EFFECT OF NaCl SALINITY ON STRENGTH AND STIFFNESS OF CEMENT–FLY ASH–LIME TREATED CLAYEY SOILS

Tran Van Khanh[1,2*], Do Huu Dao[1], Pham Van Ngoc[1], Le Dinh Viet[1]

[1]*The University of Danang - University of Science and Technology, Vietnam*

[2]*Tra Vinh University, Vietnam*

*Corresponding author: tranvankhanh@tvu.edu.vn

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Abstract - Unconfined compressive strength (UCS) and elastic modulus (E_{50}) are key parameters governing the load-bearing capacity and deformation behavior of stabilized soft soils. This study investigated the effect of NaCl salinity on clayey soil stabilized with a cement–fly ash–lime binder system. Two experimental schemes were conducted. In Scheme 1, cement and fly ash contents were fixed at 20% and 30% of dry soil weight, respectively, while lime content varied from 2% to 6%. In Scheme 2, NaCl contents of 1–4% were introduced into the corresponding mixtures. Specimens were cured under standard conditions and tested by unconfined compression after 7, 14, 28, and 56 days. The results were used to evaluate the influence of NaCl salinity on UCS and E_{50}, providing an experimental basis for mixture design and performance assessment of stabilized soft soils in saline environments.

Key words - Mekong Delta soil; fly Ash; cement; lime; unconfined compressive strength (UCS); elastic modulus (E_{50})

1. Introduction

In recent years, the demand for transportation infrastructure development in coastal areas and the Mekong Delta has increased significantly. However, the ground in these regions mainly consists of soft clay with high compressibility, low strength, and frequent exposure to saline and acidic environments [1], [2], which creates considerable difficulties for the design and construction of foundation systems. To improve the mechanical properties of weak soils, ground improvement methods using inorganic binders such as cement, lime, and fly ash have been widely studied and applied to enhance load-bearing capacity and reduce deformation [3] – [8]. During stabilization, the mineral phases in Portland cement, such as C_3S, C_2S, and C_3A, react with pore water in the soil to form stable cementitious gels such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) [9] – [12]. These hydration products fill the pores and bind soil particles into a stable skeleton structure, thereby significantly increasing the unconfined compressive strength (UCS) and elastic modulus of stabilized soils [13], [14]. In addition to cement, lime is also widely used to improve clay through cation exchange reactions and long-term pozzolanic reactions, which increase the alkalinity of the system and significantly improve the mechanical properties of soil [15], [16]. However, the effectiveness of soil stabilization depends on several factors such as soil type, binder content, curing time, and environmental conditions [14]. In particular, the presence of salts in the soil environment may significantly affect the chemical reactions of the binder system.

In coastal regions, the presence of salt ions, especially NaCl, may significantly affect the hydration of binders and the formation of cementitious gel products. Many studies have shown that salinity may have contrasting effects on the strength of stabilized soils. Yin et al, a study on dredged clay from Baima Lake (China) stabilized with 150 kg/m³ of cement, reported that UCS decreased almost linearly as the NaCl concentration increased to 8%, with a reduction of up to 60.2% after 28 days of curing [12]. This was mainly attributed to the reaction between Cl^- ions and the aluminate phase of cement to form Friedel's salt, a non-cementitious product that increases the porosity of the soil–cement structure [17].

Conversely, at low concentrations, NaCl may act as a chemical activator that promotes pozzolanic reactions. Baldovino et al showed that adding 2% NaCl to soil stabilized with 9% lime could significantly increase the strength and elastic modulus of dispersive clay in Cartagena (Colombia) [15]. Similarly, for organic marine clay, a salt concentration of about 5% was identified as optimal for maintaining an alkaline environment and improving UCS [13]. However, when the salt content exceeds the optimal threshold, excess ions in the pore solution may cause particle dispersion and hinder hydration, leading to long-term strength reduction [13], [18].

Although many studies have examined the influence of salinity on stabilized soils, studies on the quantitative relationship between UCS and (E_{50}) of stabilized soils in saline environments remain limited, especially for the blended binder system of cement–fly ash–lime under the soft clay conditions of the Mekong Delta. Therefore, this study was carried out to evaluate the effect of NaCl content on the strength and stiffness of soft clay stabilized with cement, fly ash, and lime through unconfined compression tests. In addition, the relationship between UCS and E_{50} was analyzed to provide an experimental database for the design and evaluation of ground improvement in saline environments.

The novelty of the present study lies in the systematic evaluation of NaCl salinity effects on both UCS and E_{50} of soft clay treated with a ternary binder system of cement–fly ash–lime, which has not been investigated previously under the saline conditions typical of the Mekong Delta. Unlike prior studies that focused on binary systems (e.g., cement–fly ash or lime–NaCl) or examined only a single salinity level, this study simultaneously varies lime content

(2–6%) and NaCl content (0–4%) to establish the interaction between lime-activated pozzolanic reactions and chloride-induced mechanisms within a triple-binder system. In comparison with the literature: (1) Yin et al. (2019) reported a near-linear reduction of UCS with NaCl up to 8% in a binary cement–clay system, contrasting with the non-linear trend observed here, which is modulated by the presence of lime and fly ash; (2) Baldovino et al. showed that 2% NaCl improved strength of lime-stabilized dispersive clay, consistent with our low-salinity findings; and (3) Joy et al. identified an optimal NaCl threshold for organic marine clay stabilized with lime, supporting the optimum observed in this study. However, none of these works addressed the combined cement–fly ash–lime system under varying lime levels, which is the principal contribution of the present study.

2. Materials and properties

2.1. Soil

In this study, the clay sample was collected from Duyen Hai ward, Vinh Long province. The physical and mechanical properties of the natural soil are presented in Table 1. As a result, the soil exhibits typical characteristics of soft clay commonly found in the Mekong Delta region.

Table 1. *Physical and mechanical properties of soil*

ID	Properties	Unit	Value
1	Water content	%	38.58
2	Unit weight	g/cm³	1.56
3	Dry density	g/cm³	1.19
4	Specific gravity (G_s)		2.61
5	Void ratio (e_0)		1.192
6	Liquid Limit (LL)	%	50.66
7	Plastic limit (PL)	%	26.31
8	Plasticity Index (IP)	%	24.35
9	Viscosity (B)		0.504

2.2. Binder materials

The binders used include Ha Tien PC40 Portland cement, fly ash obtained from Duyen Hai 1 Thermal Power Plant (Vinh Long province), and lime. The chemical composition of the soil and binder materials is presented in Table 2.

Table 2. *The chemical composition of Soil, Cement, Fly ash and Lime*

ID	Oxide	Soil (S) (%)	Cement (C) (%)	Fly Ash (F) (%)	Lime (L) (%)
1	SiO_2	62.27	20.54	62.05	1.2
2	Al_2O_3	14.26	4.38	20.75	0.68
3	Fe_2O_3	9.41	4.92	9.11	0.49
4	CaO	2.26	63.48	2.36	96.69
5	MgO	1.18	1.45	0.01	0.04
6	SO_3	0.13	2.91	0.51	0.36
7	Na_2O	0.31	1.16	0.49	0.42
8	K_2O	2.82	0.48	2.73	0.07
9	Other	7.36	0.68	1.99	0.05

The analytical results show that the soil and fly ash contain relatively high amounts of SiO_2 and Al_2O_3, while cement and lime provide a significant CaO source. The combination of these silica, alumina, and calcium sources creates favorable conditions for hydration and pozzolanic reactions during stabilization. These reactions contribute to the formation of cementitious products such as C-S-H and C-A-H, thereby significantly improving the strength and stiffness of the treated soil.

3. Experimental method

This study was conducted to evaluate the influence of NaCl salinity on the mechanical behavior of soft soil stabilized with a mixture of cement (20%), fly ash (30%), and lime (2 – 6%) through UCS testing according to TCVN 9403:2012 [19].

The experimental program consisted of two main groups of mixtures. In the first group, soil samples were stabilized with 20% cement and 30% fly ash, while lime content was varied at 2%, 4%, and 6% to evaluate the role of lime in activating pozzolanic reactions. In the second group, NaCl was added to the mixtures of the first group at concentrations of 1%, 2%, 3%, and 4% to simulate saline conditions commonly encountered in coastal areas.

In this study, the NaCl content was calculated as a percentage of the total dry soils. For example, a 2% NaCl content means that 2 g of NaCl was added per 100 g of total dry soils. NaCl was pre-dissolved in the mixing water prior to combining with the dry soil–binder blend to ensure homogeneous chloride distribution throughout the specimen and to replicate naturally occurring saline pore water conditions, consistent with the procedures [11], [12].

The natural soil had an initial in-situ water content of approximately **38.58%** (Table 1). For specimen preparation, the soil water content was adjusted to a fixed value of **85%** before mixing with cement, fly ash, lime, and NaCl to ensure consistent moisture conditions across all stabilized mixtures.The water-to-binder ratio was maintained at **0.70**, where the binder content refers to the total dry mass. In this study, the NaCl content was calculated as a percentage of the **dry soil mass**. NaCl was first dissolved in the mixing water before being incorporated into the dry soil–binder mixture to ensure a uniform chloride distribution throughout the specimens and to simulate natural saline pore-water conditions. This procedure is consistent with the methods adopted in [11], [12].

The soil–binder mixture was placed into cylindrical molds measuring **71.1 mm in diameter and 142.2 mm in height**. The specimens were prepared in three approximately equal layers. After the placement of each layer, the mold was vibrated on a vibrating table for **3 min** to improve mixture homogeneity and reduce entrapped air within the specimens.

Standard curing was performed in accordance with TCVN 9403:2012 at a temperature of 27 ± 2°C and a relative humidity of ≥ 95%. After demolding, the specimens were stored in a standard curing chamber to maintain stable temperature and humidity conditions throughout the curing period. These curing conditions helped minimize moisture loss, reduce the risk of salt leakage or salt loss from the specimens, and promote the development of cementitious bonding within the stabilized soil. This controlled curing procedure is also consistent with [11], [12].

These parameters were used to evaluate the load-bearing capacity and deformation characteristics of the stabilized soil. The experimental program is presented in Figure 1.

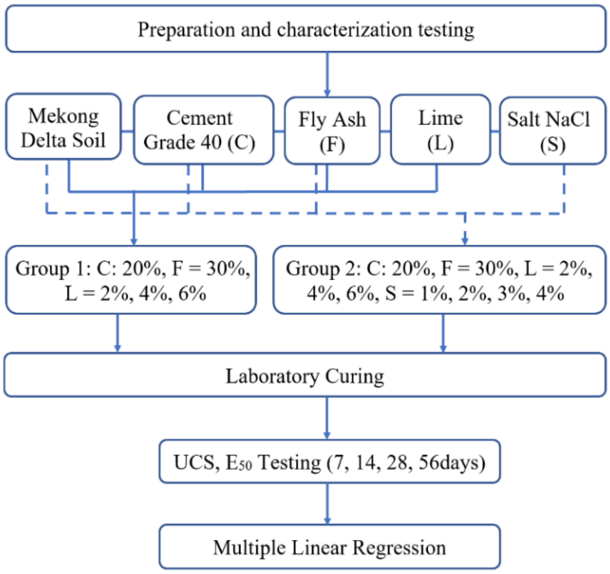
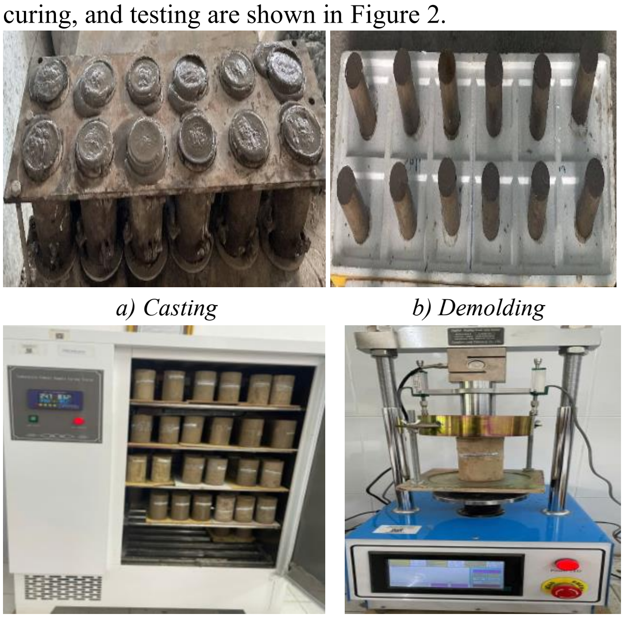


Figure 1. *Flow chart of the study*

After thorough mixing, the soil – binder mixture was cast into cylindrical specimens with a diameter of 71.1 mm and a height of 142.2 mm. The specimens were cured under standard conditions and then subjected to unconfined compression tests at curing ages of 7, 14, 28, and 56 days to evaluate the development of strength and stiffness over time. The procedures for specimen preparation, demolding, curing, and testing are shown in Figure 2.



a) Casting *b) Demolding*

c) Curing *d) Testing*

Figure 2. *Stabilized soil samples: (a) Casting, (b) Demolding, (c) Curing, (d) Testing*

The main parameters analyzed were UCS and E_{50}, obtained from the stress – strain curves. The E_{50} value was determined at 50% of the peak compressive stress [12]. UCS was calculated using the following equation.

$$q_u = P/A \quad (3.1)$$

where, q_u is the compressive strength of the stabilized soil specimen at the testing age (MPa), P is the failure load applied during the test (kN), and A is the compressed cross-sectional area of the specimen (mm²).

4. Results and Discussion

4.1. Results of UCS

The mix designations follow a systematic notation where each letter represents a component and the following number indicates its content (%) by dry soil weight: S = Soil, C = Cement, F = Fly ash, L = Lime, and S (suffix) = NaCl. For example, S20C30F2L denotes a mixture with 20% cement, 30% fly ash, and 2% lime added to the soil, with no NaCl. The designation S20C30F6L3S indicates 20% cement, 30% fly ash, 6% lime, and 3% NaCl. The number following the suffix S specifies the NaCl content in percent of the total dry mixture mass.

The UCS results were determined based on groups of three specimens. If the result of one specimen deviated by more than ±15% from the average value of the group, only the remaining two specimens were used to calculate the representative value. If fewer than two valid specimens remained, the test was repeated. The average UCS values of the mixtures are presented in Table 3.

Table 3. *Average UCS results of different mixtures*

ID	Mix design	UCS (MPa)			
		7 days	14 days	28 days	56 days
Group 1	S20C30F2L	0.14	0.20	0.25	0.32
	S20C30F4L	0.28	0.43	0.56	0.92
	S20C30F6L	0.29	0.48	0.67	1.00
Group 2	S20C30F2L1S	0.35	0.55	0.77	1.27
	S20C30F2L2S	0.14	0.20	0.34	0.45
	S20C30F2L3S	0.08	0.24	0.39	0.49
	S20C30F2L4S	0.10	0.17	0.26	0.56
	S20C30F4L1S	0.11	0.19	0.31	0.65
	S20C30F4L2S	0.14	0.34	0.45	0.81
	S20C30F4L3S	0.14	0.30	0.42	0.60
	S20C30F4L4S	0.15	0.40	0.67	0.85
	S20C30F6L1S	0.11	0.26	0.35	0.63
	S20C30F6L2S	0.19	0.36	0.75	1.03
	S20C30F6L3S	0.20	0.44	1.05	1.46
	S20C30F6L4S	0.14	0.31	0.55	0.60

The UCS of the stabilized soil increased with curing time for all mixtures. This is due to cement hydration and pozzolanic reactions that form binding gels (C–S–H and C–A–H), making the soil structure denser. In addition, higher lime content improved the strength by increasing alkalinity and promoting pozzolanic reactions [10, 13, 16, 19].

The results also show that NaCl salinity significantly affects the strength of the stabilized soil. The relationship between UCS and NaCl content follows a nonlinear trend. Within the studied range, UCS increased as NaCl content increased to about 3%, but decreased when the salt content further increased to 4%. This indicates the existence of an optimal salinity threshold for soil stabilization.

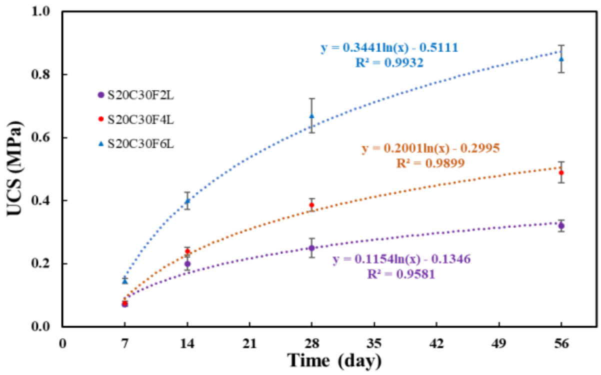


Figure 3. *Effect of lime content on UCS development with curing time*

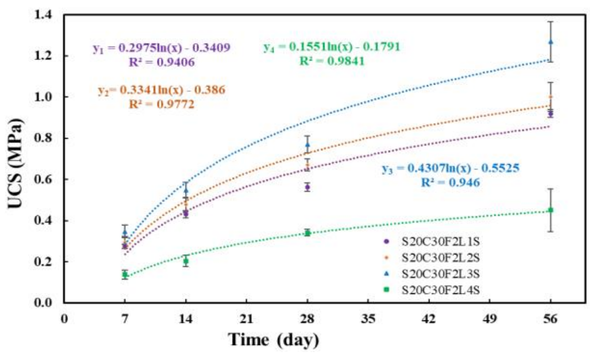


Figure 4. *Effect of NaCl content on UCS of S20C30F2L*

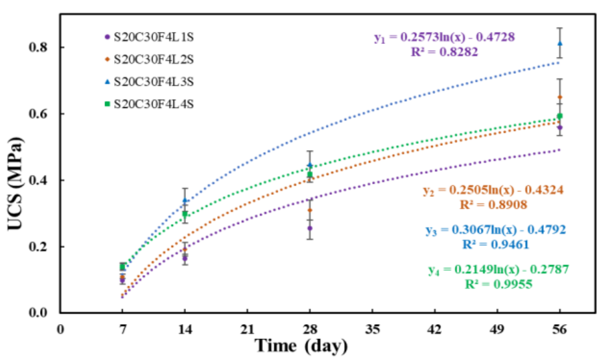


Figure 5. *Effect of NaCl content on UCS of S20C30F4L*

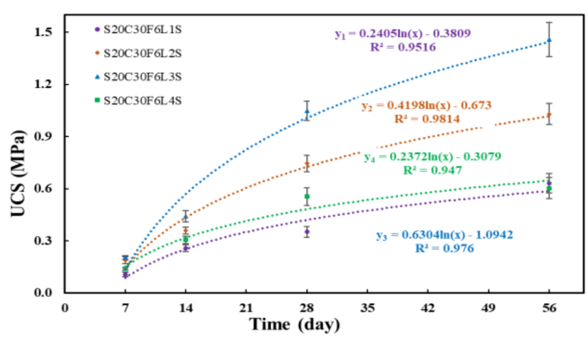


Figure 6. *Effect of NaCl content on UCS of S20C30F6L*

At low concentrations, Na^+ and Cl^- ions may compress the diffuse double layer surrounding clay particles, reduce electrostatic repulsion, and promote flocculation and aggregation of the soil structure [13]. At the same time, the saline environment may maintain a high pH value, thereby promoting pozzolanic reactions and the formation of cementitious products such as C-S-H and C-A-H [15].

However, when NaCl content exceeds the optimal level, excess chloride ions may react with the aluminate phase of cement to form Friedel's salt, which is a non-cementitious product that increases the porosity of the soil–cement structure [18], [19]. In addition, a high-salinity environment may hinder the normal hydration of cement, resulting in a reduction in the strength of the stabilized soil [12], [20].

A more detailed analysis of the data in Table 3 reveals that the optimum NaCl content is not universal but varies depending on the lime level. For the 2% lime series (S20C30F2L), the highest UCS at 56 days was achieved at 1% NaCl (1.27 MPa), and UCS declined at higher NaCl contents, indicating that low lime capacity limits tolerance to salinity. For the 4% lime series (S20C30F4L), the UCS values at 2% and 4% NaCl are comparable (0.81 and 0.85 MPa, respectively), suggesting a broad optimum at 2–4% NaCl. For the 6% lime series (S20C30F6L), the highest UCS was recorded at 3% NaCl (1.46 MPa at 56 days), indicating that a higher lime content generates more $Ca(OH)_2$ and sustains a more alkaline pore environment, enabling the system to tolerate a higher salinity before Friedel's salt formation becomes dominant. These observations highlight that the optimal NaCl content should be selected in conjunction with the lime content, rather than applying a single global optimum.

The positive effect of low NaCl concentrations can be explained by the following interconnected mechanisms: (1) Clay flocculation: Na^+ ions compress the diffuse double layer surrounding negatively charged clay particles, reducing electrostatic repulsion and promoting particle flocculation, which produces a denser fabric and improves binder-to-particle contact. (2) Pore water chemistry: the ionic strength of the pore solution is elevated, maintaining the alkaline pH conditions required for sustained cement hydration and pozzolanic activation of fly ash. (3) Cement hydration: Na^+ ions may act as an accelerator for the early-stage hydration of C_3S and C_3A phases, promoting the formation of C-S-H and C-A-H gels. (4) Pozzolanic reactions: the alkaline environment maintained by low NaCl content enhances the reaction between $Ca(OH)_2$ (from cement hydration and lime) and the SiO_2/Al_2O_3 phases in fly ash and clay minerals, producing additional cementitious products. At NaCl contents exceeding 3–4%, the proposed detrimental mechanisms include: (a) reaction of excess Cl^- ions with the C_3A phase of cement to form Friedel's salt ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$), a non-cementitious product that increases porosity [17]; (b) impairment of normal cement hydration; and (c) dispersion of clay particles. These mechanisms are proposed as plausible interpretations supported by existing literature and are recommended for direct verification in future studies via XRD or SEM analysis.

4.2. Results of elastic modulus (E_{50})

The elastic modulus E_{50} is a parameter representing the deformation capacity of a soil specimen under axial compression. It is determined at the stress corresponding to 50% of the peak compressive stress (q_u) on the stress – strain curve obtained from the unconfined compression test. The test results of E_{50} are presented in Table 4.

Table 4. *Average E_{50} results of different mixtures*

ID	Mix design	E_{50} (MPa)			
		7 days	14 days	28 days	56 days
Group 1	S20C30F2L	4.87	6.39	10.22	18.62
	S20C30F4L	4.12	15.38	17.28	23.31
	S20C30F6L	5.40	18.65	23.82	32.09
Group 2	S20C30F2L1S	21.22	42.95	51.09	76.73
	S20C30F2L2S	24.56	47.49	61.70	80.80
	S20C30F2L3S	28.94	61.00	73.33	86.89
	S20C30F2L4S	10.62	20.74	29.00	32.18
	S20C30F4L1S	6.75	16.50	21.34	33.10
	S20C30F4L2S	7.39	15.97	26.86	37.71
	S20C30F4L3S	10.09	20.67	30.48	40.70
	S20C30F4L4S	9.27	17.03	26.86	29.75
	S20C30F6L1S	10.69	28.70	38.30	45.09
	S20C30F6L2S	20.85	38.26	57.69	64.32
	S20C30F6L3S	20.00	44.14	59.13	81.03
	S20C30F6L4S	15.34	30.55	35.47	37.69

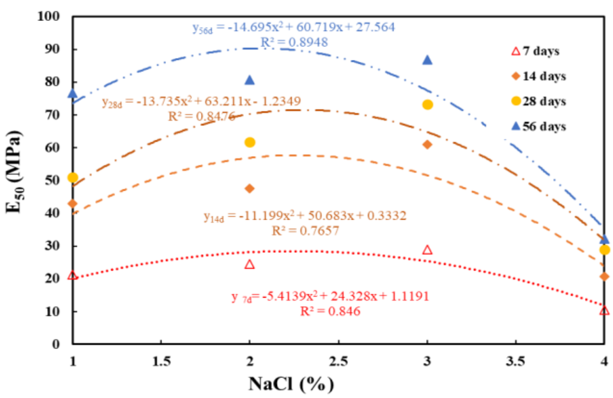


Figure 7. *Effect of NaCl content on the development of E_{50} with curing time of S20C30F2L*

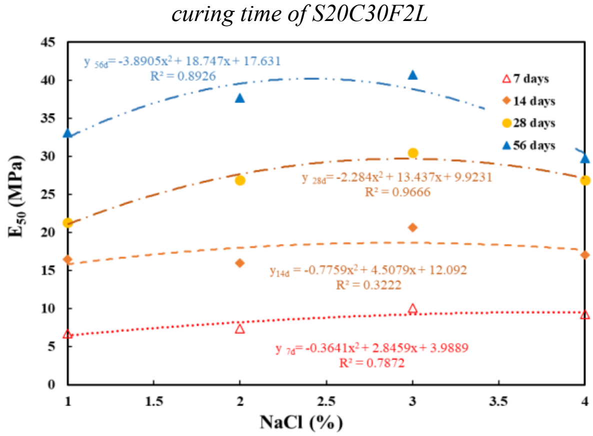


Figure 8. *Effect of NaCl content on the development of E_{50} with curing time of S20C30F4L*

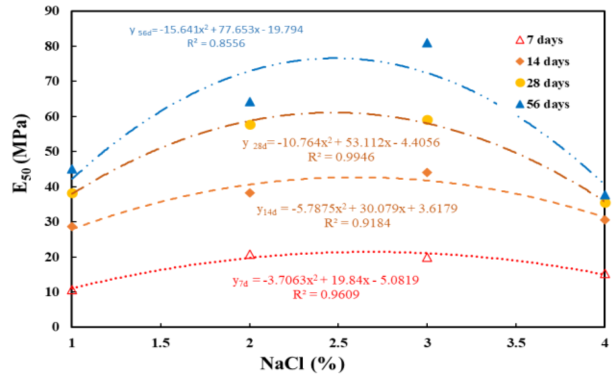


Figure 9. *Effect of NaCl content on the development of E_{50} with curing time of S20C30F6L*

The deformation elastic modulus E_{50} increased with curing time and binder content, indicating that the stiffness of the stabilized soil improved due to the development of hydration and pozzolanic products, which increased bonding and densification within the soil structure.

The results also show that the elastic modulus E_{50} of the stabilized soil increased with curing time, reflecting the development of hydration and pozzolanic reactions that made the soil–cement–fly ash–lime structure denser. At the same time, E_{50} varied with NaCl content in a nonlinear manner, with E_{50} increasing as the salt content increased to about 2–3%, and then decreasing as salt content increased further. This indicates the existence of an optimal salinity level at which the ionic environment promotes flocculation and pozzolanic reactions. In contrast, higher salt concentrations may weaken the bonding structure and reduce the stiffness of the stabilized soil.

4.3. Relationship between UCS and elastic modulus E_{50} of stabilized mixtures Custom segmentation analysis

The relationship between deformation elastic modulus and UCS is presented in Figure 10.

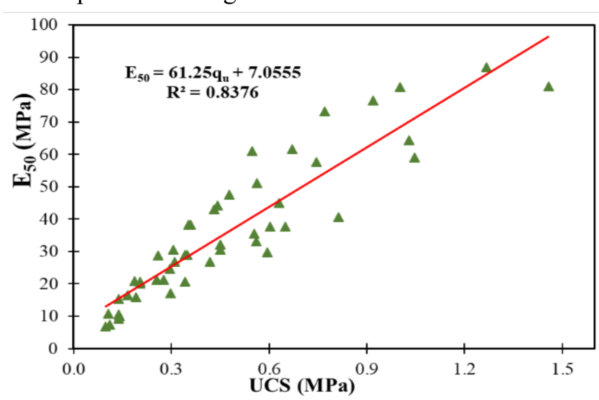


Figure 10. *Relationship between UCS and E_{50}*

The results Figure 11 shows that NaCl content markedly influenced both peak strength and stress–strain response of the stabilized clay. For the S20C30F2L group, the 3S specimen reached the highest peak stress, but its rapid post-peak stress drop indicates a more brittle failure mode and limited strain capacity. In contrast, the S20C30F6L3S mixture exhibited the most favorable behavior, with the highest peak stress and a sustained stress response up to relatively large strain levels, suggesting improved ductility and stabilization efficiency. The 4S specimens in both groups showed reduced strength, indicating that excessive NaCl may hinder cementitious bonding and weaken the stabilized soil structure.

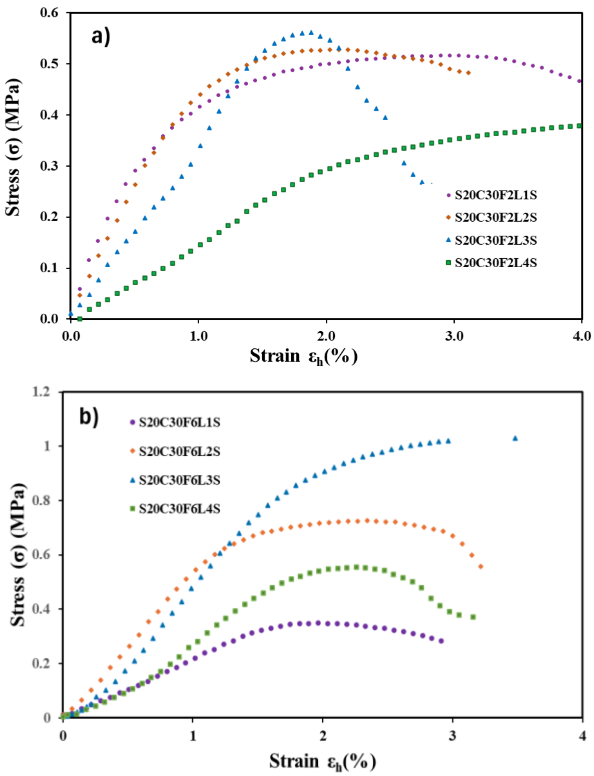


Figure 11. *Stress–Strain Behavior of Stabilized Clay under NaCl Exposure: (a) S20C30F2L; (b) S20C30F6L*

The results show that the elastic modulus E_{50} has a linear correlation with the compressive strength q_u, which is described by the equation $E_{50} = 61.25q_u+7.0555$. The experimental results indicate that the relationship between elastic modulus E_{50} and UCS q_u of the treated soil is a strong positive linear correlation, reflecting the simultaneous increase in stiffness and load-bearing capacity of the stabilized soil mass. This result is also consistent with the study on ground improvement in Bangkok using jet grouting, which reported $E_{50} = 50.84q_u$ [21]. However, compared with previous studies, the stiffness development per unit strength in the present study is lower. Specifically, a study on soft clay stabilized with cement – GGBFS in Vietnam reported $E_{50} = 101.4q_u - 22.26$ [10]. Similarly, a study on cement-stabilized lateritic soil in Malaysia reported $E_{50} = 106.82q_u$ [14]. The value obtained in this study still falls within the range reported in previous studies. Fang et al. [22]. reported that the elastic modulus generally ranges from 30 to 300 times q_u for soils treated with ordinary Portland cement. In addition, Vu Ngoc Binh [23] reported that the elastic modulus typically ranges from $50q_u$ to $184q_u$ for soft soils stabilized with inorganic binders in the Mekong Delta region.

5. Conclusion

This study evaluated the effect of NaCl salinity on the strength and stiffness of clayey soil treated with cement, fly ash, and lime under soft ground conditions in the Mekong Delta. The results clarified the effects of lime content, salinity level, and curing time on the development of UCS and E_{50}, providing an experimental basis for binder selection in saline environments.

From the experimental results, several main conclusions can be drawn as follows:

1. The UCS of cement–fly ash–lime treated soil increased with curing time and generally followed a logarithmic trend. Strength gain was more pronounced at early ages due to hydration and pozzolanic reactions forming C–S–H and C–A–H products.

2. Lime content significantly affected the strength development of the stabilized soil. As lime content increased from 2% to 6%, UCS increased markedly, showing that lime played an important role in activating pozzolanic reactions of fly ash and clay minerals in an alkaline environment.

3. NaCl content significantly influenced the strength of the stabilized soil. UCS increased as NaCl content rose from 1% to about 3%, then decreased at 4%. This suggests an optimum salt content for improving mechanical properties, whereas higher salinity may reduce strength by hindering hydration and promoting non-cementitious products.

4. The elastic modulus E_{50} showed a strong linear relationship with the UCS of the stabilized soil, expressed as:

$$E_{50} = 61.25q_u + 7.0555$$

This result is consistent with previous studies on soils stabilized with inorganic binders.

The findings provide an important experimental database for evaluating and designing ground improvement solutions in saline environments, particularly in coastal areas and the Mekong Delta.

At 28 days, the UCS of the control mixture S20C30F6L reached 0.67 MPa, while the best-performing mixture S20C30F6L3S achieved 1.05 MPa, representing an improvement of approximately 57%. Increasing lime from 2% to 6% raised UCS from 0.32 MPa to 1.00 MPa at 56 days (a 3.1-fold improvement) in the absence of NaCl. The optimum NaCl content was found to depend on the lime level: 1% for 2% lime, 2–4% for 4% lime, and 3% for 6% lime. The E_{50}–UCS relationship $E_{50} = 61.25q_u + 7.0555$ ($R^2 = 0.8376$, N = 60 data points) indicates that E_{50} spans approximately 18–97 MPa across all tested conditions.

For practical application, the mixture S20C30F6L3S (6% lime, 3% NaCl) is recommended as the optimal binder combination within the tested range, achieving the highest strength and stiffness at 56 days. For projects in mildly saline environments (NaCl ≤ 2%), the mixture with 6% lime and 1–2% NaCl is recommended as a conservative design choice. The empirical E_{50}–UCS relationship $E_{50} = 61.25q_u + 7.0555$ can be used in preliminary settlement and deformation analyses to estimate elastic modulus directly from UCS data, provided that the binder type and proportions are consistent with those of this study.

This study is still limited in terms of soil type, salinity range, binder proportion, and curing duration, while the evaluation was mainly based on UCS and E_{50}. In particular, the absence of microstructural analyses (SEM, XRD, EDS, FTIR, or TG/DTG) is acknowledged as a limitation; the proposed mechanisms of Friedel's salt formation and pozzolanic activation are consistent with the existing literature but require direct experimental confirmation. Therefore, future studies should consider a wider range of soils, binder mixtures, salinity conditions, and curing periods, together with microstructural and durability analyses, to better explain the governing mechanisms and improve field applicability.

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