

Article

Road Performance and Durability of Dredged Soil Stabilized Using a Calcium Carbide Slag–GGBS–Fly Ash Binder

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Abstract

Dredged soil treatment and reuse remain major economic and environmental challenges in geotechnical and highway engineering. Cement-based stabilization can effectively improve the engineering properties of dredged soil, but its large-scale use is associated with high material costs, energy consumption, and carbon emissions. In this study, a solid-waste-based binder composed of calcium carbide slag (CS), ground granulated blast-furnace slag (GGBS), and fly ash (FA) was developed as a potential cement alternative for stabilizing organic-rich dredged soil in road applications. Based on mortar-performance screening, a CS:GGBS:FA mass ratio of 0.25:0.50:0.25 was selected, and the road performance and durability of the resulting CS-GGBS-FA (CGF)-stabilized soil were systematically evaluated. Laboratory tests, including California bearing ratio (CBR), dynamic resilient modulus (M_R), wet–dry (W–D) cycling, and freeze–thaw (F–T) cycling, were conducted, with cement-stabilized soil used as a reference. The results showed that the CBR and M_R of the CGF-stabilized soil increased significantly with binder content and curing time, meeting the requirements for subgrade and subbase applications under different highway classes. Compared with cement-stabilized soil, the CGF-stabilized soil showed slightly lower CBR and M_R values at the same binder content but exhibited favorable strength retention and mass stability during W–D and F–T cycling. Overall, a CGF content of at least 8% provided sufficient strength, stiffness, and durability for road use.

Keywords: multi-solid-waste binder; dredged soil; California bearing ratio; dynamic resilient modulus; durability

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1. Introduction

River siltation is a complex phenomenon resulting from both natural processes and human activities and poses significant challenges to the functioning of surrounding eco-systems and to sustainable socio-economic development. Accordingly, river dredging and sediment management have received increasing attention in recent years. Common disposal methods for dredged soil include reclamation, landfilling, and marine dumping; however, these approaches are typically accompanied by extensive land occupation, secondary environmental pollution, and high post-treatment costs [1]. In the context of the “carbon peaking and carbon neutrality” policy, sand and gravel extraction has been sub-

ject to increasing regulatory constraints, leading to a rise in material costs and a growing shortage of high-quality fill materials for highway subgrade construction [2–5]. Against this background, the reuse of dredged soil as an engineered subgrade material represents a promising and sustainable alternative. Such reuse can alleviate the shortage of earth materials for highway construction while substantially reducing the disposal and treatment costs associated with dredged soil. Nevertheless, dredged soil is typically characterized by high organic matter content, a large natural void ratio, high compressibility, high natural water content, and low bearing capacity, all of which severely restrict its direct use as subgrade fill [6]. Appropriate treatment is therefore required before engineering application.

Extensive research has investigated chemical stabilization as a means of improving the engineering properties of dredged soil and ensuring compliance with design requirements. Conventional stabilizers, such as cement and lime, have been widely used; however, their effectiveness remains limited in some cases. Shen et al. [7] reported that dredged soil treated solely with cement exhibited pronounced brittle failure, resulting in rapid deterioration of engineering performance. Likewise, lime stabilization often provides only limited improvement. For example, Sundary et al. [1] found that lime treatment increased the internal friction angle from 15.2° to 25.1° , whereas cohesion increased by less than 10% and the CBR remained only slightly above 10%. To overcome these limitations, partial replacement of lime or cement with industrial solid wastes, such as FA and GGBS, has been widely explored. Yoobanpot et al. [8] demonstrated that the combined use of ordinary Portland cement (OPC) and FA significantly improved the unconfined compressive strength (UCS), splitting tensile strength, resilient modulus, and durability of dam-bottom sediments. Hu et al. [9] reported that although quicklime was more effective than GGBS when used individually, their combined use produced superior improvement in dredged silt. Similar conclusions were drawn by Nguyen et al. [10], who showed that FA alone was less effective than hydrated lime or OPC, while their synergistic combinations produced enhanced stabilization performance.

From the viewpoint of alkali-activated binder chemistry, GGBS and FA play different but complementary roles in calcium-rich binder systems. GGBS is generally regarded as a latent hydraulic precursor, whose glassy structure can be gradually dissolved and activated under alkaline conditions, whereas low-calcium FA mainly behaves as a pozzolanic precursor and reacts more slowly with available calcium hydroxide [11–13]. In $\text{Ca}(\text{OH})_2$ -activated slag systems, the calcium-rich alkaline environment usually promotes the dissolution of reactive Si and Al species and favors the formation of C-S-H/C-A-S-H-type gels, which differs from the reaction products commonly reported in sodium-silicate-activated systems [14]. Lime-FA and related low-clinker binder systems also indicate that the balance between calcium-rich activators and aluminosilicate precursors strongly affects reaction kinetics, product formation, and long-term performance [15]. Similar continued-hydration mechanisms have also been reported in modified cementitious systems, where delayed or enhanced C-S-H development at later ages contributed to improved microstructure and performance [16,17]. Moreover, alkali-activated materials may exhibit wet–dry and freeze–thaw durability responses that differ from those of ordinary Portland cement systems [18]. Therefore, these reaction characteristics provide a useful basis for designing calcium-rich solid-waste binders as potential cement alternatives for dredged-soil stabilization. However, the manufacture of cement and lime is energy-intensive and involves extensive raw-material extraction and fossil-fuel consumption, thereby contributing substantially to carbon emissions and environmental pollution [19]. Accordingly, the development of low-cost, environmentally friendly alkaline activators that can partially or fully replace conventional binders is essential for improving both ecological and economic sustainability.

CS is a strongly alkaline industrial solid waste generated during the production of acetylene gas. Long-term stockpiling of CS has led to a range of environmental problems, including water and soil contamination [20]. Because CS is rich in calcium-bearing alkaline phases and typically shows a high CaO-equivalent content in XRF analysis, it can provide both alkalinity and calcium sources for activating slag- and fly ash-based binders [21,22]. Compared with conventional lime or cement, the use of CS as an alkaline activator can also contribute to the resource utilization of industrial waste and reduce dependence on high-carbon binders. Chu et al. [23] employed CS in combination with iron tailings sand to stabilize expansive soil and confirmed its effectiveness in improving water stability, reducing volumetric expansion, and enhancing the *CBR* and *UCS*. Xu et al. [24] investigated the synergistic stabilization effect of CS and GGBS on chloride saline soil and demonstrated that the strong alkalinity of CS effectively activated the reactivity of GGBS, thereby promoting the formation of hydration products such as calcium silicate hydrate (C-S-H), calcium aluminosilicate hydrate (C-A-S-H), and ettringite (Aft). These reactions resulted in significant improvements in *UCS*, permeability, and salt-crystallization resistance. Likewise, Liu et al. [25] reported that the combined use of CS and rice husk ash produced remarkable improvement in expansive soil, as evidenced by substantial reductions in swelling potential and notable increases in *UCS* and shear strength with increasing binder content. Ma et al. [26] examined the mechanical and microstructural properties of silty clay stabilized with CS, GGBS, and phosphogypsum (PG) and found that the CS-GGBS combination contributed more strongly to strength development than PG. However, they also observed that excessive CS adversely affected both strength and water stability. Overall, these studies indicate that CS can provide an effective alkaline and calcium-rich environment for slag-based and fly ash-containing stabilization systems. In particular, when combined with GGBS, CS exhibits high stabilization efficiency and has therefore become a preferred activator in many soil-improvement applications [27–29]. Nevertheless, the proportioning ratio among CS, GGBS, and FA plays a critical role in determining the strength development of stabilized soils. The amount of CS incorporated into the stabilizer system must therefore be carefully considered in binder design.

Based on the above considerations, this study developed a ternary CS-GGBS-FA binder as a potential cement alternative for the road-oriented stabilization of organic-rich dredged soil. Although CS-GGBS-FA and related solid-waste binders have been investigated in previous soil-stabilization studies, their application to organic-rich dredged soil remains challenging because of the high organic matter content, high water demand, and weak bearing capacity of the soil. Moreover, existing studies have mainly focused on *UCS* or microstructural evolution, whereas limited attention has been paid to road-service-related indices such as *CBR*, M_R , and durability under W–D and F–T cycling. The selected CGF binder was assessed for bearing capacity, deformation resistance, and durability through *CBR*, M_R , W–D cycling, and F–T cycling tests, with cement-stabilized soil used as a reference. The main contribution of this study is to evaluate the laboratory-scale feasibility of CGF-stabilized organic-rich dredged soil for road applications from the perspectives of bearing capacity, resilient response, environmental durability, and multi-solid-waste utilization. The findings provide a useful reference for the sustainable and resource-efficient use of dredged soil in road engineering.

2. Materials and Methods

2.1. Materials

The dredged soil used in this study was collected from a sewage-project site in Rencheng District, Jining City, Shandong Province, China. The material was deposited mainly at the bottom of the pond, with a thickness ranging from 0.5 m to 2.5 m, and exhibited a dark gray color and a fluid–plastic state. The appearance and microstructure of

the dredged soil are shown in Figure 1. The collected material was first cleaned to remove foreign matter, such as branches, leaves, and other impurities. It was then air-dried, ground, and passed through a 2 mm sieve before testing. The chemical composition of the dredged soil was determined by X-ray fluorescence (XRF) using an Axios Advanced X-ray fluorescence spectrometer (Malvern Panalytical B.V., Almelo, The Netherlands), as listed in Table 1, and its main physical and mechanical properties are summarized in Table 2.

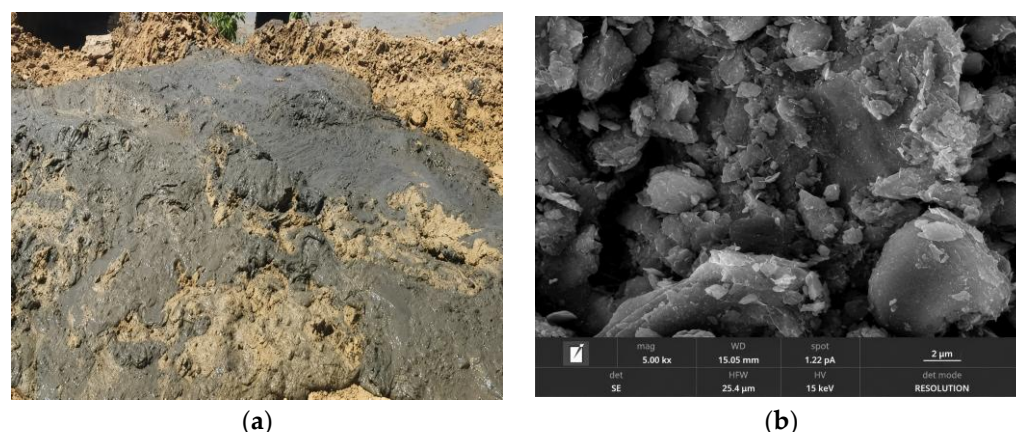


Figure 1. Appearance and microstructure of the dredged soil: (a) macroscopic appearance; (b) microstructure.

Table 1. Chemical compositions of the materials (%).

Component	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃	SO ₃	Others
Dredged soil	1.35	2.78	17.24	58.42	0.18	3.07	7.70	0.88	7.01	-	1.37
CS	-	0.10	1.45	3.10	0.02	0.04	91.53	-	0.60	1.19	1.97
GGBS	0.50	11.03	16.73	27.49	0.03	0.32	38.95	0.77	0.51	-	3.67
FA	0.84	0.86	34.90	45.96	0.58	1.16	6.03	1.52	5.88	-	2.27

Table 2. Physical and mechanical properties of the dredged soil.

Properties	Value
Specific surface area	153.7 m ² /kg
Liquid limit	34.1%
Plastic limit	19.2%
Plasticity index	14.9%
Silt content (0.002–0.075 mm)	74.2%
Clay content (<0.002 mm)	25.8%
Maximum dry density	1.75 g/cm ³
Optimum water content	16.7%
Natural water content	40%~90%
Organic content	12.19~17.4%

The CS used in this study was obtained from a chemical plant in Wuhan, Hubei Province. According to the supplier information, its specific surface area (SSA) was 488.5 m²/kg, and its particle size was mainly distributed between 0.005 mm and 0.015 mm. As shown in Table 1, CS exhibited a high CaO-equivalent content of 91.53%. It should be noted that the CaO content determined by XRF represents the oxide-equivalent calcium content and does not directly distinguish between Ca(OH)₂ and carbonated calcium phases. Therefore, the CaO value was used only to characterize the calcium-rich nature of CS rather than to quantify its active Ca(OH)₂ content.

The GGBS used in this study was supplied by an iron plant in Nanjing. The SSA of GGBS was 492 m²/kg, and its particle size was mainly distributed between 0.005 mm and 0.023 mm. Its principal constituents were CaO, SiO₂, Al₂O₃, and MgO, which together accounted for 93.75% of the total composition, as shown in Table 1.

The FA used in this study was obtained from a chemical plant in Jinan, Shandong Province. Its specific surface area was 579.8 m²/kg, and its particle size was mainly distributed between 0.005 mm and 0.039 mm. It consisted primarily of Al₂O₃, SiO₂, CaO, and Fe₂O₃, and the detailed composition is listed in Table 1.

The appearance and microstructure of the binders (CS, GGBS, and FA) are presented in Figure 2, and the microstructures were observed using a scanning electron microscope (SEM; JSM-5600LV, JEOL Ltd., Akishima, Tokyo, Japan).

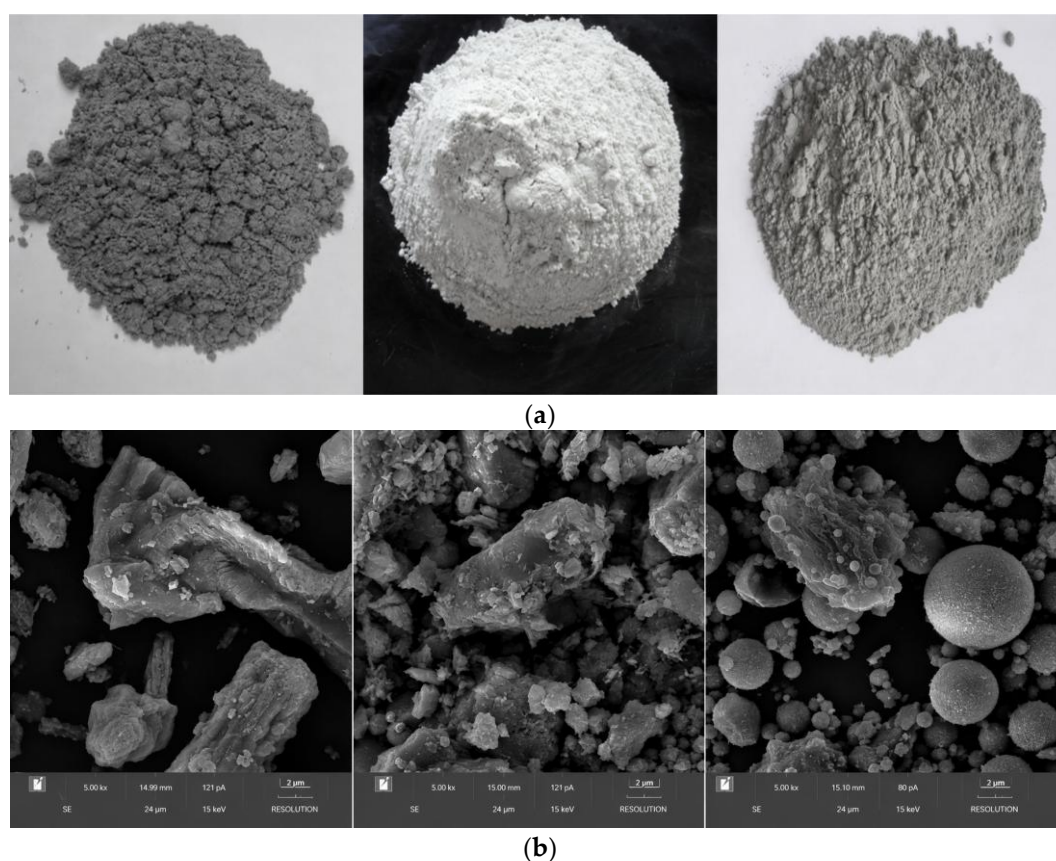


Figure 2. Appearance and microstructure of CS, GGBS, and FA: (a) macroscopic appearance; (b) microstructure.

2.2. Methods

2.2.1. Mix Design

In this study, CS, GGBS, and FA were blended to produce a composite binder, in which CS acted as the alkaline activator, while GGBS and FA served as the latent hydraulic and pozzolanic components, respectively. The proportions of these components should allow sufficient interaction between the activator and the reactive binder components, thereby enabling the binder system to achieve satisfactory early- and long-age strength.

A feasible range of CS-GGBS-FA proportions was adopted from previous mortar-based studies by Ju [30] and Yang [31], as shown in Figure 3. These proportions were established through compressive and flexural strength tests on solid-waste-based mortar. The mortar specimens were prepared in accordance with the Chinese standard GB/T 17671-2021 [32], with a binder-to-standard sand-to-water ratio of 1:3:0.5. The curing ages were 7, 28, and 56 d, and the corresponding test results are presented in Figure 4. As

shown in Figure 4, two local high-strength regions were observed in the mortar-strength results. The CGF-1 mixture showed slightly higher 7 d and 28 d strengths, whereas the CGF1-2-1 mixture exhibited the highest 56 d flexural and compressive strengths among all tested mortar mixtures. Therefore, considering the importance of long-term strength development for stabilized soil, the CS:GGBS:FA mass ratio of 0.25:0.50:0.25 was selected as a mortar-screened candidate binder ratio and adopted for the dredged-soil stabilization tests in the present study. It should be emphasized that this ratio was not intended to represent a universally optimal proportion for all dredged soils but was used to evaluate the feasibility of CGF-stabilized dredged soil under a fixed binder composition.

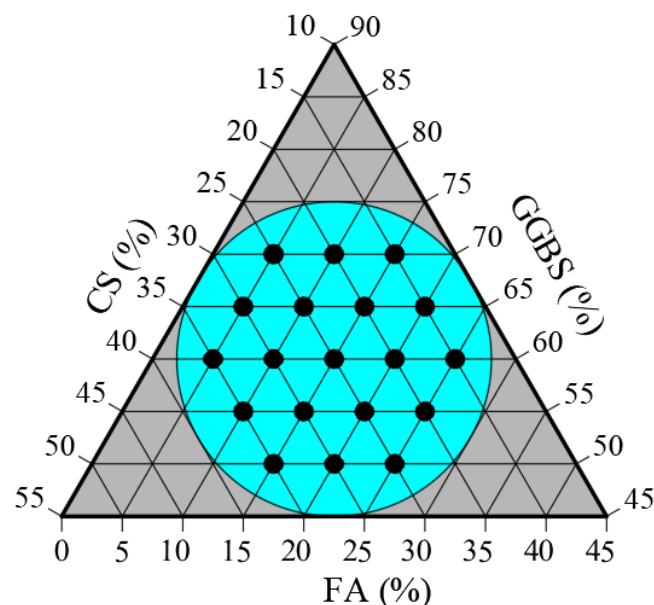


Figure 3. Proportioning range of CS, GGBS, and FA [30].

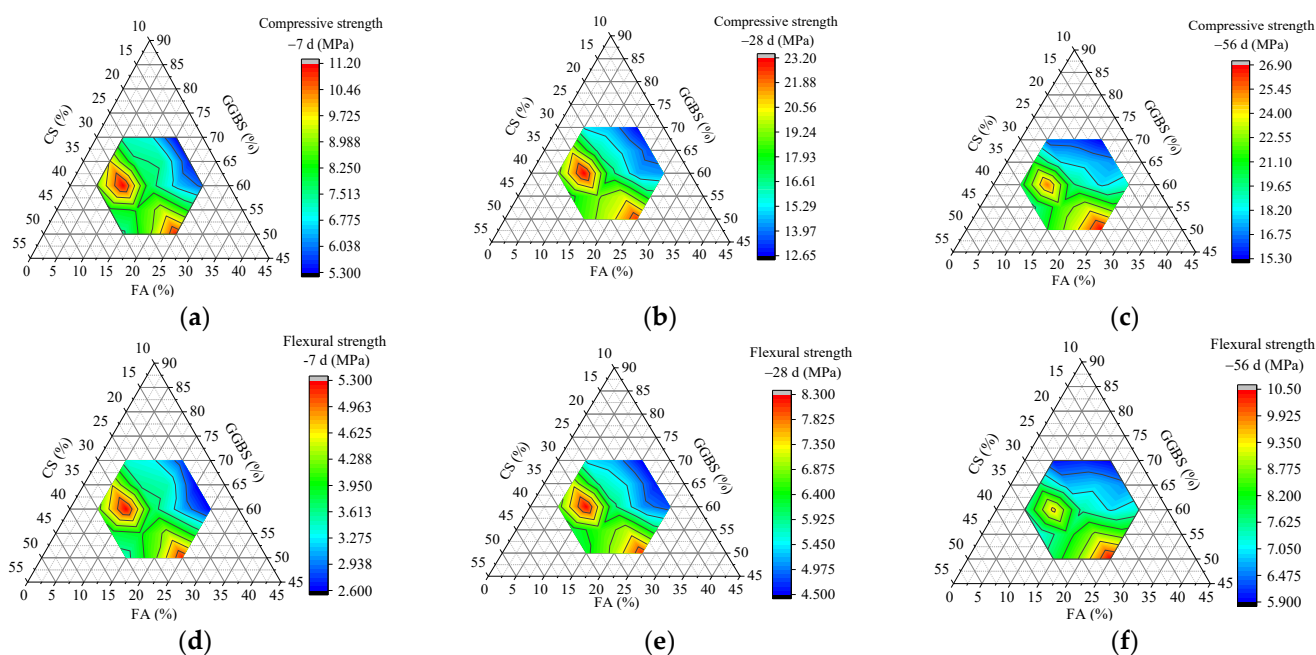


Figure 4. Mortar strength test results [30]: compressive strength at (a) 7 d, (b) 28 d, and (c) 56 d, and flexural strength at (d) 7 d, (e) 28 d, and (f) 56 d.

Because limited information is available on the dosage of this binder for dredged-soil stabilization, a relatively wide binder-content range of 6–15% was considered in this study.

Cement-stabilized dredged soil was used as the control to evaluate the improvement achieved by the proposed binder system. The detailed mix proportions of the CS-GGBS-FA (CGF)-stabilized dredged soil and the control specimens are presented in Table 3.

Table 3. Mix proportions of the CGF-stabilized dredged soil and the control specimens [30].

No.	Type	Binder Content (%)
1	CGF-stabilized dredged soil	6
2		8
3		10
4		12
5		15
7	Cement-stabilized dredged soil (control specimens)	4
8		6
9		10

Note: The cement used for the control specimens was ordinary Portland cement (P.O 42.5).

2.2.2. Specimen Preparation

The durability of the CGF-stabilized dredged soil was evaluated based on the UCS evolution of specimens subjected to W–D and F–T cycling.

The specimens used for the UCS test and the dynamic triaxial cyclic loading test were identical in size and were cylindrical, with a diameter of 50 mm and a height of 100 mm. All specimens were molded at the optimum moisture content (OMC), and the compaction degree was set at 96% to simulate practical roadbed construction conditions. To improve specimen uniformity, all samples were statically compacted in three layers using a steel mold. The specimens for the CBR test were prepared by heavy compaction in accordance with the Chinese standard JTG 3430-2020 [33], and the compaction mold had an inner diameter of 152 mm and a height of 120 mm. The specimens were compacted in three layers with 50 blows per layer, resulting in a compaction degree greater than 96%. The maximum dry density (MDD) and OMC of each mixture are listed in Table 4.

Table 4. MDD and OMC values of CGF- and cement-stabilized dredged soils.

Binder Type	Binder Content (%)	MDD (g/cm ³)	OMC (%)
CGF	6	1.683	20.1
	8	1.671	20.6
	10	1.647	21.0
	12	1.624	21.9
	15	1.613	23.2
Cement	4%	1.647	16.9
	6%	1.636	17.5
	10%	1.608	18.8

As shown in Table 4, increasing binder content generally decreased the MDD and increased the OMC of both CGF- and cement-stabilized dredged soils. This trend can be mainly attributed to the increasing proportion of fine binder particles and the corresponding increase in water demand. Compared with cement-stabilized soil, the CGF-stabilized soil showed a higher OMC at comparable binder contents, indicating a higher effective water demand of the CS-GGBS-FA binder system. This may be related to the fine-particle characteristics and water-absorbing capacity of the ternary solid-waste binder, as well as the interaction between the calcium-rich binder and the organic-rich dredged soil. In particular, the relatively high OMC of CGF15 may be associated with the increased amount of fine binder and the water-binding effect of organic matter in the dredged soil.

The specimen preparation procedure was as follows. Because GGBS and cement exhibit rapid hardening characteristics, the pre-weighed water and pretreated soil were first mixed until no visible lumps remained, and the mixture was then sealed in a plastic bag for 24 h to allow moisture equilibration. Subsequently, CS, GGBS, and FA were weighed and blended thoroughly before being added to the prepared soil-water mixture, after which mixing continued until a homogeneous paste was obtained. Following the target mix proportions, sufficient material was prepared for each specimen group. After molding, the specimens were demolded and wrapped with cling film to prevent moisture loss. They were then labeled and transferred to a curing room maintained at 20 ± 2 °C and $90 \pm 5\%$ relative humidity for curing periods of 7, 28, and 56 d. To ensure the reliability of the test results, at least three parallel specimens were prepared for each test condition.

2.2.3. Testing Procedures

In this study, the road performance of CGF-stabilized dredged soil was evaluated using the CBR test and the dynamic resilient modulus test.

For the CBR test, specimens cured for the specified periods were soaked in water for 96 h prior to testing. During the test, four surcharge plates and a penetration rod (50 mm in diameter and 100 mm in height) were placed on the specimen in sequence, and penetration loading was applied using a universal testing machine at a rate of 1 mm/min. Loading continued until the penetration depth reached 5 mm. The loads ($P_{2.5}$ and P_5) corresponding to penetration depths of 2.5 and 5 mm were recorded, and the CBR values ($CBR_{2.5}$ and CBR_5) were calculated using Equations (1) and (2). The larger of the two values was taken as the final CBR of the tested specimen.

$$CBR_{2.5} = \frac{P_{2.5}}{7000} \times 100 \quad (1)$$

$$CBR_5 = \frac{P_{5.0}}{10500} \times 100 \quad (2)$$

For the dynamic resilient modulus (M_R) test, a GDS dynamic triaxial loading system was used to apply cyclic loading to the specimens. Two application scenarios, namely roadbed and embankment conditions, were considered. Based on the lateral and axial stresses expected in different structural layers under self-weight and vehicle loading, the corresponding cyclic loading program was established, as listed in Table 5 [30]. Previous studies have shown that when the cyclic load reaches 5000 cycles, the mechanical response of undamaged specimens tends to stabilize [34]. Accordingly, 5000 loading cycles were adopted in this study to meet the requirements for dynamic-strength evaluation.

Table 5. Test parameters for dynamic triaxial cyclic loading [30].

No.	Confining Pressure σ_3 (kPa)	Contact Stress (kPa)	Cyclic Deviator Stress σ_1 (kPa)	Maximum Axial Stress (kPa)
1	60	12	35	107
2	60	12	50	122
3	60	12	75	147
4	60	12	90	162
5	45	9	35	89
6	45	9	50	104
7	45	9	75	129
8	45	9	90	144
9	30	6	35	71
10	30	6	50	86

11	30	6	75	111
12	30	6	90	126
13	15	3	35	53
14	15	3	50	68
15	15	3	75	93
16	15	3	90	108

For durability assessment, a series of W–D and F–T cycling tests was conducted to evaluate the performance of the stabilized dredged soil under different environmental conditions. Specimens cured for 28 d were used for these tests, and both the W–D and F–T tests were conducted for 10 cycles. The W–D and F–T cycling tests were conducted with reference to the Chinese standard JTG 3441-2024 [35], which specifies test methods for inorganic-binder-stabilized materials used in highway engineering. During each W–D cycle, the specimen was immersed in tap water with a pH of approximately 7 for 24 h, removed, and drained for 1 h. Its UCS, mass, and surface condition were then recorded. The specimen was then placed in an oven and dried at 40 °C for 24 h, after which the same indices were recorded again. For the F–T cycling test, the specimens were immersed in tap water for 24 h before freezing. During immersion, the specimens were completely submerged, and the water level was maintained approximately 25 mm above the top surface of the specimens. After immersion, the surface water was gently removed using a wet cloth before the specimens were transferred into the freezing chamber. Each F–T cycle consisted of 16 h of freezing at −15 °C and 8 h of thawing in a 20 °C water bath, and 10 cycles were conducted in total. During F–T cycling, the specimens were not sealed or wrapped. The freezing chamber was controlled by setting the target temperature, and the temperature ramp rate and internal specimen temperature were not independently measured. Therefore, the stated freezing duration refers to the exposure time under the target chamber temperature. This 24 h free-immersion preconditioning was adopted to represent a practical moisture exposure condition before freezing, because water ingress into stabilized soil during service generally occurs through rainfall infiltration, groundwater fluctuation, capillary absorption, and pore-water migration rather than forced saturation. In addition, the amount of water absorbed within a given immersion period is closely related to the pore structure and permeability resistance of the stabilized soil itself, which is also an important aspect of its freeze–thaw resistance. Therefore, the F–T results should be interpreted as comparative laboratory durability results under the adopted chamber-controlled condition and 24 h free-immersion preconditioning, rather than as results under a fully forced-saturated condition.

3. Results and Discussion

3.1. CBR of the Stabilized Dredged Soil

Figure 5 illustrates the effects of binder content and curing time on the CBR of the CGF- and cement-stabilized dredged soils. As shown in Figure 5a, the untreated dredged soil had a CBR of only 5.58%, whereas the addition of either CGF or cement substantially increased the CBR. Specifically, when the CGF content increased from 0% to 6%, the 28 d CBR increased by 4.42 times, while increasing the cement content from 0% to 4% led to a 5.85-fold increase. With further increases in binder content, the CBR of both the CGF- and cement-stabilized dredged soils continued to rise. When the binder content increased from 6% to 10%, the CBR of the CGF- and cement-stabilized soils increased by 127.43% and 34.66%, respectively. This indicates that, within the tested 6–10% binder content range, the CBR of the CGF-stabilized soil was more sensitive to binder dosage than that of the cement-stabilized soil. This behavior may be related to the different reaction characteristics and moisture demand of the two binder systems. Cement is a hydraulic binder

with a relatively fast hydration rate, and a large proportion of its strength is generally developed before 28 d. However, under the OMC-based compaction condition, the available water must first satisfy soil wetting, compaction, and pore-water demand, and may not be sufficient to support further hydration as cement content increases. Therefore, the increase in *CBR* with increasing cement content at 28 d may be relatively limited. In contrast, the CGF binder contains GGBS and FA, whose latent hydraulic and pozzolanic reactions develop more gradually under the alkaline and calcium-rich environment provided by CS. As a result, the *CBR* of the CGF-stabilized soil showed a more pronounced increase with binder content at 28 d, reflecting the combined effects of gradual cementation, pore filling, and skeleton stabilization. This interpretation is consistent with the findings of Guo et al. [36] who reported that the improvement in engineering performance of stabilized soil arises from both the filling effect and the bonding effect of the binder, and that the contribution of these mechanisms varies with binder type. Compared with *UCS*, the contribution of the filling effect to *CBR* is more pronounced.

The variations in *CBR* with curing time for CGF- and cement-stabilized dredged soils are presented in Figure 5b. The *CBR* of both stabilized soils increased continuously with curing time, although the growth rates differed. When the curing period was shorter than 7 d, the *CBR* growth rate of the CGF-stabilized dredged soil was slightly lower than that of the cement-stabilized soil. However, the trend reversed once the curing time exceeded 7 d. Specifically, from 7 to 28 d, the *CBR* of the CGF- and cement-stabilized dredged soils increased by 171.62% and 118.81%, respectively; the increase in the CGF-stabilized soil was approximately 1.44 times that in the cement-stabilized soil. From 28 to 90 d, the corresponding increases were 105.88% and 64.97%, respectively; the increase in the CGF-stabilized soil was approximately 1.63 times that in the cement-stabilized soil. These results indicate that the CGF-stabilized soil exhibited more pronounced medium- and long-term *CBR* development under the tested conditions. This behavior may be attributed to the complementary effects of GGBS and FA, whereby GGBS contributes to earlier strength development and FA enhances later-age performance.

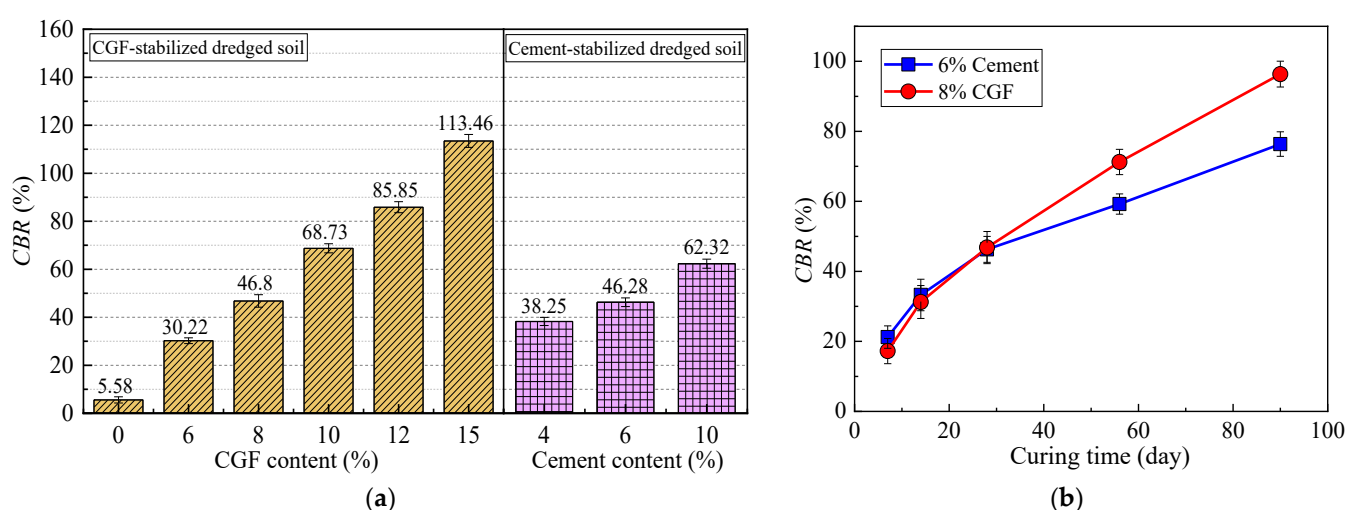


Figure 5. *CBR* values of CGF- and cement-stabilized dredged soil: (a) effect of binder content; (b) effect of curing time.

According to the subgrade bearing-capacity requirements specified in the Chinese standard JTG 3430-2020 [33], all the CGF- and cement-stabilized dredged soils shown in Figure 5a satisfy the minimum *CBR* requirement for subgrade filling. For road-base construction, and with reference to the *CBR* requirements for graded crushed stone in JTG/T F20-2015 [37], the dredged soil stabilized with 15% CGF and cured for 28 d can satisfy the

subbase requirements for expressways and first-class highways under heavy traffic conditions. The soil stabilized with 12% CGF and cured for 28 d can meet the subbase requirements for expressways and first-class highways under medium to light traffic conditions. In addition, the dredged soil stabilized with 10% CGF and cured for 28 d can be used as subbase fill for secondary and lower-grade highways under medium to light traffic conditions.

3.2. M_R of the Stabilized Dredged Soil

To evaluate the effect of binder content on the M_R of dredged soil used in different structural layers, the stabilized soils cured for 28 d were examined under roadbed and embankment application scenarios (Figure 6). Based on the stress states listed in Table 5, a confining pressure of 15 kPa and a deviator stress of 50 kPa were adopted to simulate the roadbed condition, whereas a confining pressure of 30 kPa and a deviator stress of 35 kPa were used to represent the embankment condition.

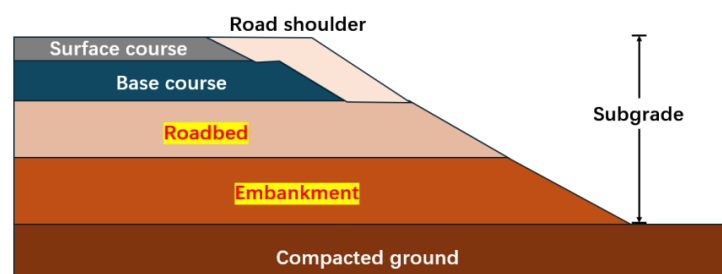


Figure 6. Schematic diagram of road structure.

Figure 7 shows the effect of binder content on the M_R of the stabilized soils under roadbed and embankment conditions. Considering that the cement content commonly used for subgrade improvement is approximately 4%, a cement content of 10% was not included here. As shown, the M_R of both the CGF- and cement-stabilized dredged soils increased with increasing binder content. Specifically, as the CGF content increased from 6% to 15%, the M_R of the CGF-stabilized dredged soil increased from 237.6 MPa to 374.08 MPa in the roadbed area and from 209.6 MPa to 348.25 MPa in the embankment area, corresponding to increases of 57.44% and 66.16%, respectively. For the cement-stabilized dredged soil, increasing the cement content from 4% to 6% raised the M_R from 219.06 to 248.7 MPa in the roadbed area and from 196.29 to 213.21 MPa in the embankment area, corresponding to increases of 13.53% and 8.62%, respectively. According to the subgrade resilient-modulus requirements specified in JTG D50-2017 [38], all M_R values of the CGF- and cement-stabilized dredged soils within the investigated binder-content range far exceed the requirement for subgrades subjected to very heavy traffic.

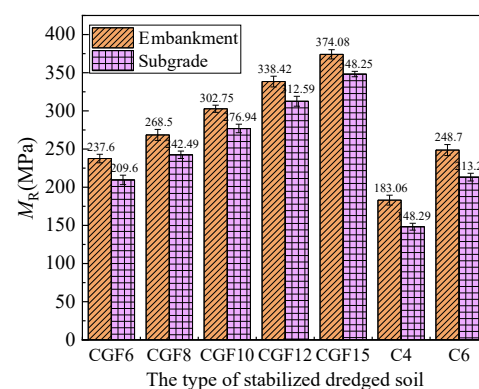
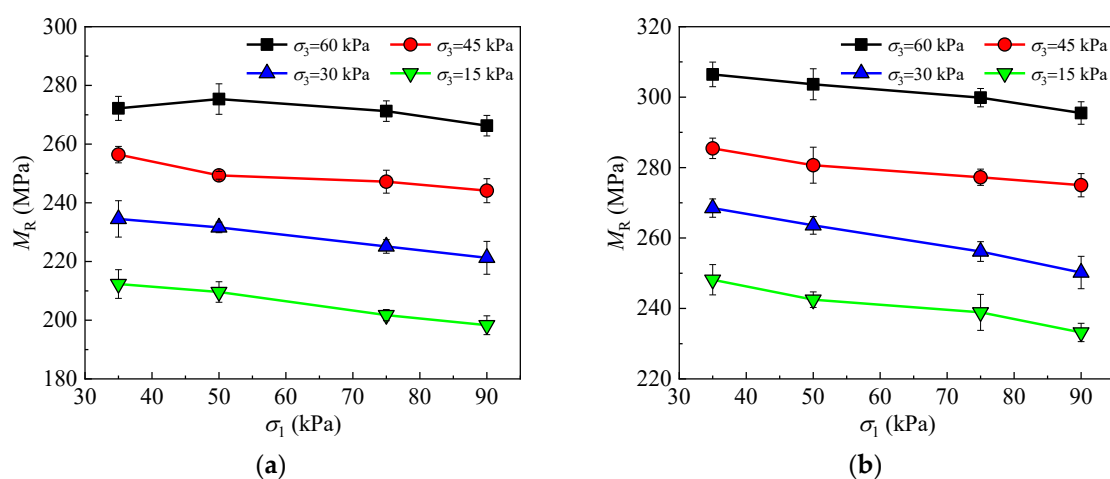


Figure 7. M_R of stabilized dredged soil with different binder contents.

Compared with the variation in *CBR*, the M_R of both stabilized soils exhibited relatively low sensitivity to changes in binder content. Moreover, high M_R values were achieved for all stabilized soils within the investigated binder-content range at a compaction degree of 96%, indicating that the degree of compaction plays a more important role in M_R development than binder content. Therefore, in practical design, the selection of binder content should primarily be guided by the *CBR* requirement, provided that an appropriate compaction degree can be achieved.

Overall, although the *CBR* and M_R of the cement-stabilized dredged soil were slightly higher than those of the CGF-stabilized dredged soil at the same binder content, the CGF-stabilized soil still satisfied the relevant road-performance requirements under the adopted laboratory conditions. Therefore, the CGF binder shows potential as a cement alternative for dredged-soil stabilization, particularly from the perspective of multi-solid-waste utilization and cement reduction.

To verify the applicability of the stabilized dredged soils under different traffic loads and road layers, a range of loading conditions was designed, as shown in Table 5. The effects of confining pressure and deviator stress on the CGF-stabilized dredged soils cured for 28 d are presented in Figure 8. At a given confining pressure, increasing the deviator stress led to greater vertical deformation and lower M_R . Conversely, at a given deviator stress, increasing the confining pressure reduced vertical deformation and increased M_R . These results reflect the stress and deformation states experienced by subgrades during service. In actual subgrade structures, the region closer to the road surface is subjected to larger deviator stress and lower confining pressure and is therefore more susceptible to vertical deformation. Taking the CGF6-stabilized dredged soil as an example, when the confining pressure was 15 kPa, the M_R values corresponding to deviator stresses of 35 kPa, 50 kPa, 75 kPa, and 90 kPa were 212.32 MPa, 209.6 MPa, 201.72 MPa, and 198.29 MPa, respectively. When the deviator stress was 90 kPa, the M_R values corresponding to confining pressures of 15 kPa, 30 kPa, 45 kPa, and 60 kPa were 198.29 MPa, 221.25 MPa, 244.13 MPa, and 266.28 MPa, respectively. These results indicate that even the soil stabilized with 6% CGF satisfied the resilient-modulus requirement for very heavy traffic, demonstrating sufficient resistance to deformation.



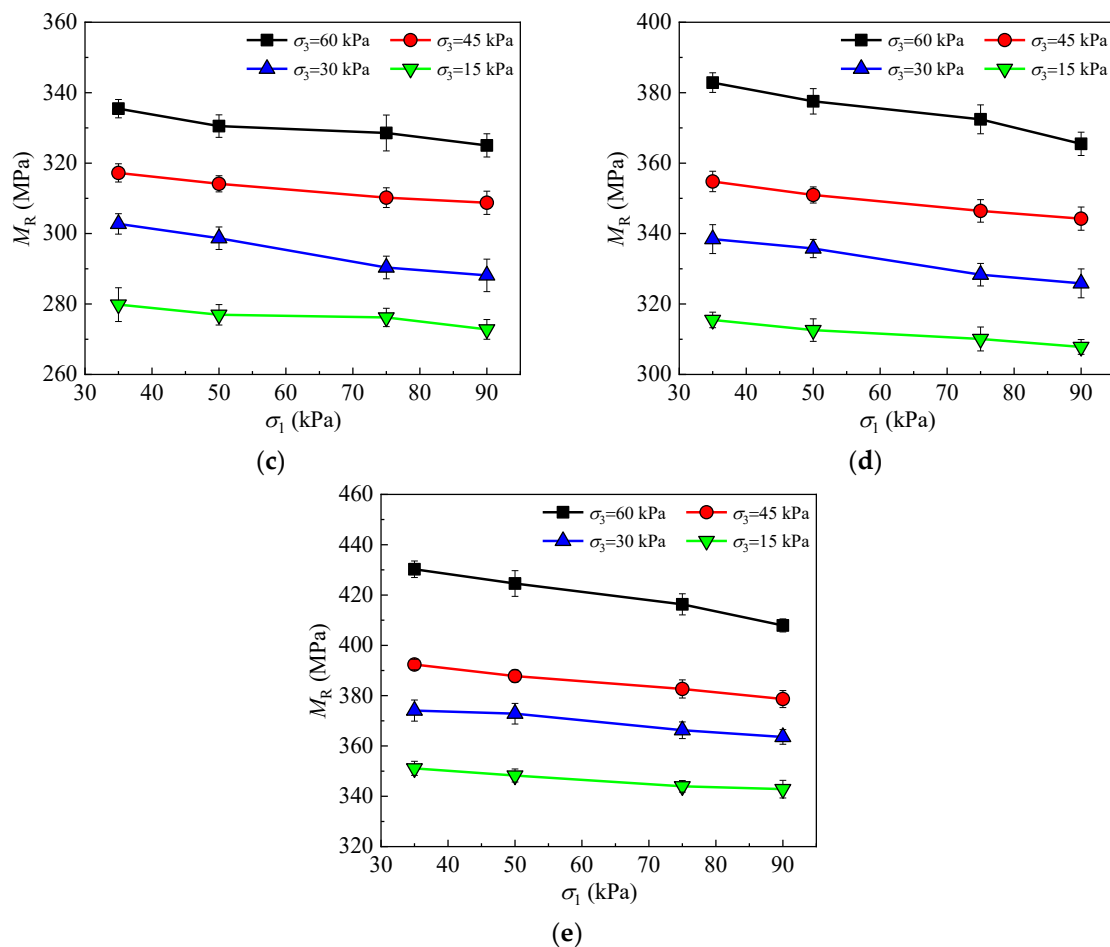


Figure 8. Effects of confining pressure and deviator stress on M_R : (a) CGF6; (b) CGF8; (c) CGF10; (d) CGF12; (e) CGF15.

3.3. Durability of the Stabilized Dredged Soil

3.3.1. Effect of W–D Cycle

The W–D cycling test is widely used in construction and road-material research to evaluate material stability and reliability under alternating wet and dry conditions. In this study, W–D resistance was assessed in terms of changes in strength, mass, and appearance.

Figure 9 shows the UCS evolution of the CGF- and cement-stabilized dredged soils during W–D cycling. The CGF6 and C4 specimens failed after 8 and 5 W–D cycles, respectively, making it impossible to obtain further performance data. As shown in Figure 9a, the UCS of the CGF-stabilized dredged soils exhibited a fluctuating downward trend with increasing W–D cycles, initially decreasing, then slightly increasing, and finally decreasing again. For the specimens that survived 10 W–D cycles, the UCS increased with increasing CGF content. Specifically, the UCS of the lowest-content specimen decreased to 0.21 MPa after 8 cycles, representing a reduction of 84.9%, whereas the CGF15 specimen still retained a relatively high UCS of 2.4 MPa after 10 cycles, corresponding to a decrease of 32.4%. As shown in Figure 9b, the UCS of the C6 specimen also displayed a fluctuating downward trend during W–D cycling, decreasing from 1.13 MPa to 0.2 MPa, a reduction of 82.3%. The comparison shown in Figure 9c indicates that the UCS of the CGF6 specimen was higher than that of the C6 specimen during the first four W–D cycles, after which the CGF6 and C6 curves intersected and gradually converged to a similar residual strength level of approximately 0.2 MPa. This result suggests that the W–D resistance of the two low-content stabilized soils should be interpreted according to the full cycling process

rather than only the early-cycle response. Although CGF6 exhibited a higher *UCS* in the initial cycles, its strength decreased rapidly in the later cycles and reached a very low level after eight cycles, whereas C6 still maintained measurable strength until the tenth cycle. Therefore, the low-content comparison does not support a consistent superiority of either binder system under W–D cycling. More importantly, these results suggest that conventional cement stabilization with 4–6% cement, as well as 6% CGF stabilization, is insufficient for improving this dredged soil under repeated W–D exposure. For CGF-stabilized dredged soil, a higher binder content is necessary to achieve more stable strength retention during W–D cycling.

The degradation of stabilized dredged soil during W–D cycling can be attributed to repeated water infiltration, flushing, and erosion within the specimen, which gradually generate new pore channels and even cracks, thereby reducing *UCS* [39]. Notably, all *UCS* curves exhibited fluctuating trends during the W–D cycling. This behavior reflects the combined action of two competing processes: the detrimental effect of W–D cycling and the beneficial effect of ongoing binder reactions. During W–D cycling, infiltrated water erodes the internal structure of the specimen while simultaneously promoting the hydration and pozzolanic reactions of the binders. When deterioration dominates, the internal structure becomes looser, the material density decreases, and the *UCS* declines. When the reaction products compensate for, or locally repair, the induced damage, the internal structure becomes denser and the *UCS* may temporarily increase.

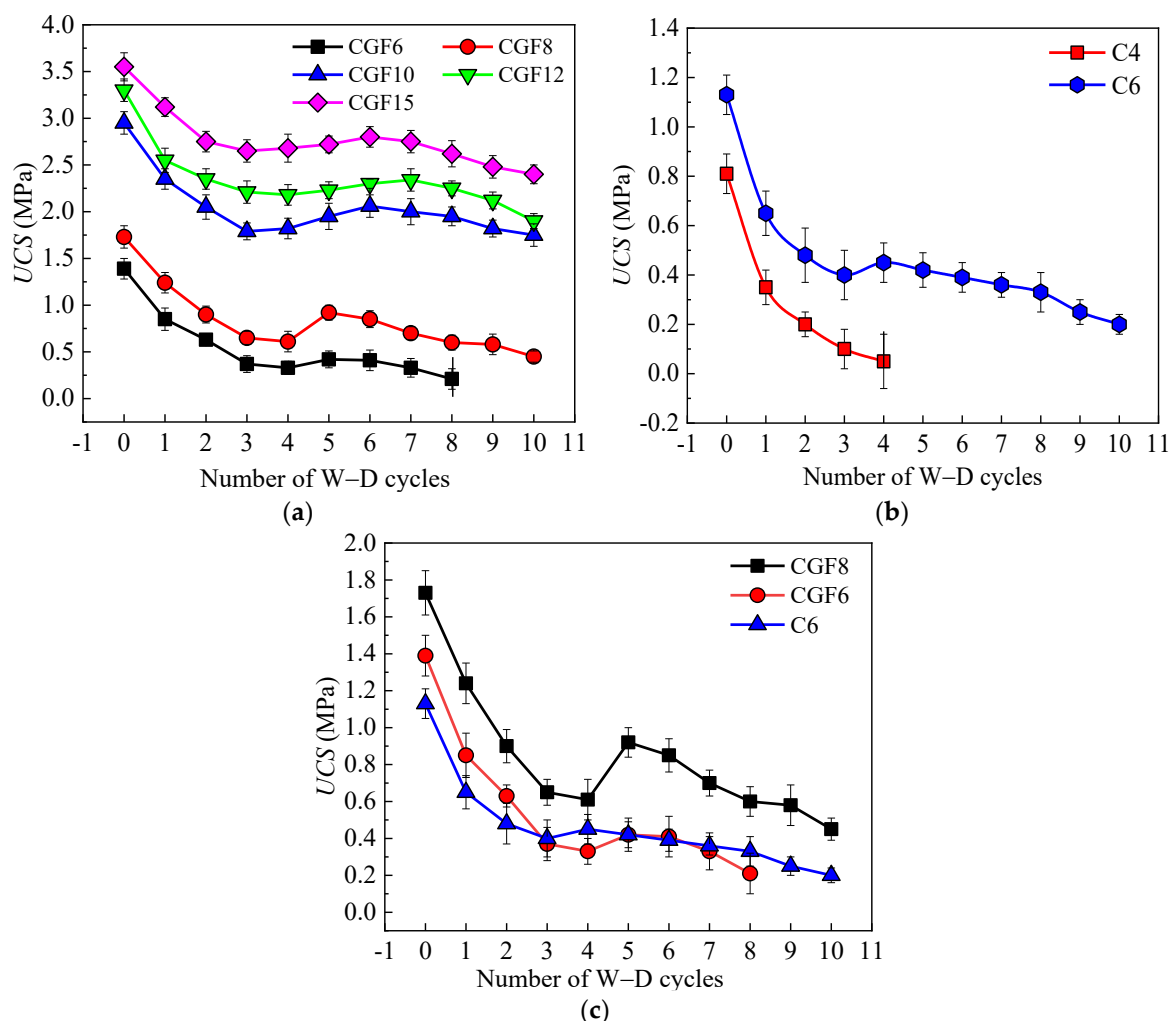
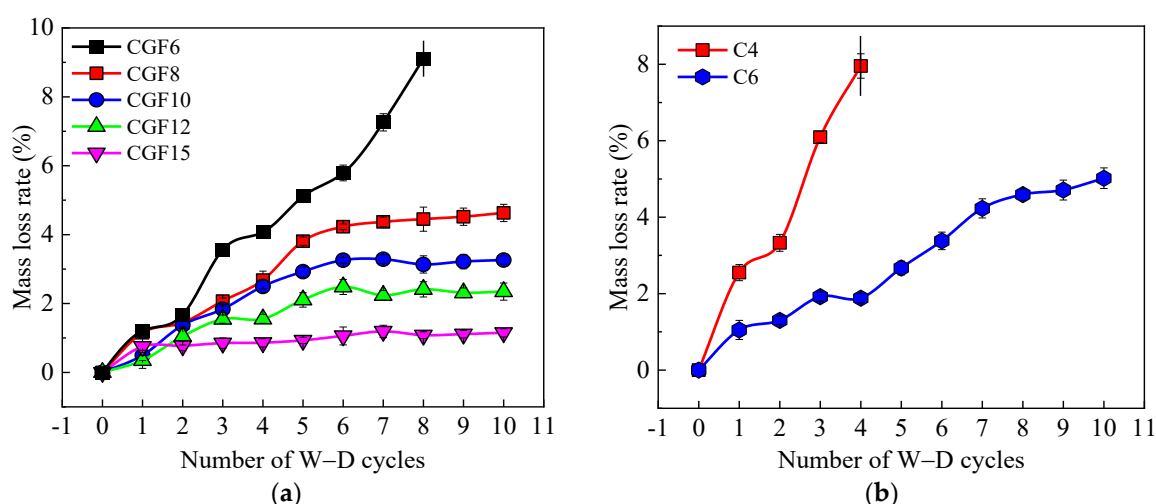


Figure 9. *UCS* of stabilized dredged soil during W–D cycling: (a) CGF-stabilized dredged soil; (b) cement-stabilized dredged soil; (c) comparison between CGF- and cement-stabilized dredged soils.

Figure 10a,b show the evolution of mass-loss rate in the CGF- and cement-stabilized dredged soils during W–D cycling. The mass-loss rate of all stabilized-soil specimens generally increased with the number of cycles. The increase was pronounced during the early stage (the first five or six cycles) but slowed or decreased during later cycles. For specimens subjected to the same number of cycles, the mass-loss rate decreased as binder content increased. The CGF6 and C4 specimens failed after 8 and 4 cycles, respectively, with final mass-loss rates of 9.11% and 7.96%. For the CGF-stabilized dredged soils after 10 W–D cycles, increasing the CGF content from 8% to 15% reduced the mass-loss rate from 4.63% to 1.15%, corresponding to a reduction of 75.16%. For the C6 specimen, the mass-loss rate after 10 W–D cycles was 5.02%, which was close to that of the CGF8 specimen, as shown in Figure 10c.

As in the case of UCS, the mass-loss rate of the stabilized soils resulted from the combined action of two opposing factors. On the one hand, infiltrated water dissolved and eroded mineral particles, fine particles, and reaction products, thereby causing mass reduction. On the other hand, the continued reactions of the binders contributed to mass gain. During the early stage of W–D cycling, mass loss mainly originated from loosened edges and unstable soil particles, leading to relatively large values. At later stages, mass loss was mainly associated with the gradual dissolution of mineral components and reaction products. When these losses were balanced by, or became smaller than, the mass gain associated with continued binder reaction, the mass-loss rate tended to stabilize or even decrease. For CGF12 and CGF15, the mass-loss rates tended to stabilize or even decrease after approximately six to seven W–D cycles. This phenomenon may be related to the combined effects of continued binder reactions, possible carbonation-induced precipitation, and residual water retention in the stabilized matrix. The calcium-bearing alkaline phases in CS may react with CO₂-containing air during the drying stage, leading to the formation of carbonation products such as CaCO₃ on the specimen surface or within near-surface pores. In addition, residual reactive phases in the CGF system may retain or re-adsorb part of the water that is not completely removed under the adopted drying condition. These processes may partially compensate for material loss and thus affect the measured mass-loss rate during later W–D cycles.



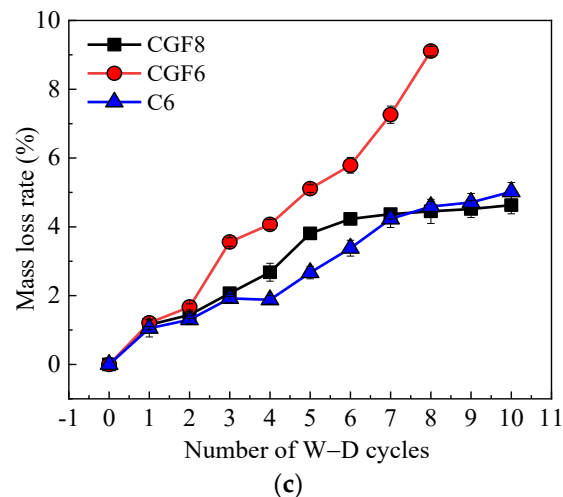


Figure 10. Mass-loss rate of stabilized dredged soil during W-D cycling: (a) CGF-stabilized dredged soil; (b) cement-stabilized dredged soil; (c) comparison between CGF- and cement-stabilized dredged soils.

Figure 11 presents the appearance evolution of the CGF6 and CGF15 specimens under increasing numbers of W-D cycles. For the CGF6 specimen, the damage progression followed a clear pattern. After one cycle, local damage appeared at the specimen edges, accompanied by corner spalling. After five cycles, edge damage became more severe and cracks developed along the specimen length. After eight cycles, corner damage and cracking intensified markedly, forming through-cracks and ultimately causing complete specimen failure. By contrast, after 10 cycles the CGF15 specimen showed only slight edge spalling at the ends, while the specimen as a whole remained largely intact.

Figure 12 shows the appearance evolution of the C4 and C6 specimens under increasing numbers of W-D cycles. As shown in Figure 12, the C4 specimen exhibited poor resistance to W-D cycling, with severe end damage appearing after only one cycle. As the number of W-D cycles increased, the C6 specimen displayed a damage pattern similar to the CGF6 specimen, initially showing end spalling and eventually developing longitudinal through cracks. Overall, the resistance to W-D cycles of the C6 specimen was slightly stronger than that of the CGF6 specimen.

In summary, under the adopted laboratory W-D cycling condition, 8% CGF can be regarded as a minimum binder content for subgrade use of the tested dredged soil. However, higher CGF contents are needed when higher strength retention, lower mass loss, or subbase applications are required.

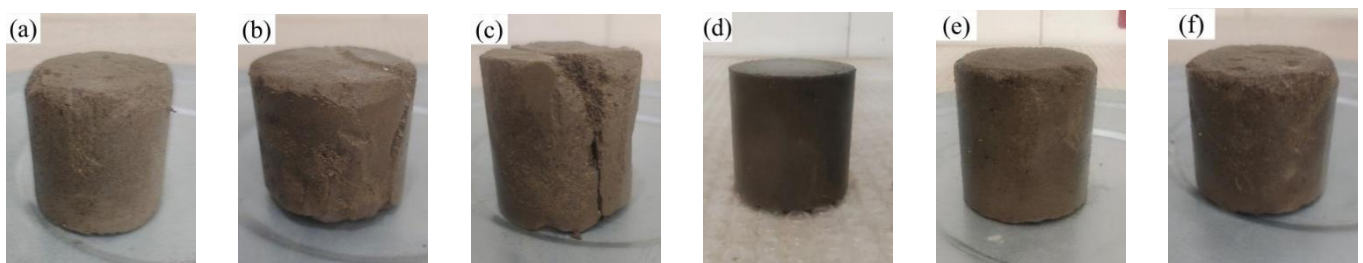


Figure 11. Appearance evolution of CGF6- and CGF15-stabilized dredged soil specimens under different numbers of W-D cycles: (a) CGF6-1 cycle; (b) CGF6-5 cycles; (c) CGF6-8 cycles; (d) CGF15-1 cycle; (e) CGF15-5 cycles; (f) CGF15-10 cycles.

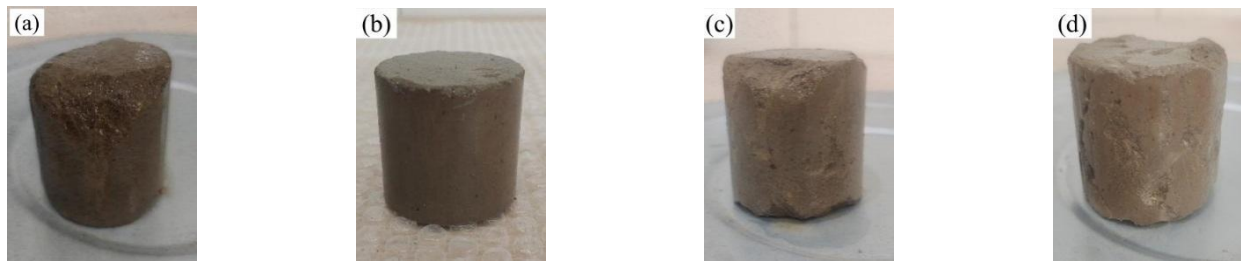


Figure 12. Appearance evolution of C4- and C6-stabilized dredged soil specimens under different numbers of W–D cycles: (a) C4-1 cycle; (b) C6-1 cycle; (c) C6-5 cycles; (d) C6-10 cycles.

3.3.2. Effect of F–T Cycles

In construction and road engineering, the F–T cycling test is commonly used to characterize the stability of stabilized soils under repeated temperature fluctuations. Because no obvious visual changes were observed in any specimen during testing, the F–T resistance of the CGF- and cement-stabilized dredged soils was evaluated solely in terms of strength and mass variation.

Figure 13 shows the *UCS* evolution of the CGF- and cement-stabilized dredged soils subjected to F–T cycling. The *UCS* of the stabilized dredged soils exhibited different trends depending on binder type and content. For the CGF6, CGF8, CGF10, and CGF12 specimens, the *UCS* showed an overall decreasing trend, with reductions of 25.90%, 11.56%, 8.13%, and 1.52%, respectively, whereas the *UCS* of the CGF15 specimen increased by 7.61% after 10 F–T cycles. This slight increase is more appropriately interpreted as stable strength retention rather than definitive strength enhancement. It may be associated with the continued reaction of GGBS and FA under the alkaline and calcium-rich environment provided by CS, the additional water supply during thawing, and possible carbonation-induced pore filling. Moreover, the later-stage strength recovery became more evident as the CGF content increased from 10% to 15%, suggesting that the continued formation of cementitious products may partly compensate for F–T-induced damage in high-CGF-content specimens. In contrast, the *UCS* of the cement-stabilized dredged soils decreased much more substantially, with reductions of 54.32% and 40.71% for the C4 and C6 specimens, respectively, after 10 cycles. In addition, the strength evolution of all specimens can be divided into three stages. In the first stage (0–2 cycles for the CGF-stabilized soils and 0–3 cycles for the cement-stabilized soils), the *UCS* decreased rapidly, with reductions of 14.08–24.46% and 33.62–48.15%, respectively. In the second stage (2–5 cycles for the CGF-stabilized soils and 3–5 cycles for the cement-stabilized soils), the *UCS* increased slightly, with gains of 15.24–25.36% and 8.0–16.67%, respectively. In the third stage, the *UCS* of the CGF6, CGF8, C4, and C6 specimens decreased by 14.88%, 11.56%, 27.45%, and 21.18%, respectively, whereas the *UCS* of the CGF10, CGF12, and CGF15 specimens increased slightly by 1.12%, 6.19%, and 5.53%, respectively. These results suggest that the CGF binder provided more favorable F–T resistance than cement under the adopted laboratory conditions.

The adverse effect of F–T cycling on soil strength mainly arises from repeated frost heave, which promotes the development of micro-pores and fine pores [40]. Because the moisture content of the specimens was maintained during F–T cycling in this study, the repeated freezing and thawing of pore water had only a limited effect on pore expansion. As a result, the *UCS* fluctuated more strongly in the early stage of F–T cycling and less in the later stage. Meanwhile, hydration and pozzolanic reactions may continue within the stabilized soils during cycling, and the resulting reaction products may partially compensate for the deterioration induced by repeated freezing and thawing, thereby contributing to strength recovery. This interpretation is consistent with previous microstructural studies on stabilized soils and cementitious composites, which reported that newly formed

cementitious phases can fill pores, improve interparticle bonding, and densify the matrix [41,42]. Therefore, the better strength retention of high-CGF-content specimens may be associated with the more persistent reaction process of the CGF binder during F–T cycling.

Figure 14 presents the mass-loss rate of the CGF- and cement-stabilized dredged soils subjected to 10 F–T cycles. The mass-loss rates of all specimens generally increased with the number of F–T cycles, although local fluctuations were observed. For the CGF-stabilized dredged soils, increasing the CGF content from 6% to 15% reduced the mass-loss rate after 10 cycles from 0.99% to 0.22%. In the control group, the mass-loss rates of the C4 and C6 specimens reached 1.3% and 0.9%, respectively. These results indicate that the CGF-stabilized dredged soils experienced lower mass loss and more favorable F–T resistance than the cement-stabilized soils. Compared with the mass loss observed under W–D cycling, the mass loss caused by F–T cycling was much lower because it mainly resulted from localized surface spalling. As binder content increased, more hydration and pozzolanic reaction products were generated, leading to a denser structure and smaller mass loss under repeated freezing and thawing.

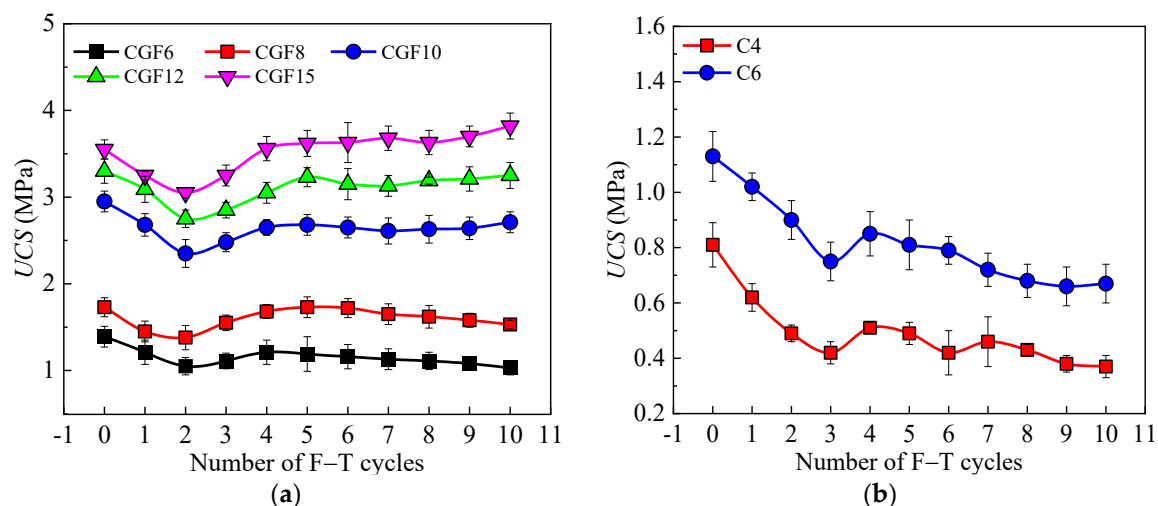


Figure 13. UCS of stabilized dredged soil during F–T cycling: (a) CGF-stabilized dredged soil; (b) cement-stabilized dredged soil.

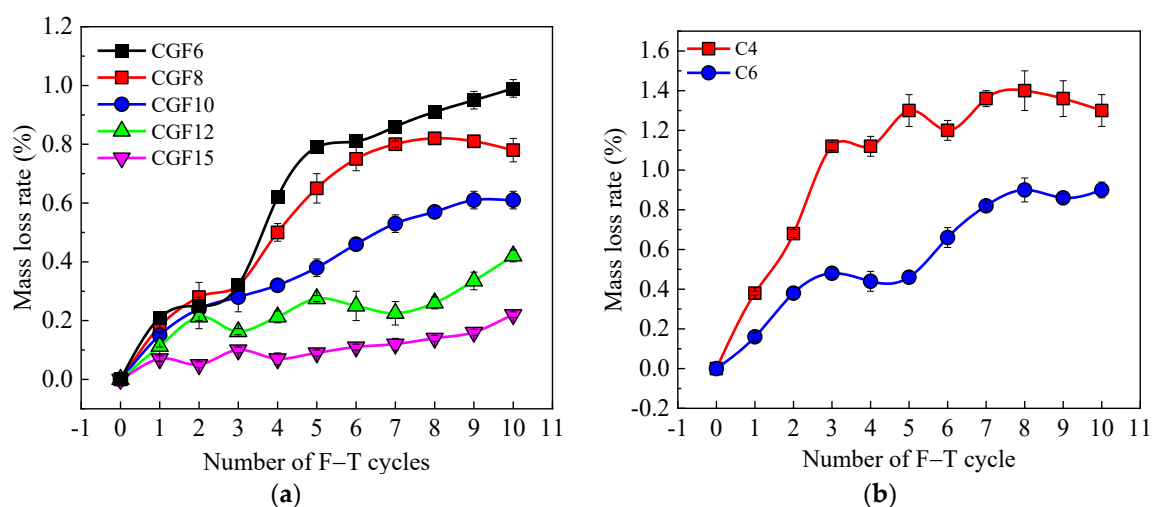


Figure 14. Mass-loss rate of stabilized dredged soil during F–T cycles: (a) CGF-stabilized dredged soil; (b) cement-stabilized dredged soil.

Overall, although the CBR and M_R of the CGF-stabilized dredged soil were slightly lower than those of the cement-stabilized dredged soil at the same binder content, the

CGF-stabilized soil showed favorable durability under the adopted laboratory conditions, indicating potential for road applications. Moreover, a CGF content of 8% can satisfy the quality requirements for stabilized dredged-soil subgrade engineering.

3.4. Discussion

This study demonstrates that the CS-GGBS-FA binder can effectively improve the road performance of dredged soil and may serve as a feasible low-carbon alternative to cement for subgrade applications. Although the CGF-stabilized soil exhibited slightly lower *CBR* and M_R than cement-stabilized soil at the same dosage, it showed favorable strength retention and mass stability under the adopted W–D and F–T cycling conditions, particularly at higher CGF contents. Therefore, the main advantage of the proposed binder lies not in maximizing short-term mechanical indices but in achieving a more balanced performance in terms of bearing capacity, stiffness, durability, cement reduction, and multi-solid-waste utilization.

Most existing studies on dredged soil stabilization have mainly focused on *UCS* and microstructural evolution, whereas the current study assessed *CBR*, M_R , and durability from the perspective of subgrade/subbase service requirements. This is important because a binder with high *UCS* does not necessarily guarantee satisfactory resilient response or durability under traffic and environmental loading. In this respect, the present results extend the practical understanding of clinker-reduced binders for transportation geotechnics. The M_R values of the CGF-stabilized dredged soil ranged from 198.29 MPa to 374.08 MPa under the tested stress states. These values exceeded the resilient-modulus requirement for subgrade applications specified in JTG D30-2015 [43], indicating that the CGF-stabilized dredged soil had sufficient deformation resistance under the investigated compaction and loading conditions. Nevertheless, M_R values reported for stabilized soils are strongly affected by soil type, binder type, curing age, compaction degree, moisture condition, and applied stress path. Therefore, the M_R results in this study are best interpreted as evidence of compliance with roadbed design requirements under the adopted test conditions, rather than as a universally high modulus level for all dredged-soil systems.

The different responses of *CBR* and M_R also provide useful implications for engineering design. *CBR* increased markedly with CGF content, suggesting that bearing capacity was sensitive to binder-induced cementation, pore filling, and skeleton stabilization. By contrast, M_R was less sensitive to binder dosage once the specimens were compacted to approximately 96%, indicating that compaction quality and stress state played a more dominant role in resilient deformation behavior. Therefore, binder dosage selection should be guided by *CBR* and durability requirements, while field compaction control remains essential for ensuring resilient performance.

The difference between the CGF and cement systems is also noteworthy. Cement produced slightly higher *CBR* and M_R at the same dosage, which is attributable to its higher early reactivity and faster generation of cementitious products. However, under the OMC-based compaction condition, the available water must first satisfy soil wetting, compaction, and pore-water demand, which may limit further hydration as cement content increases. By contrast, the CGF system contains GGBS and FA, whose latent hydraulic and pozzolanic reactions develop more gradually under the alkaline and calcium-rich environment provided by CS. This slower but more persistent reaction process helps explain the more pronounced later-age *CBR* development and the relatively stable durability response of high-CGF-content specimens. This behavior is consistent with the delayed activation characteristics of GGBS- and FA-based systems under alkaline conditions [44–47]. Therefore, the CGF binder appears more suitable for applications where long-term durability and sustainability are prioritized over the maximization of early-age stiffness.

For durability, the results indicate that the performance of CGF-stabilized soil is strongly dependent on binder content and environmental action. Under W–D cycling, the comparison between CGF6 and C6 was mixed: CGF6 showed higher *UCS* in the early cycles, whereas the CGF6 and C6 curves later intersected and converged to a similar residual strength level. Therefore, the W–D resistance of low-content CGF-stabilized soil should not be overgeneralized as superior to that of cement-stabilized soil. More stable W–D resistance was mainly observed at higher CGF contents, especially CGF12 and CGF15. The later-stage stabilization or decrease in mass-loss rate for CGF12 and CGF15 may be related to continued binder reactions, possible carbonation-induced precipitation, and residual water retention in the stabilized matrix. Under F–T cycling, the slight *UCS* increase observed for CGF15 after 10 cycles is more appropriately interpreted as stable strength retention rather than definitive strength enhancement. The later-stage strength recovery observed for CGF10, CGF12, and CGF15 suggests that the continued formation of cementitious products may partly compensate for F–T-induced damage in high-CGF-content specimens.

Several limitations should nevertheless be acknowledged. First, only one dredged soil source was considered, and the heterogeneity of dredged soils may affect the applicability of the selected binder ratio and dosage threshold. For field application, variations in organic matter content, salinity, initial water content, particle-size distribution, and clay mineral composition should be carefully considered. Therefore, the results of this study should be interpreted as laboratory-scale evidence for the tested organic-rich dredged soil, rather than as a universal conclusion for all dredged sediments. Second, because CS and FA are industrial by-products, environmental safety should also be evaluated before field application. Although no leaching test was conducted in the present study, future work should include leaching tests for heavy metals and alkalinity, together with environmental risk assessment, to verify the suitability of CGF-stabilized dredged soil for large-scale reuse. Third, because direct microstructural characterization was not conducted in this study, the proposed mechanisms were interpreted based on macroscopic test results and relevant published studies. Fourth, field-scale implementation requires attention to material transportation and storage, moisture adjustment, mixing uniformity, compaction control, and quality assurance under variable site conditions. Therefore, future work should focus on three aspects. First, the applicability of the CGF binder should be verified for dredged soils with different mineral compositions and organic matter contents. Second, XRD, SEM/EDS, and pore-structure analyses should be incorporated to directly clarify the evolution of hydration products and microstructure before and after durability cycling. Third, field-scale validation, environmental leaching/toxicity evaluation, and life-cycle assessment are needed to confirm the long-term engineering and environmental benefits of the proposed system.

4. Conclusions

This study demonstrates that dredged soil can be effectively stabilized for road engineering using a ternary binder composed of CS, GGBS, and FA. A CS:GGBS:FA mass ratio of 0.25:0.50:0.25, selected through mortar-performance screening, was adopted to prepare CGF-stabilized dredged soil and evaluate its road performance and durability. Under this binder system, both the *CBR* and M_R of the stabilized dredged soil increased significantly with increasing binder content and curing time, confirming the effectiveness of the CGF binder in improving the bearing capacity and deformation resistance of dredged soil. Although the corresponding mechanical indices were slightly lower than those of cement-stabilized soil at the same dosage, the overall engineering performance remained sufficient for practical application. After 28 d of curing, CGF contents of 12–15% enabled the stabilized dredged soil to satisfy the *CBR* requirements for subbase applications in ex-

pressways and first-class highways under medium-to-heavy traffic conditions, while all investigated CGF contents provided M_R values exceeding the requirements for subgrade applications.

The durability performance of CGF-stabilized dredged soil was strongly dependent on binder content and environmental action. Under W–D cycling, the low-content comparison between CGF6 and C6 showed mixed behavior, whereas higher CGF contents, especially CGF12 and CGF15, provided more stable strength retention and lower mass loss. Under F–T cycling, the CGF-stabilized soil exhibited favorable strength retention and mass stability, and the slight UCS increase observed for CGF15 after 10 cycles was more appropriately interpreted as stable strength retention rather than definitive strength enhancement. Overall, under the adopted laboratory test conditions, a CGF content of at least 8% provided sufficient strength, stiffness, and durability for subgrade use of the tested dredged soil, whereas higher CGF contents were required for subbase applications and more stable durability performance. These findings indicate that the CGF binder is feasible at the laboratory scale as a cement alternative for road-oriented dredged-soil stabilization and can promote the beneficial utilization of multiple industrial solid wastes. Further studies involving field-scale validation, long-term performance monitoring, environmental assessment, and life-cycle analysis are needed before large-scale engineering application.

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