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Cementitious material based on Portland cement and ground granulated blast furnace slag for ground improvement of construction sites in the Mekong Delta

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Abstract: This paper presents the results of a study on the selection of binder compositions based on Portland cement combined with ground granulated blast furnace slag (GGBFS) and gypsum for ground improvement using the deep mixing method (cement deep mixing – CDM) and shallow stabilization for road base and foundation works. The study focuses on weak and aggressive foundation soils in the Mekong Delta region. The binder compositions were determined through experimental investigations using three representative types of foundation soils (clayey sand, sandy clay, and high-plasticity clay) collected from expressway construction projects in the Mekong Delta region. Unconfined compressive strength (UCS) was evaluated at curing ages of 3, 7, 28, and 91 days, while durability performance was assessed through immersion in natural seawater up to 6 months. The results show that, relative to soils stabilized with ordinary Portland cement (PC40), the selected binder system—comprising PC40 combined with 55–65% GGBFS and 3–5% gypsum—resulted in a 28-day UCS increase of approximately 1.6 to 2.3 times. The stabilized soils with this binder also exhibited significantly improved durability when immersed in seawater. No cracking or failure was observed after 6 months of immersion, whereas the samples stabilized with ordinary Portland cement showed initial cracking after 3 months and complete failure after 6 months.

Keywords: Granulated blast-furnace slag concrete, slag, durability, mineral admixture.

1. Introduction

A series of major national infrastructure and transportation projects have been implemented or are scheduled for development in the coming years, particularly in southern Vietnam. These include the North-South Expressway (Can Tho-Ca Mau section), Long Thanh International Airport, Ho Chi Minh City Ring Roads No. 3 and 4, and several expressway projects across the Mekong Delta region. According to recent geological surveys and investigations in Ho Chi Minh City and the Mekong Delta (MKD), these areas are characterized by soft ground conditions, often containing saline and sulfate-bearing soils. Therefore, ground improvement measures are essential to ensure adequate bearing capacity and long-term durability of engineering structures [1].

Among the available ground stabilization techniques, methods using inorganic binders such as cement and lime are widely applied around the world for various types of construction. These methods include deep mixing (CDM) to form soil-cement columns, as well as mass stabilization for shallow foundations in civil and transportation infrastructure. In Vietnam, cement-soil column technology has been increasingly specified in design documents of road and highway projects, especially in areas with weak ground conditions. Most expressway projects in the Mekong Delta adopt cement-based ground improvement techniques for embankments and foundations. For instance, the Chau Doc-Can Tho-Soc Trang Expressway project employs cement-soil columns to improve soft subgrade layers and approach embankments for reinforced concrete bridges. The cement and water dosages are determined based on field trial results, with a required unconfined compressive strength (UCS) after 28 days of not less than 1.1 MPa, as tested in accordance with ASTM D2166 [2].

In current ground improvement practices in Vietnam, blended Portland cement (PCB) remains the most common binder used. This type of cement is designed primarily for general construction purposes, and its application in soft soil stabilization or cement-soil column construction still faces several limitations. The stabilized soil often exhibits relatively low strength, or requires a large binder dosage to achieve the target UCS. Moreover, in areas with aggressive environments such as marine saline soils or acid sulfate soils (characterized by low pH and high SO_4^{2-} content), the long-term durability of stabilized soil is severely affected. Chemical degradation and loss of strength over time can compromise the structural performance of the treated ground.

A study by P.V. Ngoc et al. (2024) [3] demonstrated that cement-soil columns exposed to sulfate concentrations ranging from 200% to 1000% of seawater suffered significant strength loss over time. Specifically, 0.5 m diameter columns subjected to a 200% sulfate concentration exhibited strength reduction below the design value after 75 years. At higher concentrations (5-10 times seawater), columns failed to reach the minimum required strength. These results highlight the vulnerability of PCB-based cement-soil stabilization to sulfate attack. Similarly, Yang et al. (2022) [4] found that soils stabilized with ordinary Portland cement (OPC) were destroyed after 90 days of exposure to a 2.5% Na_2SO_4 solution due to the formation of ettringite and gypsum, which caused expansion, cracking, and spalling, leading to significant deterioration in strength and durability.

In contrast, the use of cementitious binders incorporating supplementary cementitious materials (SCMs) derived from industrial by-products - such as ground granulated blast-furnace slag (GGBFS) - has been scientifically and practically proven to enhance the mechanical and durability properties of stabilized soils compared to plain Portland cement [5, 6, 7, 8]. For instance, Bideux et al. [5] reported that high-clinker binders exhibited poor sulfate and carbonation resistance in clay stabilization, while ternary systems incorporating latent-hydraulic materials such as GGBFS provided superior performance. Similarly, B.T. Son et al. [3, 9] investigated the improvement of unconfined compressive strength (UCS) of soft coastal soils in Vietnam using PCB40 cement with and without GGBFS. The results showed that the inclusion of GGBFS significantly enhanced UCS-from 728 kPa (without GGBFS) to 2045 kPa (with GGBFS) after 28 days-at a binder dosage of 250 kg/m³ and a water-to-cement ratio of 0.8 [9].

Numerous studies have confirmed that combining cement with lime, GGBFS, fly ash, or gypsum substantially increases both strength and durability of stabilized soils compared with using cement alone, particularly for weak or expansive soils [10, 11, 12, 13]. N.M. Thuy et al. [14] found that adding mineral admixtures to a cement-lime blend increased the UCS of stabilized soil from 1.46 kg/cm^2 to 5.35 kg/cm^2 after 28 days of curing. V. Phan and N.P. Minh [15] achieved a UCS of 12.01 kg/cm^2 by incorporating gypsum with cement in lime-rich clay treatment. M.A. Phuong et al. [16] reported that the UCS of soils treated with PCB40 cement in An Giang increased almost linearly with binder dosage and curing duration, reaching more than twice the 28-day strength after 96 days. Research by the Vietnam Institute for Building Materials (VIBM) [17, 18] also indicated that combinations of Portland cement (PC40/PCB40) with GGBFS, fly ash, and gypsum improved UCS by 1.5-2 times compared to PCB40 alone, while significantly enhancing durability under marine and acid sulfate soil conditions.

Despite the extensive body of international research on the use of GGBFS, lime, cement, and gypsum for soil stabilization, several important issues remain insufficiently addressed. First, limited studies have focused on acid sulfate soils with very low pH and high sulfate contents, which are widely distributed in the Mekong Delta region and pose severe durability challenges to cement-stabilized ground. Second, most previous studies emphasize strength development without explicitly relating laboratory results to current design requirements for cement deep mixing (CDM) columns and shallow ground improvement in expressway projects. Third, durability assessments are often conducted using artificial sulfate solutions rather than natural seawater, which may not fully reflect the combined effects of chloride, magnesium, and sulfate ions present in real marine environments.

Based on the above, this study aims to develop an optimized binder formulation using Portland cement combined with GGBFS and gypsum at various ratios for ground stabilization applications (stabilized soil cementitious binder-SSCB). The experimental program was conducted on three representative soil types from the Mekong Delta region, with the objective of achieving the highest possible compressive strength and long-term durability under both humid and marine (seawater) curing conditions.

2. Materials and Methods

2.1. Materials

The study used Portland cement (PC40) produced by Nghi Son Cement Plant, with a 28-day compressive strength of 52.30 MPa, a Blaine fineness of 3780 cm^2/g, and a specific gravity of 3.09 g/cm^3. The ground granulated blast furnace slag (GGBFS) used was grade S75, manufactured by CHCV Co. Ltd, conforming to TCVN 11586:2016, with a Blaine fineness of approximately 4640 cm^2/g and a specific gravity of 2.82 g/cm^3. The gypsum employed was natural ground gypsum, with an SO_3 content of 54.8%. Tap water meeting the requirements of TCVN 4506:2012 was used for mixing and curing the samples. In addition, natural seawater collected from Ha Long Bay, with a pH of 7.8 and a chloride ion concentration (Cl^-) of 17.2 g/L, was used to immerse samples in order to assess the effect of aggressive environments on the stabilized materials. The chemical composition and physical-mechanical properties of the cement and GGBFS are shown respectively in Table 1 and Table 2.

Table 1. Chemical composition of the constituent materials in the soil-stabilizing cementitious material (SSCM)

Type of binder	Chemical compositions (%)										
	LOI	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	S^{2-}
PC40	2,58	19,74	3,11	5,18	63,14	1,61	1,85	0,7	0,15	0,12	-
GGBFS	-0,14	33,1	0,18	13,28	41,02	7,96	0,07	0,26	0,86	0,13	0,65
Gypsum	-	-	-	-	-	-	54,80	-	-	-	-

Table 2. Physical properties of cement, GGBFS and gypsum in SSCM

Sample	Physical properties				Physical-mechanical properties of PC40 and the mix of 50% PC40 +50%GGBFS					
	Density (g/cm^3)	Blainess specific area (cm^2/g)	Retained on sieve (%)		Normal consitency (%)	Setting time (min.)		Compressive strength (MPa) (Strength index, %)		
			80 µm	45 µm		Initial	Final	3 days	7 days	28 days
PC40	3,09	3780	0,1	-	28,0	120	190	36,3	42,1	52,3
GGBFS	2,82	4640	-	0,1	27,5	140	230	28,1 (77,6)	38,3 (91,0)	52,5 (100,3)
Gypsum	2,89	-	-	0,8	-	-	-	-	-	-

Fig. 1. Locations of soil sampling and preparation of soil specimens for testing

Soil used for the study: Three soil samples were collected from the subgrade of an expressway construction project located in Soc Trang Province. The samples were excavated using a excavator at different depths (in Table 3). Two of them were obtained from the same location but at different depths: the surface layer at a depth of 0.5-2 m (denoted as Soil A) and the underlying layer at a depth of 2-5 m (denoted as Soil B). The third sample was taken from another location at a depth of 0.5-3 m (denoted as Soil C). Each soil sample weighed approximately 600 kg, was homogenized using a twin-shaft mixer, and stored in sealed plastic containers to preserve its initial moisture content (see Fig. 1).

According to the classification of weak soils specified in TCVN 11832:2017, Soil C is classified as soft clay, characterized by a natural moisture content (w_n) of 63%, higher than the liquid limit (WL = 56.1%), a void ratio (e) of 1.51 > 1.5, an undrained shear strength (Cu) of 10.6 kPa < 15 kPa, and an internal friction angle (φ) of 6°4′ < 10°.

Regarding the degree of aggressiveness of the three soil samples, based on parameters such as pH value, sulfate ion content (SO_4^{2-}), total soluble salts, chloride ion content (Cl^-), and organic matter content, Soil C exhibits the strongest aggressiveness, as it has the highest values for all these indicators, followed by Soil B and Soil A. According to the sulfate ion contents of Soil C (1.195%) and Soil B (0.114%), both soils are classified as having high sulfate levels, corresponding to soil environment category S2 ($0.2\% \leq SO_4^{2-} \leq 2.0\%$) as defined in ACI 318-19.

Table 3. Characteristic properties of the soil samples used in the study

Properties	Unit	Soil A	Soil B	Soil C
Natural moisture	%	34.60	31.05	63.00
Natural bulk density	g/cm³	1.870	1.820	1.610
Density	g/cm³	2.67	2.64	2.69
Liquit limit	%	37.44	34.74	56.09
Plastic limit	%	21.20	20.60	32.19
Plastic index	%	16.24	14.14	23.90
Internal friction angle (at natural moisture)	độ	12°6′	16°34′	6°4′
Shear force (at natural moisture)	kPa	22.60	24.20	20.50
Organic content	%	4.41	1.55	5.84
pH	-	7.87	7.88	3.69
Soluable salt content	%	0.50	1.13	1.67
Sulfate content SO_4^{2-}	%	0.023	0.114	1.195
Chloride content Cl^-	%	0.053	0.129	0.150
Soil classification		Gray brown clay AASHTO: A-6 (17); ASTM D2487: CL (lean clay with sand)	Grayish silty sand AASHTO: A-6 (8); ASTM D2487: SC (clayey sand)	Grayish clay AASHTO: A-7-5 (30); ASTM D2487: MH (high plasticity silt)

2.2. Mix Proportion

Three representative subgrade soil samples from the upper soil layers (0-5 m) in the Mekong Delta region were used to evaluate the effectiveness of the binder in ground improvement. The binder was formulated as a mixture of Portland cement (PC40), ground granulated blast furnace slag (GGBFS), and gypsum. The experimental mix designs were divided into two groups: Group 1: Investigation of the effect of cement, GGBFS, and gypsum proportions on the unconfined compressive strength (UCS) of stabilized soils, with a total of 21 mix compositions. The UCS tests were performed at curing ages of 3, 7, 28, and 91 days; Group 2: Evaluation of the influence of curing conditions (natural moist curing and immersion in seawater) up to 182 days.

2.3. Method Test methods

The stabilized soil samples were prepared as follows: The binder mixture, consisting of Portland cement (PC40), ground granulated blast furnace slag (GGBFS), and gypsum, was first dry-mixed using a 5-liter planetary mixer. This dry mixture was then blended with water at a predetermined water-to-cementitious-material ratio (W/CM) to form a homogeneous paste. Subsequently, pre-homogenized soil with uniform moisture content was gradually added into the mixer and mixed at a low speed until all soil was incorporated, followed by high-speed mixing for 1 minute. The mixture was then scraped, re-mixed at high speed for an additional 1 minute, and immediately molded into test specimens. After molding, the cement-soil specimens were cured under three different conditions: (1) Standard curing: At 27 ± 2 °C, specimens were sealed with plastic film to prevent moisture loss; (2) Water curing: Specimens were immersed in tap water immediately after demolding at 27 ± 2 °C; and (3) Seawater curing: After 7 days of standard curing, specimens were transferred to immersion in natural seawater. The stress-strain relationship of the stabilized soil was determined through unconfined compressive strength (UCS) testing, following the procedures specified in TCVN 9403:2012, at designated curing ages.

For each mix proportion, at least three identical specimens were prepared and tested at each curing age, and the reported UCS values represent the average of these measurements. Cylindrical specimens with a diameter of 50 mm and a height of 100 mm were used for UCS testing. The initial moisture content of each soil was maintained close to its natural moisture, and no additional compaction energy was applied other than that induced by molding to ensure uniform specimen formation.

3. Result and discussion

3.1. Effect of Binder Composition on the Strength of Stabilized Soil

When the GGBFS content in the cementitious binder (SSCB) increased from 0% to 45%, 55%, and 65%, the unconfined compressive strength (UCS) of the stabilized soils showed a clear improvement for all three soil types (A, B, and C), compared with those stabilized solely with Portland cement PC40 (Fig. 2), under both 0% and 5% gypsum contents. The strength enhancement relative to PC40-stabilized soil ranged approximately from 93-120.6% at 7 days, 78-128.6% at 28 days, and 81.7-197.3% at 91 days, averaged across the three soil types. Among them, low- to medium-plasticity clays (samples A and B) exhibited a greater increase in strength than high-plasticity clay (sample C) when stabilized with the composite binder (Table 4).

The enhancement in the compressive strength of stabilized soils with increasing GGBFS content in the SSCB can be attributed to both physical and chemical mechanisms. Physically, because GGBFS particles have a lower specific gravity than cement, the same mass of GGBFS occupies a greater volume, thereby contributing to a denser packing of the soil-cement matrix. Chemically, in the alkaline environment generated by the hydration of cement, GGBFS particles are activated and gradually form calcium silicate hydrates (C-S-H), which enhance the long-term strength of the system. Although the reaction rate of GGBFS at early ages (3-7 days) is slower than that of cement, it continues to develop over time, leading to a significant increase in strength at later ages (28 days and beyond). Additionally, GGBFS also participates in pozzolanic reactions with clay minerals under alkaline conditions, further densifying the microstructure of the soil-cement composite. These combined effects explain the remarkable improvement in strength observed for GGBFS-modified systems.

The results shown in Fig. 2 also indicate that when gypsum was added to the VLGC binder at levels of 0%, 3%, and 5% while maintaining the GGBFS content at 65%, the unconfined compressive strength of the stabilized soils increased notably compared to that of mixtures containing only PC40 cement. At 28 days, the strength increase of VLGC with 5% gypsum relative to the gypsum-free mixture ranged from 8.4-9.4%, 7.4-15.9%, and 9.0-9.9% for soils A, B, and C, respectively. Compared with the reference mixture using only PC40 cement, the strength gains correspond to (104.4-110)%, (93.6-128.6)%, and (77.8-82.7)%, equivalent to approximately 2.04-2.11 times, 1.93-2.29 times, and 1.78-1.82 times increases in UCS for soils A, B, and C at 28 days, respectively.

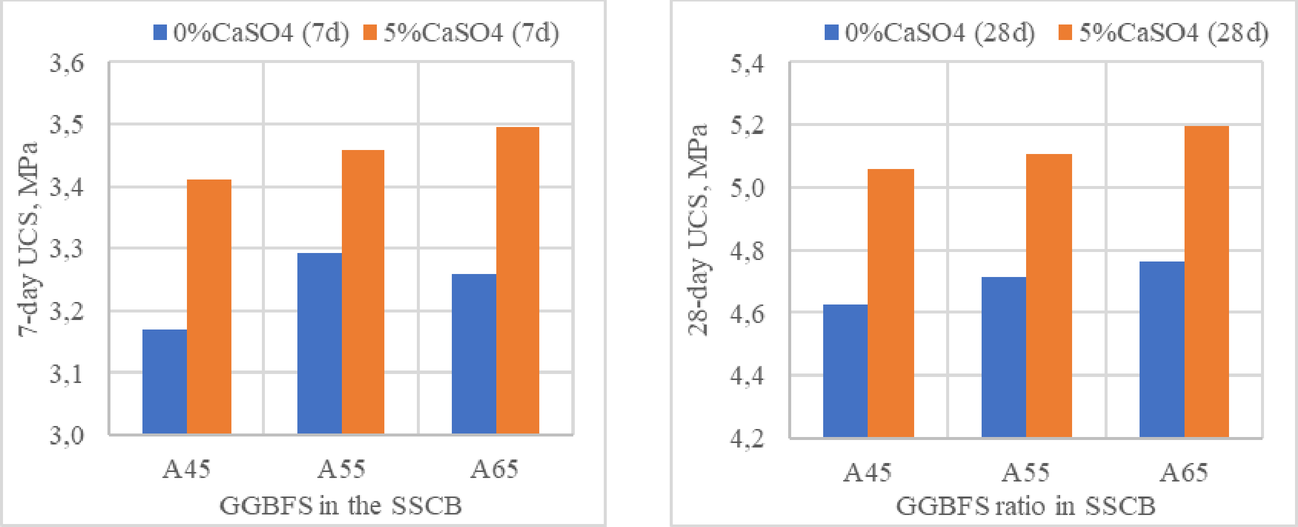
The synergistic improvement in strength when combining GGBFS and gypsum with PC40 cement can be explained by the dissolution of gypsum, which releases Ca^{2+} and SO_4^{2-} ions. These ions react rapidly with the C_3A phase of cement to form ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) - a needle-like crystal with high water content and large molar volume. Ettringite contributes to the formation of a rigid skeleton that encapsulates clay particles, thereby increasing the integrity and strength of the soil-cement system.

However, when comparing mixtures containing 3% and 5% gypsum, the UCS values at 7 and 28 days are generally higher for the 5% gypsum mixtures. Yet, at 6 months, this trend reverses, with the 3% gypsum mixtures showing comparable or even higher strength. This behavior is similar to that observed in cement systems: excessive gypsum can lead to long-term strength reduction due to the overproduction of ettringite and gypsum ($CaSO_4 \cdot 2H_2O$) at later ages, resulting in microcracking within the hardened matrix and, consequently, a decline in overall strength.

Based on the 28-day UCS results, several binder combinations clearly satisfy the minimum design requirement of 1.1 MPa for cement deep mixing columns specified in current expressway projects in the Mekong Delta, particularly for soils A and B. In contrast, mixtures that do not reach this threshold are more suitable for shallow ground improvement applications. This distinction provides practical guidance for selecting appropriate binder compositions according to engineering requirements.

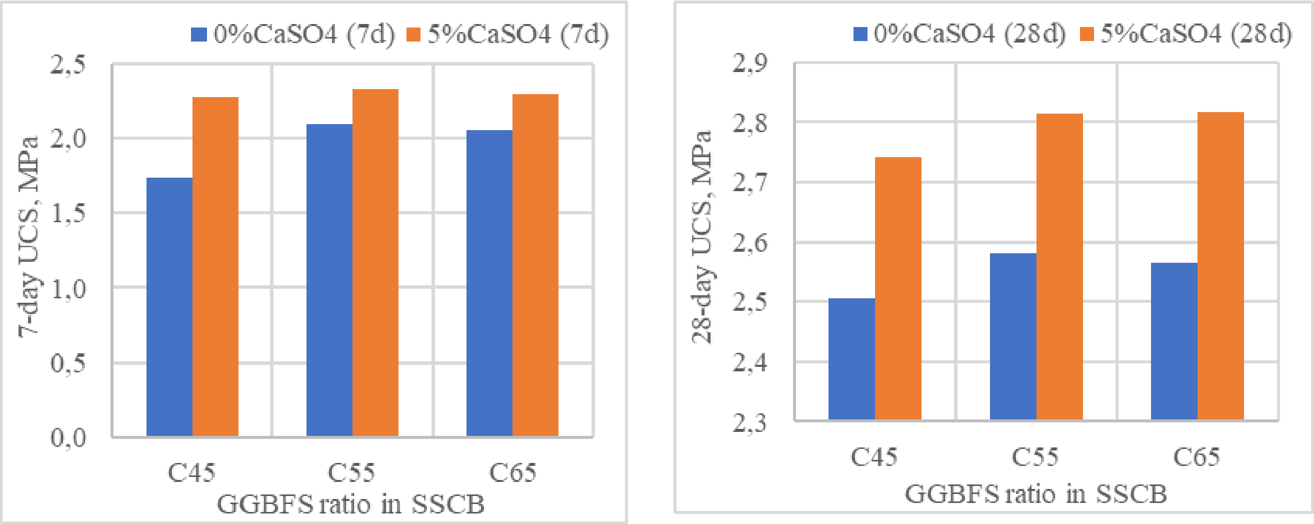
Table 4. Mix proportions of stabilizing binders for selecting the optimal VLGC composition for subgrade soils in the Mekong Delta region

Soil type	Mix ID	Mix proportions of the binder (% wt)			Water ratio $t_{w/c}$ (% wt)	Binder content (a_w), kg/m^3
		W_{PC40}	W_{GGBFS}	W_{TC}		
Soil A, B, C	(A,B,C)0	100	0	0	80	200
	(A,B,C)45-5	50	45	5	80	200
	(A,B,C)55-5	40	55	5	80	200
	(A,B,C)65-5	30	65	5	80	200
	(A,B,C)65-3	32	65	3	80	200
	(A,B,C)45-0	55	45	0	80	200
	(A,B,C)55-0	45	55	0	80	200
	(A,B,C)65-0	35	65	0	80	200



a) Stabilized A-soil at 7 and 28 days

Fig. 2. Effect of Binder Containing Different GGBFS Ratios on the UCS Strength of Stabilized Soils



b) Stabilized C-soil at 7 and 28 days

Fig. 2. (continued)

3.2. Mechanical Performance of Stabilized Soils under Different Curing Conditions

Soil samples stabilized with binders containing GGBFS and gypsum exhibited no visible cracking or spalling after six months of immersion in natural seawater, whereas samples stabilized solely with Portland cement began to crack and deteriorate after three months (samples A0, B0, C0) and became severely damaged by six months (in Fig. 3 & Fig. 4). Only sample B0 remained intact, although its strength decreased by 46.3% compared to the counterpart cured under standard moist conditions. These findings indicate the superior durability of soils stabilized with GGBFS + (3-5)% gypsum in aggressive environments such as seawater, which contains high concentrations of Na^+, Cl^-, Ca^{2+}, Mg^{2+}, and SO_4^{2-} ions.

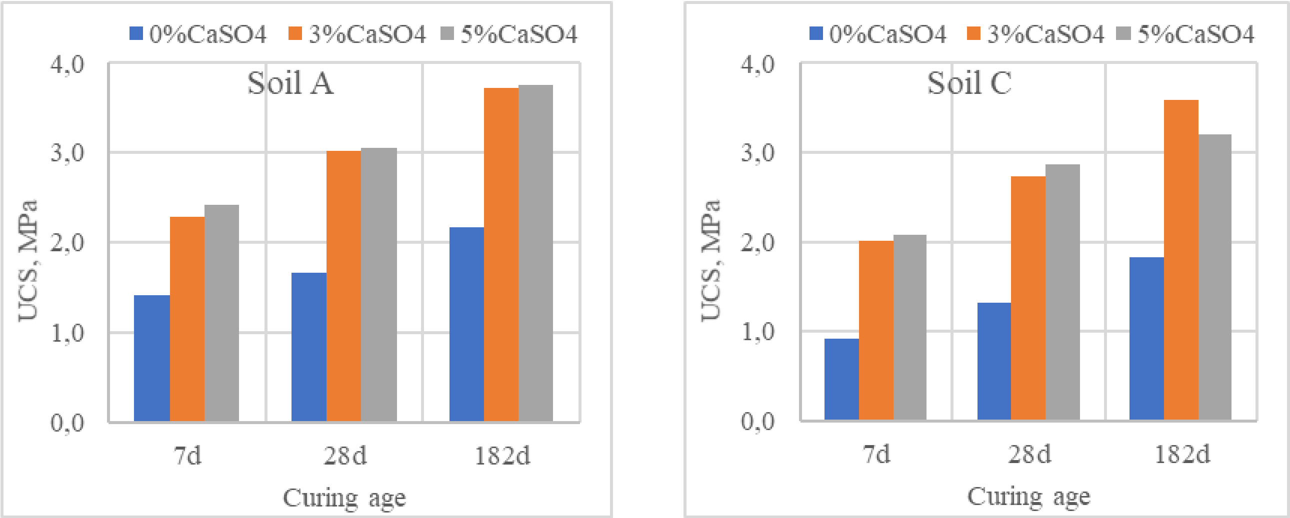


Fig. 3. Effect of Gypsum Content on the Unconfined Compressive Strength (UCS) of Stabilized Soils

This improvement can be explained as follows: at later curing ages (around six months), when the microstructure of the stabilized soil has mostly developed, the continuous ingress of Ca^{2+}, Mg^{2+}, and SO_4^{2-} ions from the seawater reacts with cement hydration products-particularly tricalcium aluminate (C_3A)-forming expansive minerals such as ettringite, gypsum ($CaSO_4{\cdot}2H_2O$), and magnesium hydroxide ($Mg(OH)_2$). The volumetric expansion of these minerals generates internal stresses, which lead to microcracking and structural degradation, a process known as sulfate attack, commonly observed in cementitious materials and concrete exposed to sulfate environments.

In contrast, samples stabilized with PC40 cement blended with GGBFS and gypsum demonstrated higher resistance to such degradation. The pozzolanic reaction between GGBFS and calcium hydroxide, along with the sulfate activation of gypsum, promotes the formation of additional calcium silicate hydrate (C-S-H) phases. Furthermore, the early formation of ettringite during the initial curing stages-due to the high availability of Ca^{2+} and SO_4^{2-} ions - helps refine the pore structure, creating a denser and less permeable matrix that limits further ion penetration from the seawater.

A0 samples A65-5 samples

B0 samples B65-3 samples

C0 samples C65-5 samples

Fig. 4. Appearance of stabilized soil specimens after 6 months of curing in natural seawater

Among the seawater-cured specimens, those containing 5% gypsum exhibited slightly lower UCS values and greater long-term strength reduction compared to those with 3% gypsum. Specifically, the UCS of the 5% gypsum samples ranged from 1.47-4.75 MPa, with a strength loss of 20.1-35.9%, while the 3% gypsum samples achieved 1.51-5.01 MPa, with a smaller strength loss of 14.1-25.9% relative to the standard moist-cured condition. This behavior mirrors that of cement pastes with excessive gypsum content, where excess SO_4^{2-} ions promote the delayed formation of ettringite and gypsum, leading to expansion, microcracking, and reduced long-term durability.

Overall, the unconfined compressive strength (UCS) of the stabilized soils decreased in the following order under different curing conditions: Standard moist curing > Tap water curing > Natural seawater curing. This trend was consistent across all three soil types (A, B, and C). At six months, the UCS reduction of VLGC-stabilized soils containing GGBFS and gypsum ranged from 4.6-18.4% under tap-water curing and 14.1-39% under seawater curing, confirming that marine environments significantly accelerate the degradation of conventional cement-stabilized soils, while GGBFS-gypsum binders markedly improve sulfate resistance and long-term performance.

Hydration Products and Microstructural Characteristics of Stabilized Soils

X-ray diffraction (XRD) analyses were performed on the raw and stabilized soil samples (A, B, and C) to identify the crystalline phases formed by the binder system. The results, summarized in Fig. 5 and Table 5, indicate that the untreated soils mainly consist of clay minerals and quartz-related phases. The dominant crystalline phases in soils A, B, and C include quartz (SiO_2), muscovite ($KAl_3Si_3O_{10}(OH)_2$), kaolinite ($Al_2Si_2O_5(OH)_4$), albite ($Na(AlSi_3O_8)$), clinochlore, and montmorillonite, together with a substantial amorphous component (44-46%).

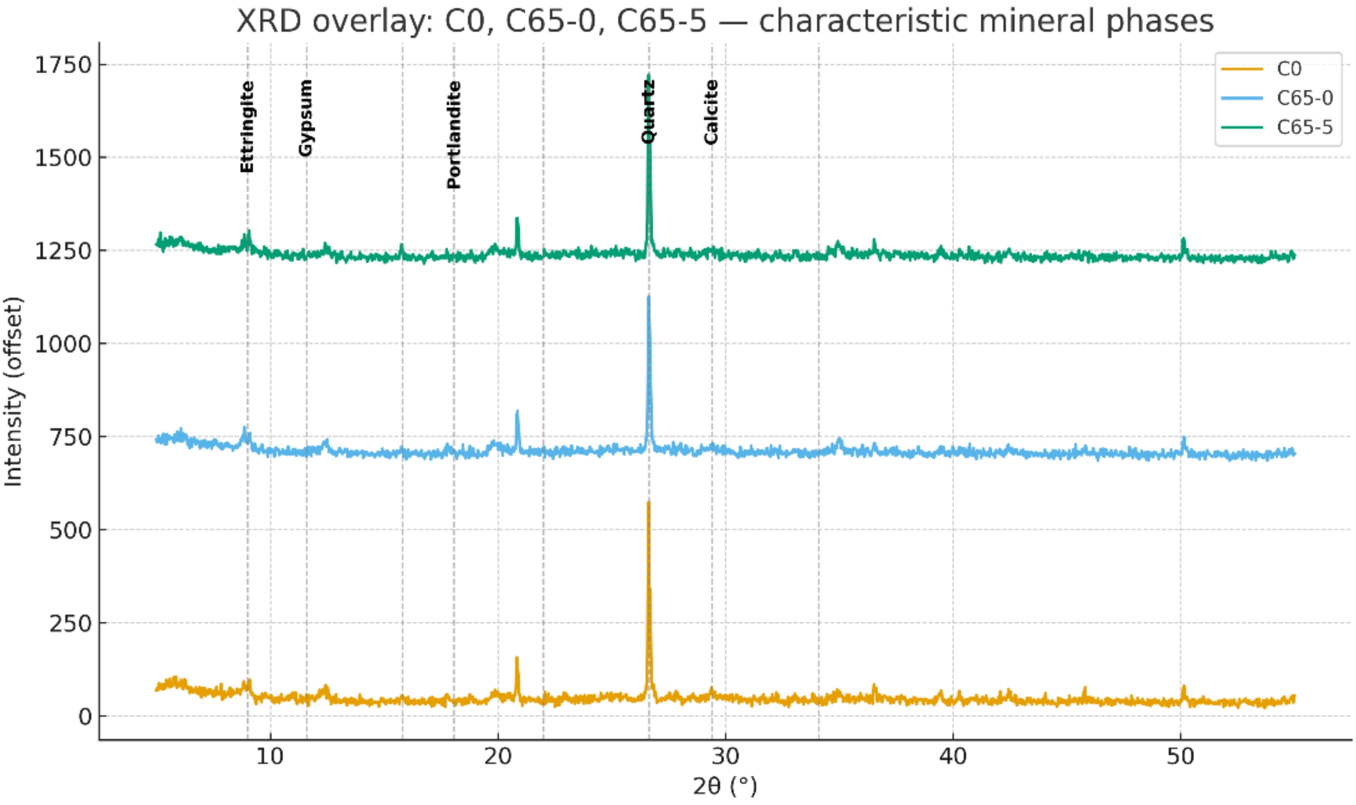


Fig. 5. XRD patterns of the C0 soil sample and the soil samples with added GGBFS and GGBFS + gypsum

Table 5. XRD Semi-quantitative analysis results of the mineral components in the soil samples and soil mixtures with GGBFS and GGBFS + gypsum from XRD spectra

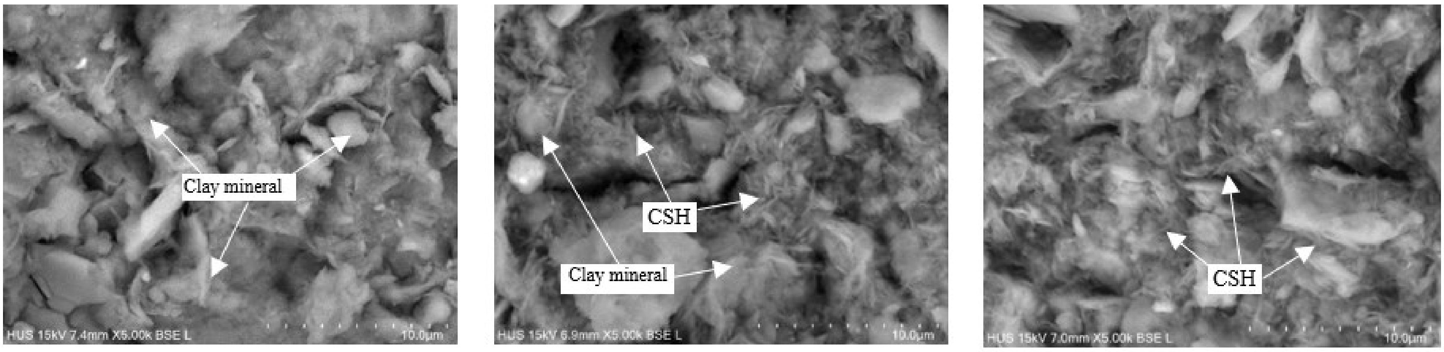
No	Compounds/phase	Unit	M0	M65-0	M65-5	H0	H65-0	H65-5	C0	C65-0	C65-5
1	Quartz: SiO_2	%	~ 30	~ 30	~ 28	~ 32	~ 43	~ 40	~ 16	~ 15	~ 14
2	Muscovite: $KAl_3Si_3O_{10}(OH)_2$	%	~ 6	~ 5	~ 6	~ 6	~ 6	~ 5	~ 6	~ 8	~ 7
3	Kaolinite: $Al_2Si_2O_5(OH)_4$	%	~ 5	~4	~3	~ 5	~4	~3	~ 5	~ 7	~ 6
4	Microcline: $KAlSi_3O_8$	%	~ 5	~ 3	~ 5	~ 1	~ 2	~ 3	~ 2	~ 1	~ 2
5	Partheite: $Ca_2Al_4Si_4O_{15}(OH)_2(H_2O)_4$	%							~ 1		
6	Albite: $Na(AlSi_3O_8)$	%	~ 5	~ 2	~ 2	~ 3	~ 5	~ 5	~ 1	~ 1	~ 2
7	Ettringite: $Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$	%	~ 1	~ 7	~ 8	~ 2	~ 6	~ 7	~ 3	~ 7	~ 8
8	Clinochlore: $(Mg_{2.96}Fe_{1.55}Fe_{.136}Al_{1.275})(Si_{2.622}Al_{1.376}O_{10}(OH)_8$	%	~ 3	~ 2	~ 3	~ 2	~ 3	~ 2	~ 5	~ 4	~ 2
10	Calcite: $CaCO_3$	%	~ 1	~ 1		~ 1			~ 3	~ 2	~ 1
11	Hematite: Fe_2O_3	%		~ 1					~ 2	~ 1	~ 3
8	Calcium Silicate: Ca_3SiO_5	%		~4	~6		~4	~6		~ 4	~5
9	Brownmillerite: $Ca_2(Al,Fe)_2O_5$	%							~ 3		
10	Calcium Aluminum Iron Oxide Carbonate Hydroxide Hydrate: $Ca_8Al_2Fe_2O_{12}CO_3(OH)_2.22H_2O$	%	~ 1			~ 5	~ 2				
11	Montmorillonite: $(Na,Ca)_{0.3}(Al,Mg)_2Si_2O_{10}(OH)_2.nH_2O$	%	~ 2	~ 2	~ 2	~ 2	~ 2		~ 3	~ 3	~ 3
12	Amorphous phase	%	~ 46	~ 53	~ 51	~ 46	~ 35	~ 43	~ 44	~ 54	~ 52

In contrast, the stabilized soil samples exhibit additional diffraction peaks attributed to hydration and pozzolanic reaction products. These include ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}·26H_2O$) (6-8%), calcium silicate (Ca_3SiO_5) (4-6%), and calcium aluminum iron oxide carbonate hydroxide hydrate ($Ca_8Al_2Fe_2O_{12}CO_3(OH)_2·22H_2O$) (1-5%), while the amorphous phase fraction increases to approximately 51-54%. These new phases originate from the hydration of cement and the activation of ground granulated blast furnace slag (GGBFS) and gypsum in the alkaline environment, leading to the formation of C-S-H gel and sulfoaluminate phases that enhance bonding and reduce porosity.

The XRD pattern of the C0 sample (soil without binder) exhibits sharp reflections of quartz and calcite, but no distinct peaks corresponding to cementitious hydration products such as portlandite or ettringite. This observation aligns with the SEM micrograph (Fig. 5), showing a loosely packed structure with numerous voids and no evidence of gel or crystal bridges. Therefore, C0 represents the unreacted baseline condition, used as a control for evaluating the effects of the binder system.

Upon incorporating 65% GGBFS (sample C65-0), the XRD spectrum reveals weak peaks indicative of hydration phases-particularly portlandite and a broad diffuse hump corresponding to the amorphous C-S-H gel. SEM observations (Fig. 6) confirm the presence of a C-S-H gel matrix enveloping soil particles, reducing porosity and improving particle bonding. This demonstrates the effectiveness of GGBFS activation under alkaline conditions supplied by cement hydration.

Further addition of 5% gypsum (sample C65-5) results in distinct ettringite peaks appearing around 2θ ≈ 9°, 15.8°, and 22°, along with the amorphous background of C-S-H. The coexistence of C-S-H gel and needle-like ettringite crystals indicates that a sulfoaluminate reaction mechanism has occurred, where sulfate ions from gypsum react with aluminates from cement and GGBFS to form ettringite. These ettringite crystals fill voids and contribute to a denser microstructure, as evidenced by SEM (Fig. 6). From a mechanical standpoint, the early formation of ettringite and C-S-H gel significantly enhances the compressive strength and compactness of the stabilized soil matrix. However, excessive sulfate content or prolonged ettringite formation at later ages could potentially cause microcracking due to volumetric expansion, which may lead to long-term strength reduction.



a) Soil C0 b) Stablized soil C65-0 c) Stablized soil C65-5

Fig. 6. SEM micrographs showing the microstructure of the C0 soil sample and the C0 samples with added GGBFS and GGBFS + gypsum at 28 days of curing

Overall, the combined XRD and SEM analyses confirm that the synergistic hydration of cement, GGBFS, and gypsum promotes the formation of beneficial binding phases-primarily C-S-H and ettringite-which densify the soil matrix and improve both early-age and long-term mechanical performance.

The results presented in this study are based on laboratory-scale specimens and a maximum curing duration of six months, which is relatively short compared with the typical service life of ground improvement structures. In addition, the experimental program focused primarily on unconfined compressive strength and durability under seawater immersion, while other important parameters such as stiffness modulus, shear strength, consolidation behavior, and full-scale column performance were not considered. Future studies should therefore include longer-term exposure tests, saline and brackish water representative of the Mekong Delta, and pilot-scale or field validation to further assess the applicability of the proposed binder system.

4. Conclusions

Based on the results of the study on the effects of binder composition using Portland cement combined with GGBFS and gypsum on the properties of stabilized soils, with representative soil samples collected from foundation soils in the Mekong Delta region, the following conclusions and recommendations can be drawn:

The soil samples used in this study were collected at different depths and locations within the Châu Đốc - Cần Thơ - Sóc Trăng Expressway project. Three types of soils were identified: Soil A: Low-plasticity clay or lean clay containing brownish-gray sand (Group A-6(17)); Soil B: Silty clayey sand of grayish color (Group A-6(8)); Soil C: Highly plastic silty clay (Group A-7-5(30)). According to TCVN 11832, soil C is classified as soft soil and acid sulfate soil with pH = 3.69 and high sulfate content (1.195%). Soil B is also acid sulfate soil with high sulfate content (0.114%). All three soil samples contain soluble salts and chloride ions at moderate to high levels (total soluble salts 0.5-1.67%, chloride ions 0.053-0.15%).

The unconfined compressive strength of soils stabilized with the binder system consisting of Portland cement (PC40) combined with GGBFS and gypsum achieved the best results when the binder contained 55-65% GGBFS and 3-5% gypsum. The use of 5% gypsum provided higher strength at 7 and 28 days but slightly lower values than 3% gypsum at longer curing ages (182 days). Compared with soils stabilized using only PC40, the mixture containing 65% GGBFS and 5% gypsum achieved strength increases of 2.04-2.11 times, 1.93-2.29 times, and 1.78-1.82 times for soils A, B, and C, respectively. These soils represent typical soil types in the Mekong Delta: sandy clay (A), clayey sand (B), and highly plastic clay (C).

3. Soils stabilized with binders containing GGBFS + (3-5)% gypsum demonstrated significantly improved durability when immersed in seawater. The samples showed no cracking or spalling after 6 months of immersion, while samples stabilized with ordinary Portland cement began to crack after 3 months and were completely damaged after 6 months.

Many ground soils in the Mekong Delta are weak, acid sulfate, saline, or organic soils, which reduce the long-term durability of cement-stabilized structures, sometimes leading to deterioration or failure over time. Therefore, the proposed binder system based on Portland cement and GGBFS shows promising potential for ground improvement applications in the Mekong Delta region and warrants further pilot studies and field validation prior to large-scale implementation.

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