To enhance the flowability and prevent segregation, a calcium-sulfoaluminate-based binder and fly ash are used in combination with two types of additives. The measured flowability of the new CLSM is 700 mm, while its compressive strength and bleeding satisfy the general criteria specified by the ACI 229R-13. In addition, the performance of the developed CLSM is compared with that of predeveloped CLSMs. The new CLSM was not only shown to exhibit the highest flowability, but also to satisfy the specified requirements for compressive strength and bleeding. Overall, it is anticipated that the developed CLSM can significantly reduce the costs related to the disposal of old pavements, the installation of new pavements, and other construction expenses compared to the costs related to the conventional method, even though the expenses for the backfill materials could increase due to the higher production costs of CLSMs than soil. In addition, there is a need to investigate its field applicability in order to evaluate the precise costs, maintenance, and long-term stabilities after installation.

Keywords: controlled low-strength material; high flowability; backfilling; fly ash; calcium-sulfoaluminate-based binder

Citation: Han, J.; Jo, Y.; Kim, Y.; Kim, B. Development of High-Performance Fly-Ash-Based Controlled Low-Strength Materials for Backfilling in Metropolitan Cities. *Appl. Sci.* **2023**, *13*, 9377. https://doi.org/10.3390/app13169377

Academic Editor: José Manuel Moreno-Maroto

Received: 16 July 2023
Revised: 10 August 2023
Accepted: 13 August 2023
Published: 18 August 2023

1. Introduction

In metropolitan cities, ground sinking generally occurs due to the deterioration, cracking, and breakage of sewage pipes (Figure S1), as well as the inadequate compaction of backfill materials (Figure S2). These factors can lead to the formation of void spaces around sewage pipes and culvert boxes. Subsequently, ground sinking occurs as void spaces become larger. Jo et al. [1] reported that the vibration transmitted by vehicles in metropolitan cities could cause the collapse of enlarged underground void spaces. The conventional method involves compacting well-graded soils around sewage pipes or culvert boxes using mechanical equipment (e.g., a vibrator) to prevent ground sinking. However, due to the limitation of mechanical equipment, the area adjacent to sewage pipes and culvert boxes is typically left uncompacted, in some cases leading to ground sinking. The foregoing is recognized as one of the causes of ground sinking in metropolitan cities. Accordingly, the utilization of controlled low-strength materials (CLSMs) has emerged as a highly effective solution for backfilling or void-filling around pipelines or culvert boxes and underneath roads.

The American Concrete Institute (ACI) 229 committee defined CLSMs as self-compacting cementitious backfill materials. Other terms used to describe CLSMs include flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil cement, soil–cement slurry, and K-Krete. CLSMs have been widely used for numerous applications (e.g., backfilling, road bases, pipeline and culvert filling, void filling, tank fills, insulation, and isolation filling) in lieu of conventional compact fillers [2–5]. Table 1 summarizes the guidelines set out by the ACI 229R-13 that need to be satisfied by each CLSM application. In accordance with these guidelines, CLSMs should exhibit a high flowability, low bleeding, early cementation, and sufficient strength [3,6,7]. The ACI 229R-13 document [8] is not only the main guideline used in the USA, but has also been widely referenced in many countries. Ling et al. [9] also noted that apart from the USA, there have been no specific standards or CLSM specifications published by other countries. Therefore, many countries have developed their own CLSM guidelines based on the ACI 229R-13 document.

Table 1. General criteria and requirements for CLSM application and target performance in this study.

References	CLSM Application	Criteria and Requirements to Be Fulfilled
ACI 229R-13	General backfilling (void filling, filling abandoned underground structures, etc.)	High degree of flowability (>200 mm spread) Setting time and early strength are not critically essential Twenty-eight-day compressive strength should be less than 0.5 MPa
	Excavatable backfilling (underground water, sewer and storm drainage pipelines, roadway trenches, etc.)	High degree of flowability Less subsidence and quick setting time Easy to re-excavate—manually or mechanically Twenty-eight-day compressive strength should be less than 2.1 MPa
This study (Target performance)	General and excavatable backfilling (void filling)	Considerably high degree of flowability (>400 mm spread) Less subsidence (<5% bleeding) Quick setting time (>0.1 MPa at 4 h) Easy to re-excavate—manually Twenty-eight-day compressive strength $\leq$ 1.0 MPa

Since the 2000s, previous researchers have developed CLSMs using various waste materials/industrial byproducts (e.g., fly and bottom ashes, ground granulated blast furnace slag, waste foundry sand, cement kiln dust, steel slag, waterworks and paper sludges, waste rubber tires, and red mud) [7,10–29]. However, the application of these previously developed CLSMs to underground facility backfilling has been challenging due to three primary reasons: (a) previous CLSMs have relatively long durations for hardening; (b) poorer flowability than grout mortar; (c) large equipment is needed for the placement of CLSMs. In addition, these CLSMs only satisfied the acceptable level of flowability recommended by the ACI 229R-13 (i.e., more than 200 mm spread, as listed in Table 1) [5,6,11,23,30–33].

Even though the performance of predeveloped CLSMs satisfied the requirements set out by the ACI 229R-13, especially flowability, those CLSMs could lead to problems of insufficient placement around underground facilities (i.e., pipes and culverts) and cause inconvenience to citizens in metropolitan cities due to the relatively long hardening time [5,6,23,34]. Therefore, there is a need to develop a new CLSM with much higher performance (i.e., high flowability, low bleeding/segregation, and quick setting time) than predeveloped CLSMs.

In this study, a new CLSM with high flowability, low segregation, and quick setting time is developed. The target performance criteria for the developed CLSM are summarized in Table 1. In particular, the water volume increased and the materials (i.e., binder and byproduct) volume was minimized in order to facilitate the placement of the CLSM. To achieve the foregoing, a series of laboratory tests were conducted to measure the flowability, density, bleeding, and compressive strength of the new CLSM in accordance with test standards [35–38]. A sensitivity analysis was performed to compare the flowability, bleeding, and compressive strength of the new CLSM according to the water–material ratio

(W/M). Finally, the performance of the newly developed CLSM was compared with that of predeveloped CLSMs based on soils and bottom ash collected in South Korea.

2. Materials and Methods

2.1. Preparation of Binder

A CLSM is typically composed of a binder, cement, byproduct materials (e.g., bottom/fly ashes and other recycled materials), an aggregate, and water. Schmitz et al. [39] reported that the characteristics of CLSMs can vary depending on the type of binder. In this study, calcium sulfoaluminate (CSA) was selected as the primary binder due to its quick hardening and early strength characteristics. Table 2 summarizes the amounts of CSA, anhydrous gypsum (AG), and water used to determine the optimal mixture ratio for the binder. To enhance the early strength and quick hardening, CSA and AG, with relatively high specific surface areas (more than 500 m^2/kg), were used. The powders were premixed and then mixed with water for 2 min. The paste was cured in a 50 mm cubic square mold at ambient conditions. The early compressive strength of the binder specimen was tested at 4 h from mixing in the water. The amount of water was fixed, and AG was used to supply sulfate ions (SO_4^{2-}), which could produce ettringite by reacting with CSA. Ordinary Portland cement (OPC), classified as a type 1 cement, was added into the CSA mixtures (i.e., CSA-6~10) in order to accelerate the generation of ettringite. Figure 1a shows the binder specimens manufactured based on the mixture proportions in Table 2.

Table 2. Mix proportions of CSA-based binder for each specimen.

Specimen		CSA (g)	AG (g)	OPC (g)	Water (g)
Without OPC	CSA-1	900	100	-	350
	CSA-2	800	200	-	
	CSA-3	700	300	-	
	CSA-4	600	400	-	
	CSA-5	500	500	-	
With OPC	CSA-6	720	180	100	
	CSA-7	640	160	200	
	CSA-8	560	140	300	
	CSA-9	490	210	300	
	CSA-10	480	120	400	
	CSA-11	400	100	500	

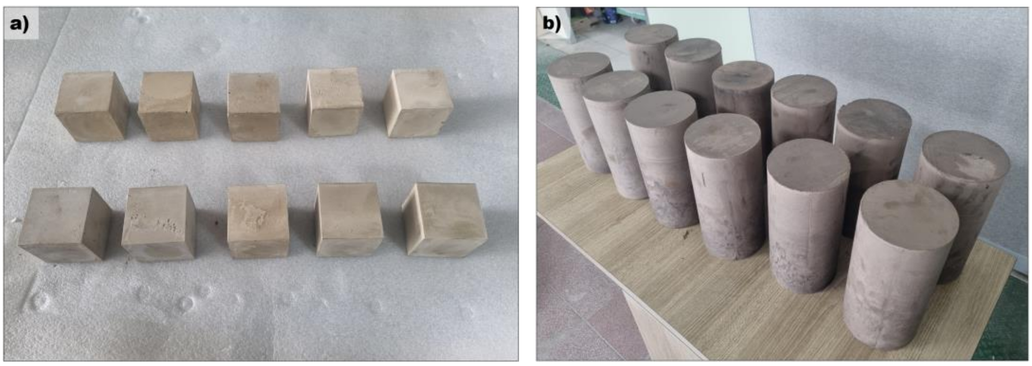

Figure 1. Specimens for compressive strength tests: (**a**) CSA-based binders; (**b**) CLSMs.

2.2. Properties of the CLSM

2.2.1. Flowability

High flowability is a crucial characteristic, enabling the CLSM to exhibit self-flowing properties during backfilling. It eliminates the necessity for compaction while effectively filling voids around civil utilities (e.g., pipelines and culvert boxes). The high flowability of the CLSM offers several advantages, including the ability to preserve the alignment of pipes and reduce the likelihood of ground sinking [40–42]. In addition, since the CLSM is injected to fill voids around pipelines, culverts, and underneath roads, it is essential to ensure sufficient flowability. This enables the CLSM to reach specific spots quickly, facilitating the efficient and precise placement of the material.

The flowability of the CLSM is influenced by the water content, with an increase in water content generally resulting in a higher flowability. However, it is crucial to maintain a balance, because an excessive water content can cause segregation and bleeding. To resolve this problem, the inclusion of high volumes of fine particles is recommended. These fine particles aid in reducing the segregation and enhancement of the overall stability of highly flowable CLSM mixtures. Ling et al. [9] reported that adequate materials and mixture proportions were important to achieve the required flowability (>200 mm) without segregation and bleeding. In this study, the flowability of the CLSM was evaluated based on ASTM D 6103. Figure 2 shows the flowability test, and the description and standard limit are listed in Table 3.

Figure 2. Flowability test of CLSM developed in this study.

Table 3. Test methods and acceptance criteria for determination of CLSM mixtures.

Property	Method	Description	Standard Limit
Flowability	ASTM D 6103 [34]	75 × 150 mm openended cylinder modified flow test	Low flowability: <150 mm Normal flowability: 150–200 mm High (good) flowability: >200 mm
Compressive strength	ASTM C 109 [35] (For binder)	Determination of compressive strength of hydraulic cement mortars using 50 × 50 × 50 mm cube specimens	Do not consider manifestly faulty specimens Maximum permissible range between specimens from the same mortar batch, at the same test age is 8.7% of the average compressive strength
	ASTM D 4832 [36] (For CLSM)	Procedures for the preparation, curing, transporting, and testing of the cylindrical specimen (150 × 300 mm) of CLSM for the determination of compressive strength Special care may be needed because the specimens are often very-low-strength and fragile	Maintaining strengths at a low level and allowing for excavation is an important consideration for CLSMs. Strengths between 0.3 and 2.1 MPa are allowed for future excavation. Even less than 0.3 MPa is also acceptable for future excavation
Density	ASTM D 6023 [37]	Test method for unit weight, yield, and air content (gravimetric) of CLSM	Density of normal CLSM in place is in the range of 18.0–22.8 kN/m^3, which is greater than most compacted materials. However, a CLSM mixture with only fly ash, cement, and water should have a density of 14.1–15.7 kN/m^3

2.2.2. Compressive Strength

Compressive strength is one of the essential properties for CLSMs. In general, the ACI 229 committee defined that the 28-day compressive strength of CLSMs should be 8.3 MPa or less to be sufficient. Moreover, they stated that a long-term compressive strength of less than 2.1 MPa is also allowed to enable future excavation. In this study, a compressive strength of 1.0 MPa or less was set as the target value (Table 1). Compressive tests were conducted based on the ASTM C 109 [36] for the binders and ASTM D 4832 [37] for the CLSM. Figure 1 shows the binder and CLSM specimens for the compressive strength tests. The description and standard limit are summarized in Table 3.

2.2.3. Density and Bleeding

The ACI 229 committee specified that the density of a normal CLSM in place should be in the range of 18.0–22.8 kN/m^3, which is greater than most compacted materials. However, a CLSM mixture with only fly ash, cement, and water should have a density of 14.1–15.7 kN/m^3. The density of the CLSM developed in this study was also measured based on ASTM D 6023 [38], and the measured value was described in Section 4.3. The description and standard limit are shown in Table 3. The bleeding of the CLSM was measured based on ASTM C 940 [43] at 2 h from mixing.

2.3. Filler

The specific characteristics of each CLSM can depend on the fillers and binders used. In general, byproducts and coarse or fine aggregates are used as the fillers. In particular, fly ash in a CLSM can improve its flowability and strength. Fly ash can also reduce bleeding, shrinkage, permeability, and volume changes because its particle shape is spherical and it has a low specific gravity and pozzolanic reactivity. Moreover, it functions as a binder or fine aggregate in CLSMs [11,25,44–46].

Therefore, in this study, fly ash was used as the filler material. Table 4 shows the chemical composition, specific surface area, and density of the fly ash and other materials used in this study. The chemical composition was investigated with X-ray fluorescence (XRF) and the specific surface area was determined with the Blaine test.

Table 4. Chemical composition and physical characteristics of materials used in this study.

Materials	Chemical Composition (%)									Physical Characteristics	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	S.S.A. * (m^2/kg)	Specific Gravity
Fly ash	58.42	18.42	0.89	17.4	0.83	1.8	0.05	0.28	2.41	342.6	2.36
CSA	8.67	33.5	1.75	42.51	1.43	8.45	0.14	0.31	0.7	535.0	2.88
AG	1.41	0.31	0.36	40.0	0.75	53.3	0.36	0.55	1.75	526.2	2.94
OPC	21.1	5.24	3.85	62.1	2.31	2.1	0.10	0.44	2.71	321.0	3.14

* Abbreviation of specific surface area.

3. Determination of Binder

Binder strength can vary depending on the proportions of ingredients, and can influence the strength of the CLSM. The optimum proportion of binder necessary for the rapid consolidation of the CLSM was determined in this section. In laboratory tests, the targeted initial compressive strength of the binder was 10 MPa in order to minimize the amount of binder in the CLSM composition.

Figure 3 summarizes the 4 h compressive strength of CSA-based binders without OPC (i.e., CSA-1~5 in Figure 3) and with OPC (i.e., CSA-6~11 in Figure 3). The 4 h compressive strength after curing the binder specimens was measured. This was because attaining sufficient compressive strength in the early stage was necessary for quick hardening and a short setting time in order to prevent the segregation of the highly flowable CLSM.

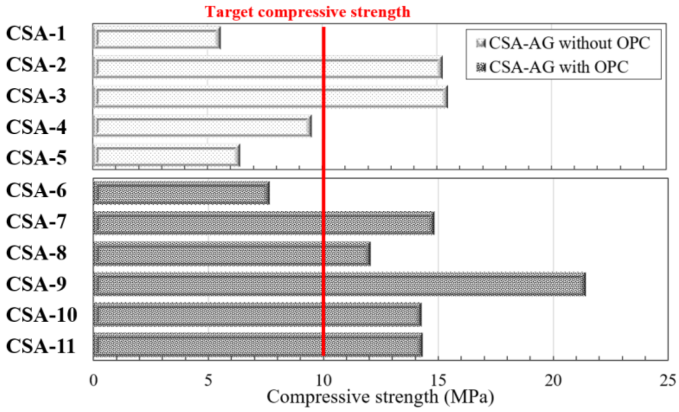

Figure 3. Compressive strength of specimens according to the ratio of base materials.

The mixed proportions are summarized in Table 2. The compressive strength of CSA-1, 4, and 5 was below the target strength (i.e., 10 MPa), whereas that of CSA-2 and 3 exceeded 10 MPa. The highest compressive strength was measured (i.e., CSA-3 in Figure 3) as the amount of AG reached 300 g. The reasons related to the foregoing were analyzed as follows: (a) the CSA produced ettringite when sufficient calcium hydroxide and sulfate existed during hydration [47–49]; (b) the compressive strength of CSA-2 and 3 was accelerated due to the supply of sufficient sulfate, facilitating the production of ettringite; (c) specimens CSA-4 and 5 contained a smaller amount of CSA compared with specimens CSA-2 and 3; consequently, the strength increase in CSA-4 and 5 was lower than that of CSA-2 and 3; (d) AG accelerated the hydration of CSA.

The measured compressive strength of the CSA-based binder with OPC (i.e., CSA-6~11 in Figure 3) was larger than the target compressive strength of 10 MPa, except for CSA-6. Overall, the compressive strength of the CSA-based binders with OPC was larger than that of CSA-based binders without OPC. This was because OPC can accelerate the hydration of CSA-based binders through calcium hydroxide ($Ca(OH)_2$), which is induced by OPC. However, due to the short curing time of 4 h, the observed compressive strength of the binders could potentially have been influenced by the free lime content of OPC rather than the hydration products. The highest compressive strength was measured (i.e., CSA-9 in Figure 3) when the amount of CSA, AG, and OPC was 490 g, 210 g, and 300 g, respectively. Subsequently, the compressive strength reduced as the amount of CSA and OPC decreased and increased, respectively. Pelletier et al. [48] stated that CSA was the main component to increase the compressive strength of the binders and an increased amount of OPC could lead to a reduction in compressive strength due to the increase in the porosity of the binders. In particular, their analysis showed that if the OPC content was high and CSA content was low, the production of ettringite and microcrystalline aluminum hydroxide, which are considerably related to the compressive strength of binders, could be reduced. In this study, the mix proportion of CSA-9, shown in Figure 3, was the most adequate for the CLSM development, because the performance of CSA-9 achieved the goal of a quick hardening binder with the highest and early-stage compressive strength.

4. Development of CLSM

In general, the mix design of CLSMs has previously been established by engineers based on experience or the trial-and-error method. Mostly, they were designed to achieve a sufficiently low compressive strength (i.e., less than 2.1 MPa) and high flowability (i.e., more than 200 mm spread) to allow re-excavation in the future, as well as to provide sufficient backfilling and void-filling [9,45,50–52].

4.1. Compressive Strength, Flowability, and Bleeding

In this section, the optimal mixture ratio between the binder and fly ash was investigated in order to develop the CLSM, satisfying the target fluidity, strength, and bleeding.

Ling et al. [9] reported that CLSMs typically consist of cement (Type 1 Portland), fly ash (Class C or F), a fine aggregate, and water. In this study, fly ash was selected as the filler, and two types of additives were supplemented to reduce the settlement of the mixtures. These materials were Na–montmorillonite as the settlement inhibitor and potassium carbonate (K_2CO_3) as the accelerator. As mentioned in Section 3, CSA-9 in Figure 3 was selected as the binder to develop the new CLSM. The water–material ratio was set to be 1:1 (i.e., W/M is equal to 100%).

Figure 4 shows the compressive strength at 4 h, 8 h, 1 d, 3 d, 7 d, and 28 d, the flowability after mixing, and bleeding at 2 h of each CLSM specimen. Detailed information related to the composition of the CLSM is shown in Table 5. The compressive strength (q_c) typically increased as the proportion of the binder increased, and the q_c of the entire specimen satisfied the target strength (i.e., 28-day compressive strength had to be less than 1.0 MPa in Table 1). The q_c of CLSM-5 and CLSM-1 showed the highest and lowest compressive strengths (i.e., 0.784 MPa and 0.099 MPa) because the proportion of binder was the highest and lowest, respectively (Figure 4a). As shown in Figure 4b, the flowability of the specimens satisfied the target value (i.e., more than 200 mm spread in Table 1). The flowability increased as the amount of binder reduced. Therefore, the flowability of CLSM-1 and CLSM-5 was the highest and lowest, respectively, contrary to the results of the compressive strength.

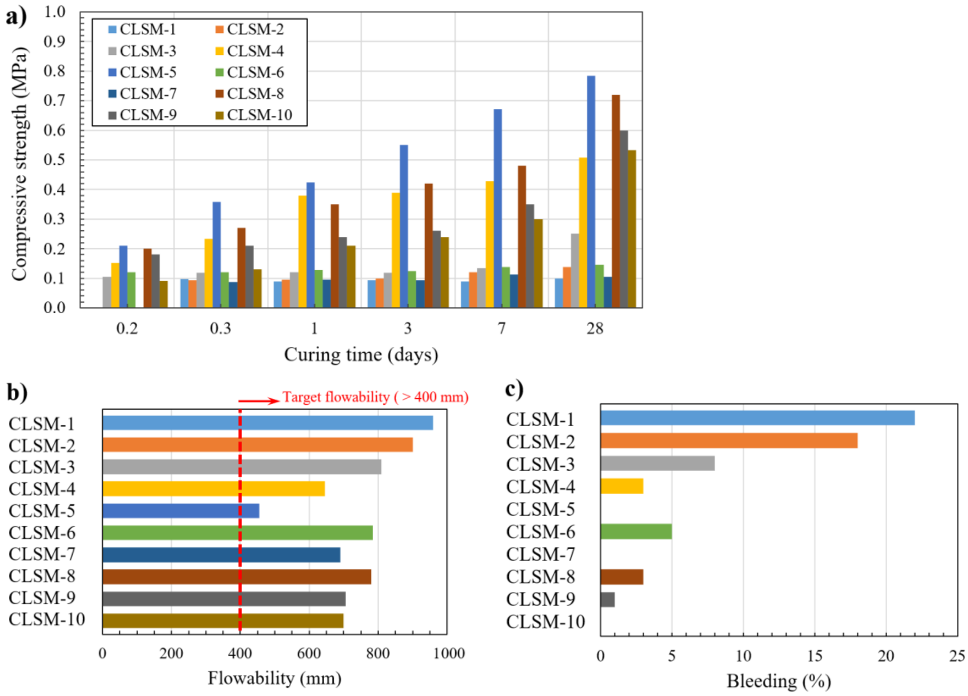

Figure 4. (**a**) compressive strength, (**b**) flowability and (**c**) bleeding for each developed CLSM specimen.

Bleeding was generated in seven specimens (i.e., CLSM-1, 2, 3, 4, 6, 8, and 9). The bleeding of CLSM-1 and CLSM-2 was approximately 20% (Figure 4c). This suggested the following: (1) bleeding can increase as the amount of binder decreases; (2) the binder content of more than 10% in CLSMs can prevent segregation caused by a high water content.

Overall, CLSM-10 exhibited the best performance based on laboratory tests. This specimen satisfied the target performance established in this study (Table 1). It showed a high degree of flowability (700 mm), no bleeding (0%), and an adequate 28-day compressive strength (0.533 MPa). The compressive strength of CLSM-5 satisfied the target strength, but the flowability of CLSM-5 was less than that of CLSM-10, even though the bleeding of CLSM-5 was 0%. The flowability and bleeding of CLSM-7 satisfied the target performance, but the compressive strength of CLSM-7 was only 0.2 times that of CLSM-10. The results indicated that fillers composed of small particles (e.g., fly ash) and the quick-hardening binder could prevent bleeding in spite of a high water content (i.e., water content was more than 100%). Furthermore, the incorporation of finer particles had the potential to reduce the required binder content and/or increase the water content within the CLSM mixture. This could increase the flowability of the CLSM and decrease the bleeding, as well as secure a sufficient compressive strength.

Table 5. The composition of CLSM specimens.

Specimen	Composition (g)				
	Binder	Fly Ash	Additive I	Additive II	Water
CLSM-1	50	950	-	-	
CLSM-2	75	925	-	-	
CLSM-3	100	900	-	-	
CLSM-4	125	875	-	-	
CLSM-5	150	850	-	-	
CLSM-6	98	900	2	-	1000
CLSM-7	96	900	4	-	
CLSM-8	98	900	-	2	
CLSM-9	96	900	2	2	
CLSM-10	96	900	3	1	

4.2. Sensitivity Analysis

The compressive strength, flowability, and bleeding of the CLSM were measured depending on the water–material ratio (W/M). In Figure 5, specimen B is CLSM-10. The W/M was changed by varying the amount of water, whereas the amount of the CLSM was fixed. The compressive strength decreased and the flowability and bleeding increased as the proportion of water increased. In addition, the compressive strength and flowability of specimens A and B were similar, and bleeding was equal to 0%. This indicated that the CLSM could be produced by changing the W/M from 90 to 100% depending on the objectives of construction and the geological properties at the sites of interest.

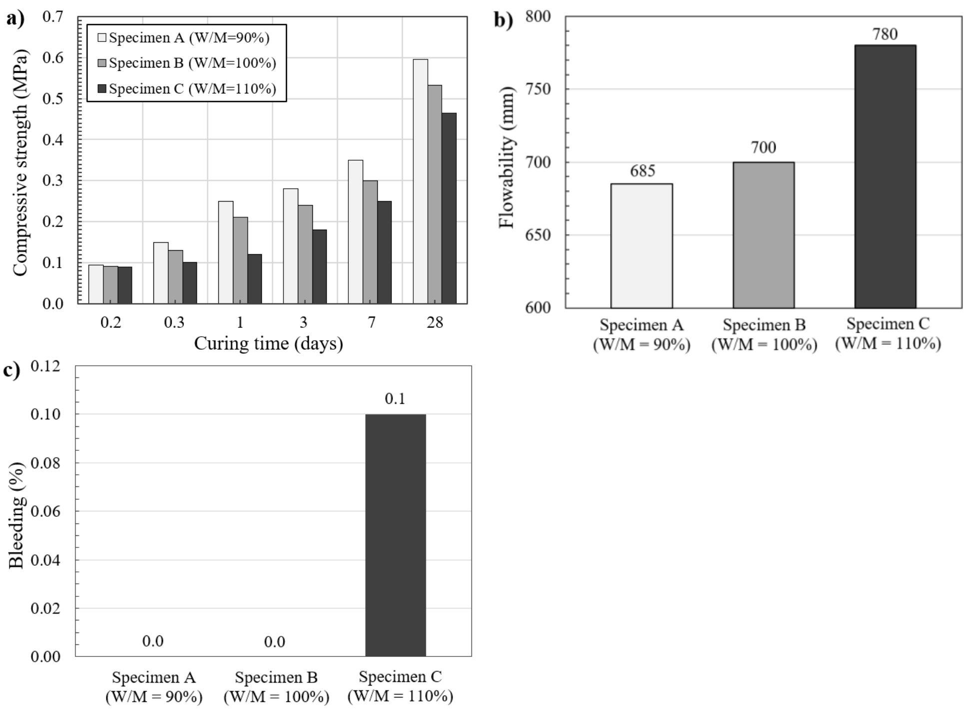

Figure 5. The results of sensitivity analysis for the developed CLSM specimens depending on the ratio of water–material; (**a**) compressive strength for each specimen; (**b**) flow for each specimen; (**c**) bleeding for each specimen.

4.3. Geotechnical Strength Parameters of the Developed CLSM

Table 6 shows the geotechnical strength parameters (i.e., friction angle, cohesion, and total unit weight) of the CLSM developed in this study (i.e., CLSM-10 in Figure 4). The friction angle and cohesion were determined through a triaxial compression test, and the total unit weight was measured based on ASTM D 6023 [38]. These parameters are planned to be used for future studies (i.e., numerical analysis).

Table 6. The results of triaxial compression test for CLSM developed in this study.

ϕ (°)	Cu (kPa)	γ_t (kN/m^3)
12.4	69.3	13.8

5. Comparison between New and Predeveloped CLSMs

In this section, the performance of the CLSM developed in this study (i.e., CLSM-10 in Figure 4) was compared with that of predeveloped CLSMs by conducting additional laboratory tests in order to measure their flowability and compressive strength. The predeveloped CLSMs were based on sandy and clayey soils and bottom ash. Based on the unified soil classification system (USCS), each soil was classified into silty sand (SM) and inorganic silt with low-to-medium compressibility (ML). They were collected at a construction site in Boryeng-si, South Korea. The detailed geotechnical characteristics and particle size distribution of this soil are shown in Figure S3 and Table S1, respectively. The bottom ash was collected at a power plant in Pohang-si, South Korea. The chemical properties of the bottom ash are listed in Table S2.

In order to investigate and compare the flowability and compressive strength of the predeveloped CLSMs with those of the new CLSM, the specimens were manufactured based on previous studies by Cho [17] and Saman [52] on soils and Lee [53] on bottom ash (Figure 6).

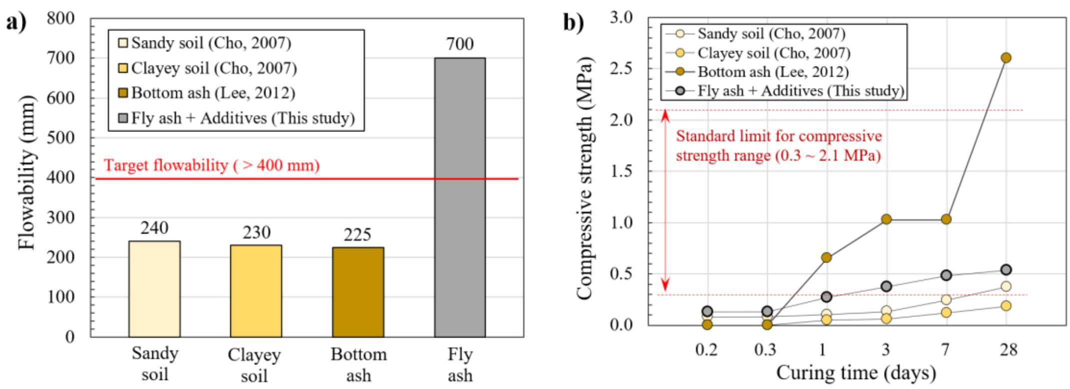

Figure 6. Comparison of (**a**) flowability and (**b**) unconfined compressive strength between CLSM developed in this study and predeveloped CLSMs [17,53].

The CLSM developed in this study showed the highest flowability (Figure 6a). This indicated that injecting the developed CLSM into desired locations near underground pipes or culverts could considerably reduce costs. As shown in Figure 6b, the 28-day compressive strength of the CLSM developed in this study was within the standard limit (i.e., from 0.3 to 2.1 MPa). Overall, the developed CLSM possessed a high flowability, which could facilitate placement and re-excavation, as well as provide sufficient compressive strength to support embedded structures, such as pipes, culverts, paved roads, etc.

Even though the new CLSM developed in this study showed good performance, future studies are needed to analyze several uncertainties as follows: (a) due to its exceptional flowability (i.e., the flowability was 700 mm), the precise endpoint and total quantity and installation timeframe of the CLSM injection in fields should be investigated; (b) in terms of the soundness (i.e., volume stability) of the CLSM specimens, it is less likely that the soundness of the binder would be a major concern, because the microstructure of the CLSM was much looser compared to that of concrete and the proportion of binder was relatively small. However, the soundness of the CLSM should be analyzed based on the acceleration test method proposed by Mehta [54] and Kabir [55] for field applicability.

6. Conclusions

In this study, a series of laboratory tests were conducted to measure the flowability, density, bleeding, and compressive strength of controlled low-strength materials (CLSMs) to develop a new CLSM that could secure high flowability and low segregation, as well as a quick setting time in order to reduce the inconvenience of citizens in metropolitan cities. In addition, the performance of the developed CLSM was compared with that of three different predeveloped CLSMs. The following conclusions were drawn from the analysis results.

The optimal binder was developed by mixing calcium sulfoaluminate (CSA), anhydrous gypsum (AG), ordinary Portland cement (OPC), and water. As the amounts of CSA and OPC increased, the compressive strength of the binder increased. Eventually, the optimal proportion of binder was determined to be 0.25:0.11:0.15:0.5 in the order CSA, AG, OPC, and water, respectively.

The compressive strength, flowability, and bleeding were measured based on the developed binder, fly ash, and two types of additives. The compressive strength typically increased with the binder's proportion. In contrast, the flowability and bleeding increased as the binder's proportion decreased. Overall, most specimens satisfied the target values. A new CLSM developed in this study showed exceptional flowability (i.e., 700 mm) as well as no bleeding and a suitable 28-day compressive strength. In addition, the CLSM could be manufactured by selecting a W/M in the range from 90 to 100%, depending on the objectives of construction and the geological properties at the sites of interest.

It is anticipated that the developed CLSM could significantly reduce the costs related to the disposal of old pavements, the installation of new pavements, and other construction expenses compared to the costs related to the conventional method, even though the expenses for backfill materials could increase due to the higher production costs for CLSMs than soil. In addition, there is a need to investigate its field applicability in order to evaluate the precise costs, maintenance, and long-term stabilities after installation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13169377/s1.

Author Contributions: Conceptualization, J.H. and Y.J.; Methodology, J.H. and B.K.; Validation, B.K.; Investigation: performed the experiments, J.H.; Investigation: data/evidence collection, Y.J. and Y.K.; Writing—original draft preparation, J.H. and Y.J.; Writing—review and editing, Y.K. and B.K.; Supervision, B.K.; Funding acquisition, J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (grant RS-2021-KA162543).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jo, Y.S.; Cho, S.H.; Jang, Y.S. Field investigation and analysis of ground sinking development in a metropolitan city, Seoul, Korea. *Environ. Earth Sci.* **2016**, *75*, 1353. [CrossRef]
2. Lee, N.K.; Kim, H.K.; Park, I.S.; Lee, H.K. Alkali-activated, cementless, controlled low-strength materials (CLSM) utilizing industrial by-products. *Construct. Build. Mater.* **2013**, *49*, 738–746. [CrossRef]

3. Kaliyavardhan, S.K.; Ling, T.C.; Guo, M.Z.; Mo, K.H. Waste resources recycling in controlled low-strength material (CLSM) : A critical review on plastic properties. *J. Environ. Manag.* **2019**, *241*, 383–396. [CrossRef]
4. Fauzi, M.A.; Arshad, M.F.; Nor, N.M. Statistical models to develop optimised controlled low-strength materials with wastepaper sludge ash. *Constr. Build. Mater.* **2021**, *286*, 122816. [CrossRef]
5. Dalal, P.H.; Patil, M.; Dave, T.N.; Iyer, K.K.R. An experimental study on controlled low-strength material (CLSM) for utilization as sustainable backfill. *Mater. Today Proc.* **2022**, *65*, 1178–1185. [CrossRef]
6. Nataraja, M.; Nalanada, Y. Performance of industrial byproducts in controlled low-strength materials (CLSM). *Waste Manag.* **2008**, *28*, 1168–1181. [CrossRef] [PubMed]
7. Dev, K.; Robinson, R. Pond ash-based controlled low-strength flowable fills for geotechnical engineering applications. *Int. J. Geosynth. Ground Eng.* **2015**, *1*, 1–13. [CrossRef]
8. *ACI 229R-13*; Report on Controlled Low-Strength Materials, ACI Committee 229. American Concrete Institute (ACI): Farmington Hills, MI, USA, 2013.
9. Ling, T.C.; Kaliyavaradhan, S.K.; Poon, C.S. Global perspective on application of controlled low-strength material (CLSM) for trench backfilling: An overview. *Constr. Build. Mater.* **2018**, *158*, 535–548. [CrossRef]
10. Tikalsky, P.; Gaffney, M.; Regan, R. Properties of controlled low-strength material containing foundry sand. *ACI Mater. J.* **2000**, *97*, 698–702.
11. Du, L.; Folliard, K.J.; Trejo, D. Effects of constituent materials and quantities on water demand and compressive strength of controlled low-strength material. *J. Mater. Civ. Eng.* **2002**, *14*, 485–495. [CrossRef]
12. Hitch, J.L.; Howard, A.K.; Baas, W.P. *Innovations in Controlled Low-Strength Material (Flowable Fill)*; ASTM STP 1459; ASTM International: West Conshohocken, PA, USA, 2002.
13. Lee, Y.S. Recycling of Waste Coal Ash for Controlled low-Strength Materials. Master's Thesis, Hanyang University, Seoul, Korea, 2002. (In Korean)
14. Pierce, C.E.; Tripathi, H.; Brown, T.W. Cement kiln dust in controlled low-strength materials. *ACI Mater. J.* **2003**, *100*, 455–462.
15. Choi, N.H. Analysis of Behavior for Underground Pipe Using Controlled Low Strength Material with Field Soil. Master's Thesis, Hanyang University, Seoul, Korea, 2004. (In Korean).
16. Naik, T.R.; Kraus, R.N.; Ramme, B.W.; Chun, Y.M.; Kumar, R. High-carbon fly ash in manufacturing conductive CLSM and concrete. *J. Mater. Civ. Eng.* **2006**, *18*, 743–746. [CrossRef]
17. Cho, D.H. Reuse of Surplus Soil by Rapid-Setting Properties of Liquefied Stabilized Soil. Ph.D. Dissertation, Joongang University, Seoul, Korea, 2007. (In Korean)
18. Taha, R.A.; Alnuaimi, A.S.; Al-Jabri, K.S.; Al-Harthy, A.S. Evaluation of controlled low-strength materials containing industrial by-products. *Build. Environ.* **2007**, *42*, 3366–3372. [CrossRef]
19. Lachemi, M.; Sßahmaran, M.; Hossain, K.M.A.; Lotfy, A.; Shehata, M. Properties of controlled low-strength materials incorporating cement kiln dust and slag. *Cem. Concr. Compos.* **2010**, *32*, 623–629. [CrossRef]
20. Horiguchi, T.; Fujita, R.; Shimura, K. Applicability of controlled low-strength materials with incinerated sewage sludge ash and crushed-stone powder. *J. Mater. Civ. Eng.* **2011**, *23*, 767–771. [CrossRef]
21. Naganathan, S.; Razak, H.A.; Hamid, S.N.A. Properties of controlled low-strength material made using industrial waste incineration bottom ash and quarry dust. *Mater. Des.* **2012**, *33*, 56–63. [CrossRef]
22. Wang, H.; Chen, B.; Wu, Y. A study of the fresh properties of controlled low-strength rubber lightweight aggregate concrete (CLSRLC). *Construct. Build. Mater.* **2013**, *41*, 526–531. [CrossRef]
23. Do, T.M.; Kim, Y. Engineering properties of controlled low-strength material (CLSM) incorporating red mud. *Int. J. Geo-Eng.* **2016**, *7*, 7. [CrossRef]
24. Wu, H.; Huang, B.; Shu, X.; Yin, J. Utilization of solid wastes/byproducts from paper mills in controlled low-strength material (CLSM). *Construct. Build. Mater.* **2016**, *118*, 155–163. [CrossRef]
25. Chompoorat, T.; Likitlersuang, S.; Jongvivatsakul, P. The performance of controlled low-strength material base supporting a high-volume asphalt pavement. *KSCE J. Civ. Eng.* **2018**, *22*, 2055–2063. [CrossRef]
26. Lin, W.T.; Weng, T.L.; Cheng, A.; Chao, S.J.; Hsu, H. Properties of controlled low-strength material with circulating fluidized bed combustion ash and recycled aggregates. *Materials* **2018**, *5*, 715. [CrossRef]
27. Fang, X.; Lei, W.; Poon, C.S.; Baek, K.; Tsang, D.C.W.; Kwok, S.K. Transforming waterworks sludge into controlled low-strength material: Bench-scale optimization and field test validation. *J. Environ. Manag.* **2019**, *232*, 254–263. [CrossRef]
28. Okuyucu, O.; Jayawickrama, P.; Senadheera, S. Mechanical properties of steel fiber–reinforced self-consolidating controlled low-strength material for pavement base layers. *J. Mater. Civ. Eng.* **2019**, *31*, 4019177. [CrossRef]
29. Kim, Y.; Dinh, B.H.; Do, T.M.; Kang, G. Development of thermally enhanced controlled low-strength material incorporating different types of steel-making slag for ground-source heat pump system. *Renew. Energy* **2020**, *150*, 116–127. [CrossRef]
30. Razak, H.A.; Naganathan, S.; Hamid, S.N.A. Performance appraisal of industrial waste incineration bottom ash as controlled low-strength material. *J. Hazard. Mater.* **2009**, *172*, 862–867. [CrossRef] [PubMed]
31. Kuo, W.T.; Wang, H.Y.; Shu, C.Y.; Su, D.S. Engineering properties of controlled low-strength materials containing waste oyster shells. *Construct. Build. Mater.* **2019**, *46*, 128–133. [CrossRef]
32. Mahamaya, M.; Jain, S.; Das, S.K.; Paul, R. Engineering properties of cementless alkali activated CLSM using ferrochrome slag. *J. Mater. Civ. Eng.* **2023**, *35*, 04022441. [CrossRef]

33. Li, Y.F.; Hsu, Y.W.; Syu, J.Y.; Chen, B.Y.; Song, B. Study on the utilization of waste thermoset glass fiber-reinforced polymer in normal strength concrete and controlled low strength material. *Materials* **2023**, *16*, 3552. [CrossRef] [PubMed]
34. *ASTM STP 1331*; The Design and Application of Controlled Low-Strength Materials (Flowable Fill). ASTM International: West Conshohocken, PA, USA, 1998.
35. *ASTM D 6103*; Standard Test Method for Flow Consistency of Controlled Low-Strength Material (CLSM). ASTM International: West Conshohocken, PA, USA, 2013.
36. *ASTM C 109*; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in or 50-mm Cube Specimens). ASTM International: West Conshohocken, PA, USA, 2020.
37. *ASTM D 4832*; Standard Test Method for Preparation and Testing of Controlled Low-Strength Material (CLSM) Test Cylinders. ASTM International: West Conshohocken, PA, USA, 2018.
38. *ASTM D 6023*; Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM). ASTM International: West Conshohocken, PA, USA, 2016.
39. Schmitz, M.E.; Parsons, R.L.; Ramirez, G.; Zhao, Y. *Use of Controlled Low-Strength Material as Abutment Backfill*; University of Kansas: Lawrence, Kansas, 2004.
40. Abelleira, A.; Barke, N.S.; Pickering, D.G. Corrosion activity of steel in cementitious controlled low-strength materials vs. that in soil. In *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*; STM STP 1331; Howard, A.K., Hitch, J.L., Eds.; American Society for Testing and Materials: West Conshohocken, PA, USA, 1998.
41. Dockter, B.A. Comparison of dry scrubber and class c fly ash in controlled low-strength materials (CLSM) applications. In *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*; ASTM STP 1331; Howard, A.K., Hitch, J.L., Eds.; American Society for Testing and Materials: West Conshohocken, PA, USA, 1998; pp. 13–26.
42. Kaneshiro, J.; Navin, S.; Wendel, L.; Snowden, H. Controlled low-strength material for pipeline backfill—Specifications, case histories and lessons learned. In Proceedings of the Pipelines 2001: Advances in Pipelines Engineering and Construction, Pipeline Division Specialty Conference, ASCE, San Diego, CA, USA, 15–18 July 2001; pp. 1–13.
43. *ASTM C 940*; Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory. ASTM International: West Conshohocken, PA, USA, 2022.
44. Hwang, C.L.; Shen, D.H. The effects of blast-furnace slag and fly ash on the hydration of Portland cement. *Cem. Concr. Res.* **1991**, *21*, 410–425. [CrossRef]
45. Trejo, D.; Folliard, K.J.; Du, L. Sustainable development using controlled low-strength material. In Proceedings of the International Workshop on Sustainable Development and Concrete Technology, Beijing, China, 20–21 May 2004; pp. 231–250.
46. Siddique, R.; Noumowe, A. Utilization of spent foundry sand in controlled low-strength materials and concrete. *Resour. Conserv. Recy.* **2008**, *53*, 27–35. [CrossRef]
47. Trauchessec, R.; Mechling, J.M.; Lecornte, A.; Roux, A.; Le Rolland, B. Hydration of ordinary Portland cement and calcium sulfoaluminate cement blends. *Cem. Concr. Compos.* **2015**, *56*, 106–114. [CrossRef]
48. Pelletier, L.; Winnefeld, F.; Lothenbach, B. The ternary system Portland cement-calcium sulphoaluminate clinker-anhydrite: Hydration mechanism and mortar properties. *Cem. Concr. Compos.* **2010**, *32*, 497–507. [CrossRef]
49. Hanic, F.; Kapralik, I.; Gabrisova, A. Mechanism of hydration reactions in the system C_4A_3S-CS-CaO-H_2O referred to hydration of sulphoaluminate cement. *Cem. Concr. Res.* **1989**, *19*, 671–682. [CrossRef]
50. Naik, T.R.; Singh, S.S. Flowable slurry containing foundry sands. *J. Mater. Civ. Eng.* **1997**, *9*, 93–102. [CrossRef]
51. NRMCA. *Guide Specification for Controlled Low-Strength Materials (CLSM)*; Report of National Ready Mixed Concrete Association; Specification Guide: Alexandria, VA, USA, 2006.
52. Saman. *Practical Use of Self-Compacting Liquifies Stabilized Method with Surplus Soil*; Construction and Transportation R&D Final Report, No. C15; Saman Corporation: Gwacheon, Korea, 2008. (In Korean)
53. Lee, H.J. Compressive Strength Characteristics of Lightweight Foamed Controlled Low-Strength Material (CLSM) Using Coal Ash. Master's Thesis, Hanyang University, Seoul, Korea, 2012. (In Korean)
54. Mehta, P.K. History and status of performance tests for evaluation of the soundness of cement. In *Cement Standards Evolution and Trends*; ASTM International: West Conshohocken, PA, USA, 1978.
55. Kabir, H.; Hooton, R.D.; Popoff, N.J. Evaluation of cement soundness using the ASTM C151 autoclave expansion test. *Cem. Concr. Res.* **2020**, *136*, 106159. [CrossRef]