

Article

Physical and Mechanical Properties of Foamed Lightweight Soil Incorporated with Desulfurization Ash

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Abstract

To promote the utilization of industrial solid waste in subgrade filling, this study investigated desulfurization ash foamed lightweight soil (DA-FLS) with a high ash content. Various binder proportions, target wet densities (600–1500 kg/m³) and activator types were used to examine molding behavior, unconfined compressive strength (UCS) and free swell. Among the activator systems tested, only the cement–GGBS–DA binder produced mixtures that could be demolded and subsequently tested. Mixes of cement and DA without GGBS, and mixes activated by RS–W–S, calcium hydroxide or carbide slag, gave slow molding or molding failure. Mix proportion, foam dosage and target density were not varied independently. Among the mixtures investigated, the 1:4:5 blend designed at 600 kg/m³ gave a measured wet density of 638.95 kg/m³. In the 1:4:5 foamed series, 28 d UCS increased with measured wet density and reached 3.3 MPa in the densest mix tested. For several types of cement-activated mixtures with a 1:4:5 mix ratio (design dosage of 600–800 kg/m³), the 28-day free vertical expansion rate remained below 0.7%. These low values of short-term expansion indicate the potential to meet the limit requirements for lightweight roadbed fill in the Chinese standard Specifications for Design of Highway Subgrades. This study provides a laboratory basis for the preparation of lightweight roadbed fill using high dosages of desulfurization ash, indicating that the material holds potential for further engineering evaluation.

Keywords: desulfurization ash; foamed lightweight soil; mechanical properties; activator

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1. Introduction

With the rapid economic development in China, the generation of industrial solid waste has become increasingly massive. According to statistics, in 2024, the newly generated general industrial solid waste nationwide amounted to 4.47 billion tons, with a comprehensive utilization volume of 2.65 billion tons and a total disposal volume of only 780 million tons [1]. The accumulation of industrial solid waste not only occupies substantial land resources but also exerts an adverse impact on the ecological environment. Guided by the “dual-carbon” goals and circular economy policies, promoting the source reduction, large-scale application, and resource utilization of bulk industrial solid waste has become a major strategic imperative for national development [2]. Concurrently, transportation infrastructure construction (e.g., highway subgrades, bridge abutment backfills, and pipeline

backfills) has an enormous demand for earth and stone materials; however, traditional natural sand and gravel resources are becoming increasingly scarce and subject to mining restrictions [3]. In response to national ultra-low emission standards, coal-fired power plants and steel enterprises widely employ limestone–gypsum wet flue gas desulfurization technology, which generates massive amounts of industrial by-products, including desulfurization ash (DA), which is primarily composed of calcium sulfate dihydrate [4]. Currently, the annual production of wet DA in China has reached approximately 130 million tons. Traditional disposal methods, such as stockpiling and landfilling, are not only costly but also prone to causing soil and groundwater pollution [5]. On the other hand, foamed lightweight soil (FLS), as a novel filling material containing numerous internal closed pores, exhibits significant advantages such as a lightweight nature, high fluidity, excellent self-supporting ability, and ease of construction [6,7]. In this paper, foamed lightweight soil (FLS) follows the meaning used in the Chinese standard Technical specification for foamed mixture lightweight soil filling engineering (CJJ/T 177) [8] and Technical specification for cast-in-situ foamed lightweight soil (CECS 249-2008) [9]: a cast-in-place lightweight fill made from cementitious materials, water and preformed foam. It contains no natural soil. The term DA-FLS refers to this FLS when DA accounts for a large fraction of the solids. Consequently, it demonstrates tremendous application potential in addressing engineering challenges like bridge abutment and pipeline backfilling. However, the relatively high cost of traditional cement-based FLS restricts its large-scale application in road engineering. Existing studies have verified that utilizing solid wastes—such as fly ash, lime, clay, and industrial residues—to partially replace cement in FLS can effectively dispose of massive industrial solid wastes and formulate viable filling materials [10–12]. Meanwhile, recent research on the disposal of DA has demonstrated that calcium sulfate dihydrate, an active component within the ash, possesses the potential for activation in the preparation of construction materials [13–16].

Therefore, incorporating desulfurization ash—which possesses latent hydration activity—as a key material into the FLS system to produce high-ash-content DA-FLS offers the potential to significantly reduce material costs and achieve the efficient disposal of bulk solid waste. Currently, research on lightweight filling materials based on desulfurization ash primarily focuses on the performance of individual materials. There is a lack of systematic mix-design studies addressing the relationship between the strength and volumetric stability of DA-FLS with a high ash content (>30%) [17,18]. Consequently, this paper investigates the effects of the cementitious material system (the ratio of cement, slag powder, and desulfurization ash), wet density, and various activators on the mechanical properties and volumetric expansion behavior of the material. This paper examines, within a limited mix matrix, the effects of the cement–GGBS–DA ratio, target wet density and activator type on molding, UCS and free swell.

2. Materials and Methods

2.1. Materials

The experimental materials utilized in this study primarily consist of desulfurization ash (DA), Ground Granulated Blast-furnace Slag (GGBS), and Ordinary Portland cement (OPC) with a strength grade of 42.5. The OPC used in this study conforms to the Chinese standard Common Portland Cement (GB 175-2023) [19]; it was procured from Henan Yongan Cement Co., Ltd. (Gongyi, China). Testing revealed an initial setting time of 301 min and a final setting time of 359 min; the 7-day and 28-day unconfined compressive strength (UCS) values were 30.2 MPa and 47.6 MPa, respectively. Detailed XRF oxide analysis results are presented in Table 1. The desulfurization ash (DA) used in this study is classified as general industrial waste and was obtained from Guoneng Changyuan Wuhan

Qingshan Thermal Power Co., Ltd. (Wuhan, China). It is a by-product of the scrubbing and absorption of SO₂ from coal-fired flue gas within the power plant's desulfurization tower and consists primarily of calcium sulfate dihydrate and calcium sulfate hemihydrate. The DA sample was freeze-dried, pulverized, and sieved through a 0.075 mm mesh before undergoing XRF analysis; the determined elemental composition is listed in Table 2. It possesses a moisture content of 16%, a pH of 7.5, a specific surface area of 495.67 m²/kg, and a median particle size of 36.91 µm. In addition to DA and OPC, GGBS—a highly active silicate waste slag generated during the blast furnace ironmaking process and primarily composed of CaO, SiO₂, and Al₂O₃—was provided by Henan Yuanheng Environmental Protection Engineering Co., Ltd. (Gongyi, China). The composition of the GGBS samples was analyzed using the same XRF testing procedure as for the DA samples, and the results are presented as oxides in Table 1.

Table 1. Main oxide components of GGBS, FA and OPC (%).

Oxide Components	CaO	SiO ₂	Al ₂ O ₃	MgO	SO ₃	TiO ₂	MnO	Cl	Fe ₂ O ₃	Na ₂ O	Other	Loss on Ignition
Materials												
OPC	59.39	20.66	5.60	3.87	4.99	NA	NA	NA	NA	NA	2.16	0
GGBS	42.22	31.33	14.82	6.83	2.31	0.79	0.40	NA	NA	NA	1.30	0
FA	4	60	28.1	1.2	0.8	NA	NA	0.01	6.2	1.30	NA	0

Table 2. Chemical composition of desulfurization ash (DA).

Chemical Composition	F	Na	Mg	Al	Si	S	Cl	K	Ca	Ti	Fe	Sr	P	Cu	Br	Mn
Content (%)	2.43	0.14	1.36	0.81	1.99	33.55	2.41	0.28	55.38	0.05	1.43	0.11	0.01	0.02	0.02	0.02

At the same time, this study selected fly ash (FA) as a possible alternative to GGBS to investigate the differences in synergistic effects between various solid waste materials and DA. The fly ash (FA) used in this study was Grade I fly ash complying with the Chinese standard Fly ash used for cement and concrete (GB/T 1596-2017) [20] and was purchased from Henan Sitong Huajian Company. Specific details of FA include: fineness (residue on a 45 µm square-hole sieve not exceeding 12%); water requirement ratio (not exceeding 95%); loss on ignition (not exceeding 5%); moisture content (not exceeding 1%); and sulfur trioxide content (not exceeding 3.5%). XRF analysis was performed in the same way to determine their major oxide chemical compositions; the results are listed in Table 1.

The specific surface area of the FA is 598.4 m²/kg. To investigate various activation effects, several specific activators were introduced into the system. These include an alkaline RS-W-S slurry solidifier designed for treating soft soils and waste slurries, an analytically pure calcium hydroxide reagent produced by Sinopharm Group (Beijing, China), and a strongly alkaline carbide slag supplied by Dongfang Cement Co., Ltd. (Yiyang, China). Furthermore, a composite foaming agent was prepared to generate the porous structure of the lightweight soil (FLS), using sodium dodecyl sulfate (SDS) as the primary foaming agent, along with sodium carboxymethyl cellulose (CMC) and MPS (modified polyethoxylated silicone) as foam stabilizers. Through orthogonal experiments, the optimal mixture was determined to be 1% SDS, 0.75% MPS, and 1.50% CMC. Ultimately, in accordance with the Chinese standard Foamed Concrete (JG/T 266-2011) [21], the prepared foam exhibited an expansion ratio of 28.63, a settlement of 1.20 mm, and a bleeding volume of 0.7 mL, all of which fully satisfy the normative requirements.

2.2. Optimization of Activators

FLS is a lightweight cementitious material produced by dispersing foam into a cementitious slurry, in which the porous structure is preserved as the slurry sets and hardens. Previous studies have shown that the setting and solidification time of the cementitious material must precede the foam dissipation time; otherwise, the system will collapse due to premature foam dissipation, making the setting process impossible [17]. According to preliminary experiments, DA-FLS with a high DA content exhibits a relatively long setting time. To be utilized as FLS, it requires the addition of activators to counteract potential collapse caused by the retarding effect. However, desulfurization ash contains active components such as calcium sulfate dihydrate and calcium sulfate hemihydrate, which may react with the activators, potentially reducing the activation efficiency and prolonging the solidification process, thereby leading to demolding failure. Consequently, to ensure the final setting performance of DA-FLS, it is necessary to appropriately select the activator. Table 3 summarizes the effects of various activator types on the molding performance.

Table 3. Influence of type and dosage of activators on molding effect.

Types of Activators	Mass Proportion of Activators, GGBS and DA	Molding Effect
cement	3:4:3, 2:4:4, 1:4:5	Normal
RS-W-S	3:4:3, 2:4:4, 1:4:5	Fail
calcium hydroxide	3:4:3, 2:4:4, 1:4:5	Slow molding
calcium carbide slag	3:4:3, 2:4:4, 1:4:5	Slow molding

Preliminary experiments were conducted using various types of activators, and the results are presented in Table 3. The outcome was assessed by a visual demolding test. Testing revealed that the type of activator significantly influenced the molding performance of the FLS. Molding performance was categorized based on the curing schedule: “normal” if demolding was possible after 2 days, “slow” if demolding was possible after 7 days of curing, and “failed” if the material could not be molded even after 7 days. The ratios 1:4:5, 2:4:4, and 3:4:3 correspond to activator contents of 10%, 20%, and 30% of the solid mass, respectively, with the GGBS content fixed at 40% of the solid mass for all groups. The results demonstrated that cement-activated GGBS ensured the normal molding of DA-FLS; it could all be demolded after 2 days, yielding identical results. In contrast, none of the other materials tested in this preliminary study achieved the solidification and molding performance of cement; furthermore, increasing the activator dosage within the specified ranges in Table 3 failed to improve molding results or reduce setting time. The reason for the molding failure is speculated to be that chemical activators promote the reaction between the sulfates in the desulfurization ash and the aluminate phases, thereby accelerating the formation of ettringite. This process triggers significant delayed expansion, ultimately resulting in the failure of the material to mold. Therefore, the cement–GGBS–DA composite binder was selected as the sole combination in subsequent testing.

2.3. Methodology

2.3.1. Mixing Proportioning and Wet Density

Through preliminary experiments, the water–solid ratio was determined to be 0.6 from Group 1 to 9, and 0.65 from Group 10 to 12. The design value is calculated as

$$w/s = \frac{W_{\text{added}} - 0.16m_{\text{DA}} + W_{\text{foam}}}{m_{\text{OPC}} + m_{\text{GGBS or FA}} + m_{\text{DA}}}$$

where W_{added} is the mixing water in Table 4; $0.16m_{\text{DA}}$ is the moisture in the as-received desulfurization ash (moisture content 16%); W_{foam} is the water contained in the preformed

foam; and the denominator is the batched solid mass, with DA taken as the as-received mass. $W_{\text{added}} - 0.16m_{\text{DA}} + W_{\text{foam}}$ is the total effective water. For the unfoamed mixes $W_{\text{foam}} = 0$.

Table 4. Material proportions and solutions.

Group	Test Plan	Design Wet Density (kg/m ³)	Activator/Cement (kg/m ³)	GGBS (kg/m ³)	Fly Ash	DA (kg/m ³)	Water (kg/m ³)	Foam (L/m ³)
1	DA-FLS 1:4:5	600	34	138		172	224	650
2	DA-FLS 1:4:5	700	41	163		203	264	586
3	DA-FLS 3:4:3	800	141	188		141	305	527
4	DA-FLS 2:4:4	800	94	188		188	305	524
5	DA-FLS 1:4:5	800	47	188		235	305	523
6	FA-DA-FLS 1:4:5	800	47		188	235	305	523
7	DA-FLS 1:0:9	800	47			423	305	523
8	DA-FLS 2:0:8	800	94			376	305	523
9	DA-FLS 1:4:5	1000	63	253		316	417	523
10	DA-FSS 1:4:5	1500	98	394		493	641	/
11	DA-FSS 0.5:4:5.5	1500	49	394		542	641	/
12	DA-FSS 0.5:3:6.5	1500	49	294		637	641	/

For Group 1 this gives $(224 - 172 \times 0.16)/344 = 0.57$ before the foam contribution; W_{foam} then brings the ratio to the design value of 0.60. The same rule is applied to Groups 2–9. A simple quotient of the Water column and the solid masses in Table 4 therefore overestimates the design w/s, because it neither deducts the moisture already present in the DA nor includes the foam water as defined above.

W_{foam} is determined by measuring the foam density in situ. First, the foam density is tested in accordance with the Chinese standard CECS 249-2008. Based on the foam volume and density for each group listed in Table 4, the mass of foam added is calculated to achieve the target water-to-solid ratio for the system.

The target wet density and component proportions of DA-FLS were designed with reference to the Chinese standard Technical Specification for Cast-in-Situ Foamed Lightweight Soil (CECS 249-2008). In this process, the water contained in the foam and the DA was taken into account and included—along with the added water—in the calculation of the water-to-solid ratio. Groups 10–12 were prepared from the same solids and water but without foam. They are referred to as flowable solidified soil (FSS). FSS is used here as an engineering name for an unfoamed, flowable DA–GGBS–cement slurry; it does not imply the presence of natural soil. To investigate the effects of varying wet densities and cement contents on the performance of the FLS, five target wet densities for the DA-FLS/DA-FSS were established, 600 kg/m³, 700 kg/m³, 800 kg/m³, 1000 kg/m³, and 1500 kg/m³, as well as eight different cement contents (34, 41, 47, 49, 63, 94, 98, and 141 kg/m³), resulting in a total of 12 mix proportions. The dosages of the remaining components were calculated accordingly, and the detailed mix proportions are presented in Table 4.

2.3.2. Sample Preparation

According to the designed mix proportions, the dry materials were weighed and charged into the mixer. The mixer operated at a constant speed of 120 rpm. First, the dry

materials were dry-mixed for 2 min, followed by the addition of water and mixing for 3 min. Subsequently, foam was introduced, and mixing continued for another 3 min to ensure thorough blending of the slurry and foam for the preparation of DA-FLS; the mixture was then immediately cast into UCS and free swelling molds. The specific preparation process is shown in Figure 1.

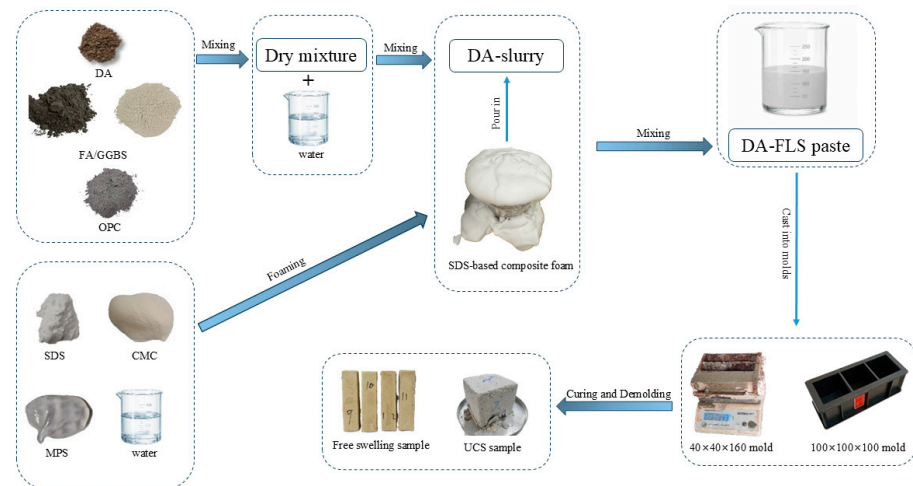


Figure 1. Preparation process of DA-FLS.

2.3.3. Wet Density Test

The wet density of the specimens was tested in accordance with the Chinese standard Test methods for foamed concrete and its products (GB/T 43487-2023) [22]. The mixture sample was first poured into a plastic measuring cup, and then slowly transferred into a measuring container. Subsequently, the exterior of the container was gently tapped with a straightedge to ensure that the sample mixture completely filled the volume and slightly overflowed its rim. The top surface was then struck off with the straightedge, making the mixture flush with the upper rim of the container. After wiping the outer wall of the container clean, the total mass of the FLS mixture and the container was weighed. The entire process, from sampling to the completion of the wet density measurement, was strictly accomplished within 6 min. The results of this test were obtained from a single test run.

2.3.4. Free Swell Test

The free swell test of the DA-FLS was conducted in accordance with the Chinese standard Test methods for performance of foamed concrete products (JC/T 2357-2016) [23]. The dimensions of the specimens were 40 mm × 40 mm × 160 mm, a size that complies with the normative requirements and maintains the exact wet density and material mix proportions as the corresponding group of compressive test specimens. After casting in molds, the specimens were left for 48 h initial curing. Immediately after demolding, the length along the 160 mm axis was measured on a vertical expansion–shrinkage apparatus using the dial gauge; this reading was taken as the initial length. The specimens were then immersed in water at $(20 \pm 2)^\circ\text{C}$. Curing age for the swell test was counted from the time of immersion. At each designated age the specimen was removed from the water and measured again on the same apparatus. Free swell test was conducted only once.

2.3.5. UCS Test

In accordance with the Chinese standard Test methods for foamed concrete and its products (GB/T 43487-2023), 100 mm × 100 mm × 100 mm cubic molds were used to prepare UCS samples. The casted DA-FLS specimens were initially left to stand for 48 h

under standard test conditions at a temperature of $(20 \pm 5)^\circ\text{C}$ and a relative humidity of $(50 \pm 15)\%$, and were subsequently demolded. After demolding, the specimens were transferred to a standard curing environment maintained at a temperature of $(20 \pm 2)^\circ\text{C}$ and a relative humidity of over 95%, where they were cured until the target age. Three replicate specimens were prepared for each curing age. Once the DA-FLS specimens reached their designated curing ages, unconfined compressive strength tests were conducted, and the standard deviation was calculated.

2.3.6. XRD Test

In this study, an Ultima IV X-ray diffractometer (Rigaku Corporation, Akishima, Tokyo, Japan) was used for XRD analysis. The instrument has a 2θ range of 5° to 140° , a minimum step size of 0.005° , and a scanning speed exceeding $5^\circ/\text{s}$. The scans were collected from 10° to 80° (2θ) at $5^\circ/\text{min}$. Samples taken after the UCS tests were freeze-dried in a YTLG-12C freeze-dryer (Shanghai Yetuo Technology Co., Ltd., Shanghai, China). The soil samples were weighed initially and re-weighed periodically during the drying process; mass changes were continuously monitored until stability was achieved, indicating the completion of drying. Subsequently, the dried soil samples were pulverized and sieved through a 0.075 mm mesh. A 10 g sample was then selected for XRD testing, and the resulting data were analyzed using MDI Jade 6.5 software to determine the composition of the products.

2.3.7. SEM Test

In this study, a Quattro S scanning electron microscope (Thermo Fisher Scientific, Waltham, MA, USA) was used to observe the micro-morphology. The instrument offers a resolution of 1.0 nm at an accelerating voltage of 15 kV and 1.3 nm at 1 kV, with an adjustable accelerating voltage range of 0.1–30 kV.

The sample preparation and testing procedures were as follows: dried soil clods were first broken into smaller pieces, and fragments with relatively flat cross-sections were selected. These fragments were then affixed to the sample stage using conductive adhesive, and loose surface dust was removed via air blowing to ensure secure bonding. To suppress charge accumulation and discharge interference on the sample surface during scanning, the specimens underwent gold sputter coating. Subsequently, the sample stage was loaded and secured within the sample chamber; the chamber door was closed, and the vacuum system was activated. Once the vacuum level met the testing requirements, the desired magnification was set, and images were acquired.

3. Results

3.1. Wet Density of DA-FLS in Relation to Mix Proportion and Target Density

The target and measured wet densities of the 12 groups are presented in Figure 2. Because mix proportion, foam volume and target wet density were not varied independently, the results are discussed in two subsets: Groups 3–8 at a common design density of 800 kg/m^3 , and Groups 1, 2, 5 and 9 at a common solid ratio of 1:4:5. In the latter subset the cementitious mass per cubic meter increases with target density, as listed in Table 4.

In general, the measured wet density of the fresh mixture deviated from the design value. This discrepancy is attributed to slurry–foam interaction and incomplete uniformity of the fresh DA-FLS, which made it difficult to match the target density exactly.

Among the foamed mixes designed for 800 kg/m^3 (Groups 3–5), the cement:GGBS:DA ratios were 3:4:3, 2:4:4 and 1:4:5. In this sequence the cement fraction falls from 30% to 10% of the solids, while the DA fraction rises from 30% to 50% (GGBS remains 40%). Group 3 (3:4:3) gave a measured wet density of 795.55 kg/m^3 , close to the target. The measured

densities of this subset stay near the 800 kg/m^3 target and do not indicate a systematic effect of DA content on wet density at fixed design density. Groups 6–8 could not undergo curing and demolding, yet the wet density test was still completed. These results indicate that, at a fixed design density, the binder combination affects moldability and the degree to which the target density is achieved, but they do not by themselves identify a universally optimal ratio.

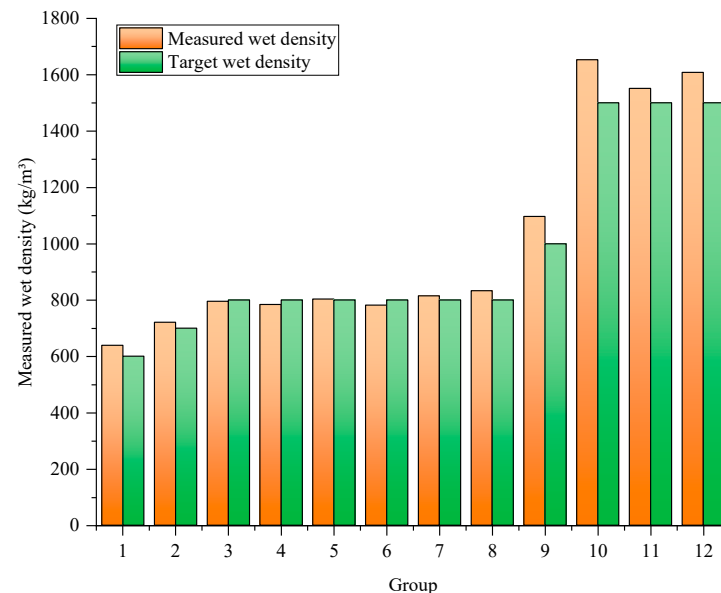


Figure 2. Target wet density and measured wet density under different ratio and wet density conditions.

Among the mixtures that shared the same solid ratio of 1:4:5 (Groups 1, 2, 5 and 9), the measured wet density increased as the foam dosage was reduced and the target density was raised, as intended by the mix design. The lowest measured value, 638.95 kg/m^3 , was obtained for Group 1, which was designed for 600 kg/m^3 with the highest foam content (650 L/m^3). The highest measured value in the foamed series, 1096.76 kg/m^3 , corresponded to the 1:4:5 mixture designed for 1000 kg/m^3 (Group 9). Thus, the ultra-low density of Group 1 reflects the high foam dosage assigned to that target, rather than an intrinsic lightweight effect of the 1:4:5 ratio.

By contrast, Groups 10–12 contained no foam. Their measured wet densities ranged from 1562 to 1758 kg/m^3 , about 1.4–2.2 times those of the foamed mixtures. The unfoamed system therefore trades part of the lightweight character for a denser structure and, as shown later, higher strength. All comparisons above are limited to the mixtures and conditions examined in this study.

CECS 249-2008 requires the measured wet density of cast-in situ foamed lightweight soil to lie within $\pm 50 \text{ kg/m}^3$ of the target. Groups 1–8 meet this limit. Group 9 does not (target 1000 kg/m^3 , measured 1096.76 kg/m^3). The excess is consistent with the higher design density of that mix and its lower foam volume, which may have allowed more foam loss or local densification before setting. Groups 10–12 contain no foam. Their measured densities (1562 – 1758 kg/m^3) exceed the 1500 kg/m^3 target by about 4–17%. Settlement and water–solids separation in the unfoamed slurry are a possible cause. The smaller offset in Groups 1–8 is consistent with the foam reducing such settlement, although partial foam collapse or an error in the material densities used in the mix calculation cannot be excluded.

3.2. Free Swell of DA-FLS and FSS

Figure 3 illustrates the free vertical swell of DA-FLS with various foam dosages and material proportions. Among the demoldable DA-FLS mixes, the 28 d free swell ranged

from 0.61% to 1.98%. Groups 3 and 4 increased markedly between 14 d and 28 d and showed no plateau. The 1:4:5 foamed mixes remained below 0.7% at 28 d but were still rising at the last measurement. These values are therefore short-term results only. For certain mix proportions the DA-FLS failed to set and could not be demolded, so no valid swell data were obtained. These cases were Group 6 (FA in place of GGBS) and Groups 7 and 8 (cement and desulfurization ash only).

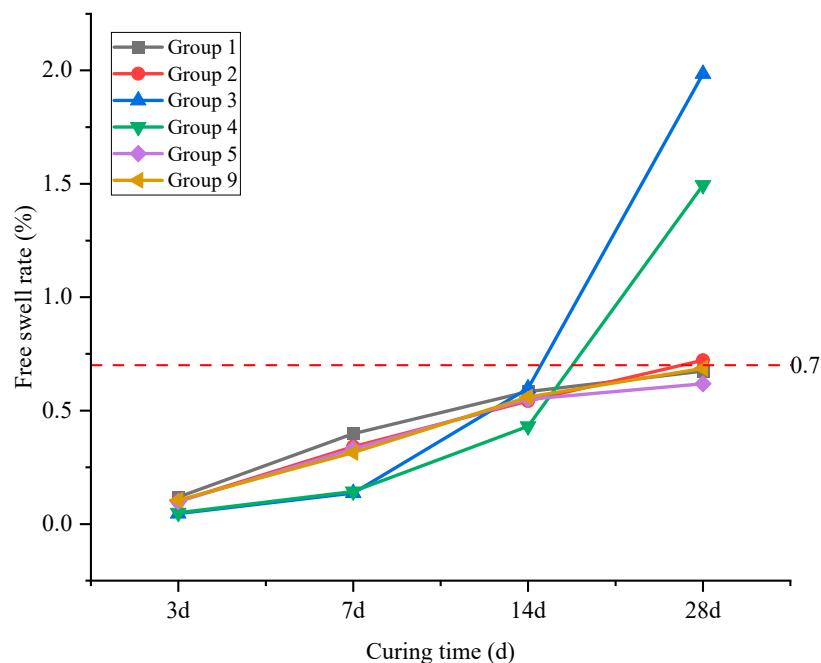


Figure 3. Free swell rate of DA-FLS under different foam dosage and material proportions. The red dashed line represents the 28-day expansion limit specified in the aforementioned standards.

Group 3 (3:4:3) combined the highest cement dosage with GGBS at a target density of 800 kg/m^3 and gave the largest 28 d swell in the foamed series (1.98%). One possible reading is that this mix was over-activated: the larger supply of portlandite and reactive aluminate, in the presence of sulphate from DA, may have produced more ettringite during the first 28 d. That reading was not confirmed by XRD on Group 3.

The present tests record the molding outcome and the swell of hardened specimens; XRD or SEM data were not collected for Groups 6–8. The failure of Group 6 is consistent with the lower reactivity of FA relative to GGBS under the alkaline conditions used here, which may have limited early formation of a load-bearing cementitious framework. The failure of Groups 7 and 8 is consistent with the low cement content in those mixes, which may have been insufficient to activate DA and generate enough binding hydrates for the foamed slurry to retain its shape. These interpretations are provisional and apply only to the mixtures and curing conditions examined in this study.

Figure 4 illustrates the free vertical swell of the DA-FSS with various material proportions under a fixed material type. With cement as the activator, the proportions of cement, GGBS and desulfurization ash were 1:4:5, 0.5:4:5.5 and 0.5:3:6.5. In this unfoamed system, as the cement and GGBS dosages decrease and the desulfurization ash content increases, the early-stage (3–7 d) swell first increases and then decreases, while the later-stage (14–28 d) swell tends to decline. Mixes with reduced cement and GGBS contents showed lower swell at later ages. Overall, the 28 d swell of the unfoamed FSS was very low, ranging only from 0.028% to 0.077%.

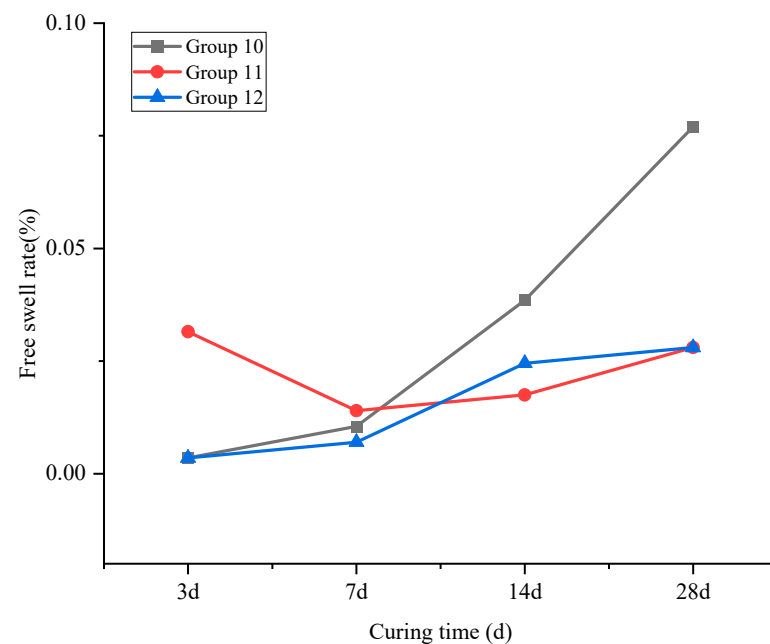


Figure 4. Free swell rate of DA-FSS with different mix proportions under cement and GGBS activation conditions.

The unfoamed matrix contains far fewer large voids than DA-FLS and develops a larger volume of solids per unit volume. This structure is consistent with the very small measured swell, in that expansive phases, if formed, would have less free space in which to produce a measurable length change. Direct identification of expansive products in Groups 10–12 was not performed, so inhibition of ettringite or other expansive phases should be regarded as a possible contributing factor rather than a demonstrated mechanism.

The 0.7% line used in the text is the total swell–shrinkage limit in the Chinese standard Specifications for Design of Highway Subgrades (JTG D30-2015) [24]. It is used here only as a reference for the 28 d free swell measurements.

3.3. UCS of DA-FLS and FSS

Figure 5 presents the UCS of DA-FLS with different foam dosage and material proportions. As shown in Figure 5, the strength of all cement-activated DA-FLS increases with curing time, reaching a high level in the late curing stage (14–28 d). This indicates that the strength of DA-FLS is primarily developed during the middle and late stages of curing, exhibiting certain retarding characteristics. For certain groups, the DA-FLS specimens could not be successfully formed and demolded; consequently, their UCS could not be measured. The groups that failed to form were Group 6 (where FA replaced GGBS) and Groups 7 and 8 (which utilized only DA and OPC), which is consistent with the previously discussed swell test results.

Groups 1, 2, 5, and 9 utilized the same solid component ratio (1:4:5) but targeted different wet densities. Within this subgroup, the DA content increased from 172 kg/m³ to 316 kg/m³; consequently, the rise in unconfined compressive strength (UCS) accompanying the increase in measured wet density reflects the higher content of cementing materials per unit volume. Thus, the increase in UCS is attributed to the combined effect of these two factors. A plausible reason is that a lower foam dosage places more solid material in a unit volume and may therefore reduce the space occupied by foam voids. The higher strength of the denser specimens is consistent with this interpretation.

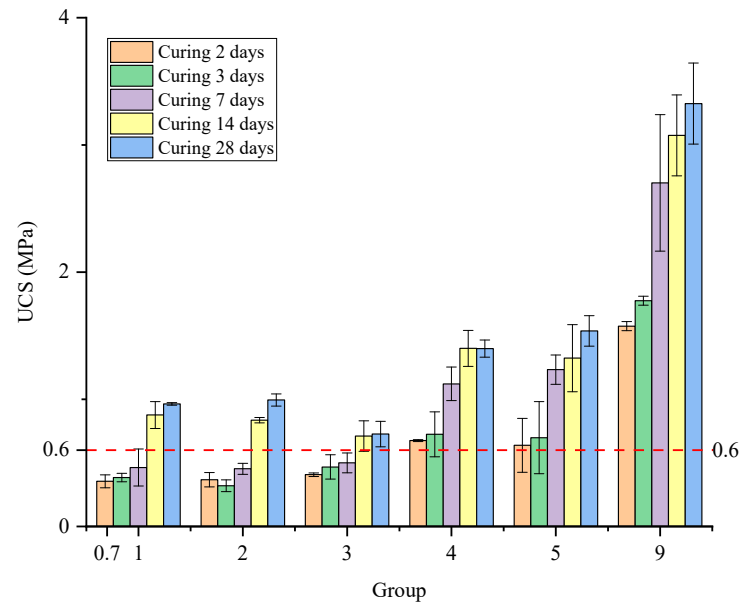


Figure 5. UCS of DA-FLS under different foam dosage and material proportions. The dashed line in the figure represents the minimum 28-day UCS limit for subgrade fill specified in the aforementioned standards.

Figure 6 presents the UCS of the unfoamed cement–GGBS–DA–FSS. Strength increased with curing age in all three groups. Without foam, the material is much stronger than DA-FLS: the 28 d UCS exceeded 10 MPa in every case and reached 20.43 MPa in Group 11. Group 11 contains less cement than Group 10 (49 vs. 98 kg/m³) yet gave the higher strength. One possible reading is a more favorable sulphate–aluminate balance in Group 11, with ettringite contributing as a filling phase rather than as a damaging expansive product; this was not confirmed by XRD or SEM on these groups. From Group 11 to Group 12, GGBS and DA were changed together, so the three unfoamed mixes are not a single-factor series.

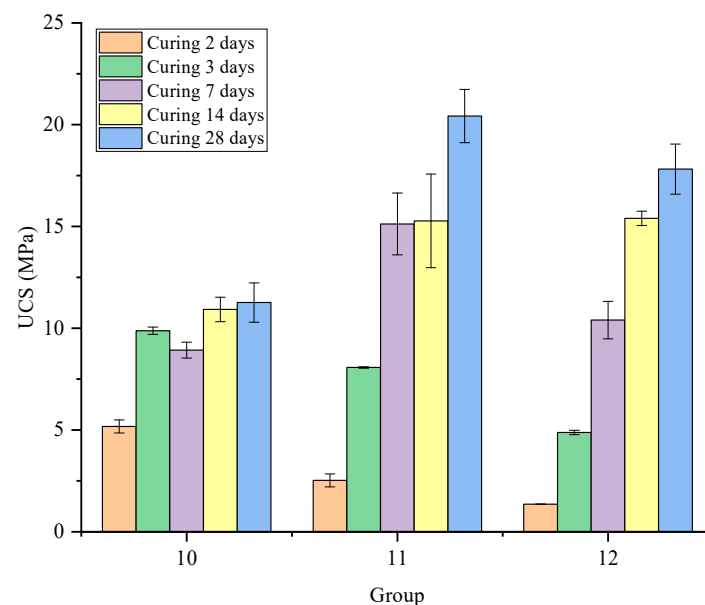


Figure 6. UCS of DA-FSS with different mix proportions under cement and GGBS activation conditions.

The design wet density of Groups 10–12 was 1500 kg/m³, but the measured values were higher, ranging from 1562 to 1758 kg/m³. Part of the high UCS of the unfoamed series should be attributed to this denser packing, in addition to the absence of foam voids. Because the measured densities also differed, the strength difference may reflect both the

binder ratio and the actual packing density, and the two contributions cannot be separated. Within Groups 10–12, the 28 d strength first increased and then decreased as the cement and GGBS contents were reduced and the DA content was raised. A possible explanation is that, at the lowest activator contents, part of the DA remained insufficiently reacted and contributed little to binding. No direct assay of unreacted DA was performed, so this explanation remains tentative and is limited to the mixtures examined here.

In accordance with the Chinese standard Specifications for Design of Highway Subgrades (JTG D30-2015), the minimum 28-day unconfined compressive strength (UCS) of subgrade fill material must exceed 0.6 MPa. All mix proportions capable of forming specimens in this study met this requirement, thereby demonstrating potential for application as highway subgrade fill.

3.4. Microscopic Experiment and Analysis

3.4.1. Mineralogical Composition Analysis (XRD)

Figure 7 presents the XRD patterns of selected DA-FLS mixtures and is used to infer the main crystalline products. Tests were conducted on Group 1 and Group 5; both groups had the same solid proportions but different wet densities—600 kg/m³ in Figure 7a and 800 kg/m³ in Figure 7b—obtained by adjusting the foam dosage. Peaks in characteristic angular ranges suggest that the hardened material contains calcium sulfate dihydrate, calcite, ettringite, calcium hydroxide and a poorly crystalline C-S-H-type phase. These assignments are based on commonly reported peak positions and should be treated as qualitative.

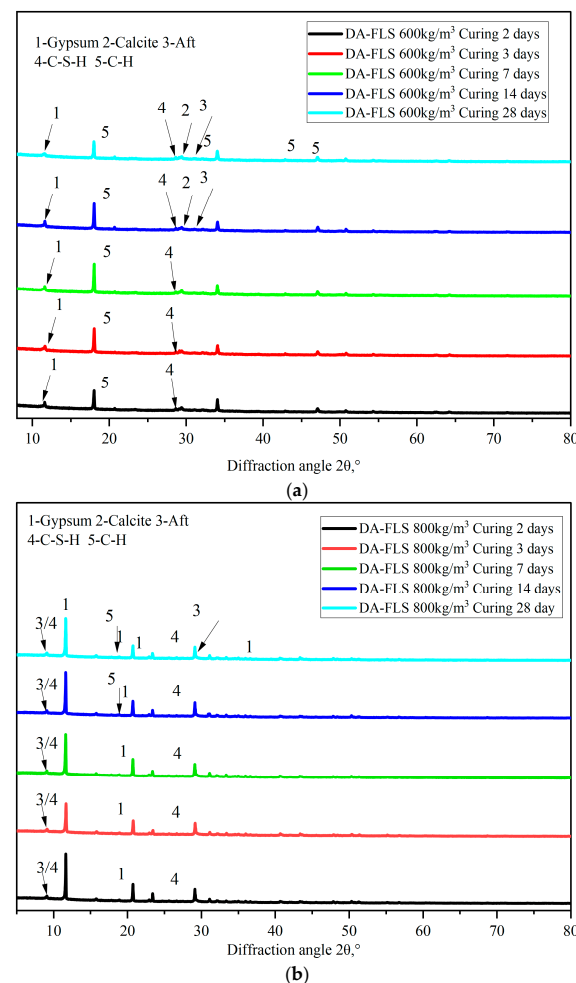


Figure 7. Mineral composition of DA-FLS at different wet densities: (a) 600 kg/m³; (b) 800 kg/m³.

As curing proceeded, the reflections assigned to ettringite appeared to become stronger, whereas those of calcium hydroxide became weaker. Broad intensity in the region often associated with C-S-H also seemed to increase. This pattern is consistent with continued hydration of the desulfurization ash and the cementitious blend, and it offers a possible explanation for the observed strength development.

A comparison between Figure 7a,b likewise suggests that some peaks assigned to ettringite and to the C-S-H region were more noticeable in the 800 kg/m³ mixture than in the 600 kg/m³ mixture. This difference may indicate more extensive hydration when the solid content per unit volume is higher. Because the patterns were not normalized for quantitative comparison, the result is reported only as a possible trend, not as evidence that higher wet density produced a larger amount of C-S-H or ettringite.

3.4.2. Scanning Electron Microscopy

Figure 8a,b present SEM micrographs of specific DA-FLS groups after 28 days of curing: Figure 8a corresponds to a wet density of 600 kg/m³ (Group 1), and Figure 8b to 800 kg/m³ (Group 5). Both groups were cured under identical conditions for 28 days, and their microstructures were examined via SEM following specimen fracture. Both specimens display a heterogeneous matrix in which flocculent gel-like material is intergrown with plate-like crystals and slender prismatic or rod-like crystals. By analogy with habits widely reported for hydrated cementitious systems, the flocculent product is tentatively attributed to C-S-H-type gel, the plates to calcium sulfate, and the prisms to ettringite; the minor granular or rhombohedral grains may correspond to calcite. The same morphologies are visible in both mixes. In Figure 8b the flocculent and rod-like features appear more closely packed, and large open voids are less apparent than in Figure 8a. This visual difference is consistent with the higher 28 d UCS of the 800 kg/m³ mixture.

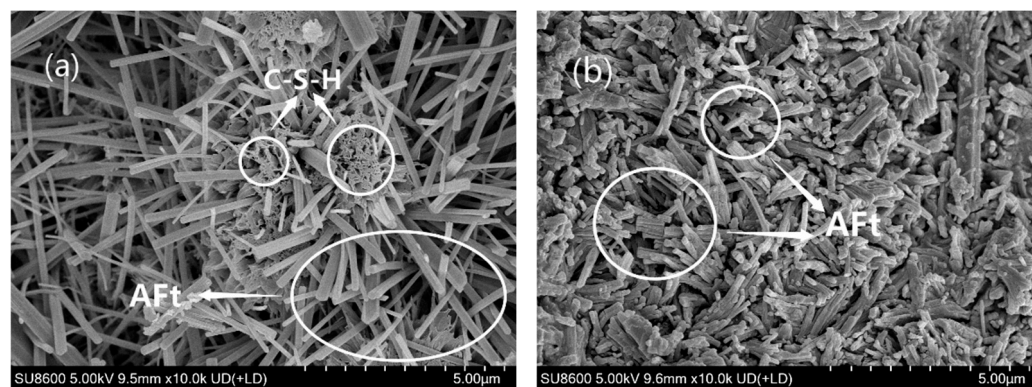


Figure 8. Microscopic morphology of DA-FLS under 28 d curing. (a) 600 kg/m³ (Group 1); (b) 800 kg/m³ (Group 5).

4. Discussion

The results indicate that a high volume of desulfurization ash can be incorporated into foamed lightweight soil when cement is used as the activator and the mix is kept within the range examined here. The result cannot be attributed to cement alone: Groups 7 and 8, without GGBS, did not set. Only the cement–GGBS–DA binder could be demolded at 2 d. Calcium hydroxide and calcium carbide slag gave slow molding: the specimens could be demolded after 7 d, but not at 2 d. RS-W-S failed and could not be demolded at 7 d. Delayed demolding and complete molding failure are therefore reported separately. A possible explanation, consistent with previous work on sulfate-rich systems, is that these activators promote a rapid reaction between sulfate from the ash and aluminate phases, favoring early or delayed

ettringite growth and thereby impairing molding or dimensional stability. Ettringite was not tracked in those failed mixes, so this mechanism remains an inference.

Swell was not measured beyond 28 d. Because Groups 3 and 4, and to a lesser extent the 1:4:5 series, had not reached a plateau, delayed ettringite growth under prolonged moist curing cannot be excluded. Future work should extend free swell tests to at least 56–90 d and couple them with phase analysis before DA-FLS is assessed for long-term volumetric stability.

Wet density and UCS did not vary with a single factor. Foam dosage, target density and binder ratio were changed together, so their effects cannot be fully separated. Within the 1:4:5 series, UCS increased with measured wet density, which is consistent with a higher solid content per unit volume and, possibly, a smaller foam-void fraction. Porosity was not measured independently, and a decrease in porosity should not be treated as a demonstrated fact. The 1:4:5 ratio combined with a design density of 600–800 kg/m³ gave, among the mixtures tested, a useful balance of low density, measurable 28 d strength and 28 d swell below 0.7% in the better-performing groups. This ratio is not claimed as a generally optimal proportion.

Relative to earlier studies that used lower ash contents or a single waste stream, the present results suggest that high-ash (>30%) DA-FLS can meet selected laboratory criteria for lightweight fill when the activator and mix window are restricted as above. Whether this route is suitable for routine highway subgrade or backfill use depends on durability and field performance, which were not assessed here. At the same time, future research should include environmental impact testing—covering leaching characteristics, sulfate release, pH levels, and potential effects on groundwater—to enable a systematic assessment of the environmental safety of DA-FLS prior to field application.

The present XRD and SEM results are only qualitative. Peak intensities were not normalized, C-S-H was not quantified, SEM features were assigned from morphology, and neither EDS nor an independent porosity measurement was performed. Future work should therefore move to a more direct microscale examination. Coupled SEM–EDS or elemental mapping would help confirm whether the flocculent, plate-like and prismatic products correspond to C-S-H-type gel, calcium sulfate and ettringite. Mercury intrusion porosimetry, or another pore-structure test, could be used to relate wet density and foam dosage to the actual void-size distribution. Quantitative or semi-quantitative phase analysis on mixes with a fixed target density or a fixed solid ratio would then allow the links among mix proportion, wet density, hydrate formation and UCS to be tested more rigorously, and would clarify the cementitious binding and strength-development mechanisms that are only inferred here.

5. Conclusions

The binder system governed molding. Among the systems in Table 3, only the cement–GGBS–DA composite binder produced DA-FLS that could be demolded at 2 d. RS-W-S failed, and calcium hydroxide and carbide slag molded slowly. Groups 7 and 8, which contained cement and DA but no GGBS, also failed to set. Cement was not a sole activator, and the three screening ratios do not show that molding is independent of cement dosage. A possible explanation is that these chemical activators promote a rapid reaction between sulfate from the desulfurization ash and aluminate phases, favoring ettringite-related expansion.

Measured wet density was jointly controlled by the binder ratio, the target density and the foam dosage; these factors were not varied independently. An ultra-low measured density of 638.95 kg/m³ was obtained for the 1:4:5 mixture designed at 600 kg/m³ with the highest foam content, rather than because that ratio is intrinsically the lightest. Unfoamed DA-FSS (Groups 10–12) had measured wet densities of 1562–1758 kg/m³, well above the foamed series, as expected in the absence of foam voids.

For normal-demolded DA-FLS, the 28 d free swell ranged from 0.61% to 1.98%. Several cement-activated 1:4:5 mixtures designed at 600–800 kg/m³ kept the 28 d swell below 0.7%, within the expansion limit cited from the Specifications for Design of Highway Subgrades for the swell check performed in this work. Groups 6–8 could not be demolded and provided no swell data. The low swell of the unfoamed FSS (0.028–0.077% at 28 d) is consistent with their denser matrix, but suppression of expansive products in those groups was not confirmed by mineralogical analysis. The results of the aforementioned short-term swelling tests indicate that the material holds potential for application as a lightweight fill; subsequent long-term swelling tests should be conducted to verify its long-term volumetric stability.

In the 1:4:5 foamed series, 28 d UCS increased with measured wet density and reached 3.3 MPa in the densest mix tested. The trend is consistent with a larger solid mass per unit volume and, possibly, a smaller foam-void fraction. Porosity and hydrate content were not measured independently, so the strength gain is not taken as proof of a lower measured porosity or of a larger quantity of binding products. Unfoamed Groups 10–12 were much stronger than DA-FLS. Group 11 gave the highest 28 d UCS among these three mixes (20.43 MPa). Their measured wet densities (1562–1758 kg/m³) exceeded the common target of 1500 kg/m³ and were not equal, which is consistent with the settlement and aggregation of the unfoamed slurry. The strength difference should therefore be read as the result of the combined effects of mix proportions and density.

The XRD patterns are consistent with gypsum, calcite, ettringite, portlandite and a poorly crystalline C-S-H-type product. Stronger signals assigned to ettringite and to the C-S-H region with age, and a visually denser SEM texture in the 800 kg/m³ mix than in the 600 kg/m³ mix, may help explain the observed strength development.

Within this laboratory program, the comparative analysis regarding practical highway engineering applications was limited to the following parameters: specimen formation, wet density, free swell ratio, and unconfined compressive strength (UCS). Based on these results, cement-activated GGBS DA-FLS with high DA content shows promise as an alternative lightweight fill material, warranting further investigation into its durability, environmental safety, and field application performance. No cost inventory or life-cycle analysis was performed. Substituting desulfurization ash and GGBS for part of the cement and natural aggregate, together with a foamed matrix, may lower binder demand and provide a route for bulk utilization of an industrial by-product. Such effects are therefore regarded only as a potential low-carbon and resource-saving benefit of the materials and methods adopted here.

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Abbreviations

The following abbreviations are used in this manuscript:

DA	Desulfurization Ash
FLS	Foamed Lightweight Soil
OPC	Ordinary Portland Cement
GGBS	Ground Granulated Blast-furnace Slag
FA	Fly Ash
SDS	Sodium Dodecyl Sulfate
MPS	Modified Polyethoxylated Silicone
CMC	Carboxymethyl Cellulose
UCS	Unconfined Compressive Strength
FSS	Flowable Solidified Soil

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