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Determination of Particles and Minerals Content in Soft Clay Soil of the Mekong Delta Coastal Provinces, Southern Vietnam for Inorganic Adhesives Stabilization

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Abstract

The paper aims at investigating the content of particles and minerals of soft clay soil in the Mekong Delta coastal provinces, southern Vietnam, as well as improving soil stability using inorganic adhesives, i.e. lime and cement-based stabilization. To study the composition of soft clay soil, a series of different laboratory methods were carried out and revealed various characteristics related to mineral composition, pH value, soluble salt content, and grain particle composition of soft clay soils. The results demonstrated five soil subtypes, namely high – saline soil (S2), low-saline soil (S1), acid sulfate soil (A), acid sulfate - saline soil (S-A), soil without salt and acid sulfate content (S0- A0). The soft clay soil (C) included 5 subtypes, which were C-S2, C-S1, C-A, C-AS, and C-S0-A0, whereas the soft sandy clay soil (SC) included three subtypes, namely SC-S2, SC- S1, and SC-S0-A0. Analysis of the above results showed that the high - saline soil, acid sulfate soil, and acid sulfate - saline soil are not suitable for lime and cement stabilization. This observation was illustrated by the initial experiment of cement – soil mixture properties.

Keywords: Sandy clay, clay, stabilization, soft soil, mineral – chemical composition.

Introduction

The Mekong Delta coastal province is a part of Mekong Delta, southern Vietnam. The Mekong Delta is the largest delta of Vietnam, is a low-lying delta plain and has been formed by the sedimentation of the Mekong River system [1,2].

It is worth noting that the previous studies on the sedimentary deposits in Mekong Delta mainly aimed at investigating the sedimentary facies and properties of sedimentary deposits in late Pleistocene – Holocene or late Holocene. Characteristics of late Holocene depositional environments and coastal evolution at the 4500-6000 years BP were clarified [1]. Ta et al. [2] studied the depositional environments in late Pleistocene – Holocene at the depth borehole BT2 of 71 meters in Ben Tre province. It was found that the Post-glacial transgression caused by sea-level rise had led to events such as the infill of the incised valley, the formation of the estuarine sediments, the opening of the bay muddy sediments, and the regressive succession composed of prodelta, delta front, sub- to intertidal flat and beach ridge in ascending order. Based on the six boreholes depth of 27~71 meters, Ta et al. [3] described the sedimentary facies, diatom and foraminifera assemblages at late Pleistocene – Holocene stage in Mekong Delta. They also showed that the Late Pleistocene–Holocene strata had three groups, namely the Late Pleistocene undifferentiated sediments, transgressive incised-valley fill sediments, and Holocene delta sediments. The delta initiation and sediment facies succession at the early Holocene stage was closely linked to the Holocene sea-level changes and the sedimentary deposits that were formed [4]. The sediment facies, the changes of delta properties and the accumulation of deposits

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were affected by the river – sea interaction [3, 5-8]. The progradation of the Mekong Delta has changed over the past 7500 years and the shoreline is currently still changing [9].

Studies on the engineering of the geological characteristics of soft soil in the Mekong Delta are still limited. Bui [10] found that some reports on geotechnical engineering did not reflect the mechanical properties of soft soil in the Mekong Delta. Takemura et al. [11] showed differences in some physico-mechanical properties of soft soil in Can Tho and Tan An. The properties of these soils were effected by deposition conditions and flow regimes of different rivers during the period of sediment deposition. Due to the low-lying plains and the intertwined network of canals, the Mekong Delta is often flooded in the rainy season; nearly half of the area is flooded in the rainy season of 3~4 months per year. Moreover, the Delta often suffers from saltwater intrusion and has a complicated hydrological regime, which is an ocean regime. Altogether, these factors lead to the complexity of the soft soil in the delta.

The soft clay soil composed of clay and sandy clay [12-14]. They were Holocene sediments and widely distributed in the Mekong Delta coastal provinces [15]. The soils had many deposits but mainly composed of alluvial – marine deposits (amQ_2^{2-3}). There were complex mineral and chemical components in these soils because of the distribution in the low-lying terrain [16]. They were also specially composed of montmorillonite, soluble salts, and acid sulfate content [17].

Soft soil relates to many construction fields, especially road construction. Before the construction of buildings, soft soil must be improved. To be effective in improving the soil with inorganic adhesives, such as lime and cement, it is necessary to study the soil composition [18-20].

The aims of the present study are to investigate and evaluate the properties of grain size distribution and minero – chemical composition of soft clay soil in the Mekong Delta coastal provinces, southern Vietnam, for the purposes of inorganic adhesive stabilization. The composition of the soil (mineral, chemical, organic, soluble salt, cation exchange adsorption, ...) is a scientific basis to design improving methods for construction.

Materials and Methods

Undisturbed soil samples were collected from the boreholes with the depth of a few meters to over ten meters. The clay soil was in soft state and belongs to Holocene deposits, i.e. clay and sandy clay, was studied. The soil samples were taken from thirty-eight sites in different parts of the Mekong Delta coastal province (Figure-1), i.e. Tien Giang (sites 1-6), Ben Tre – Tra Vinh (sites 5-21), Soc Trang (sites 22-26), and Bac Lieu, Ca Mau, and Kien Giang (sites 27-38). At each site, six soil samples were collected.

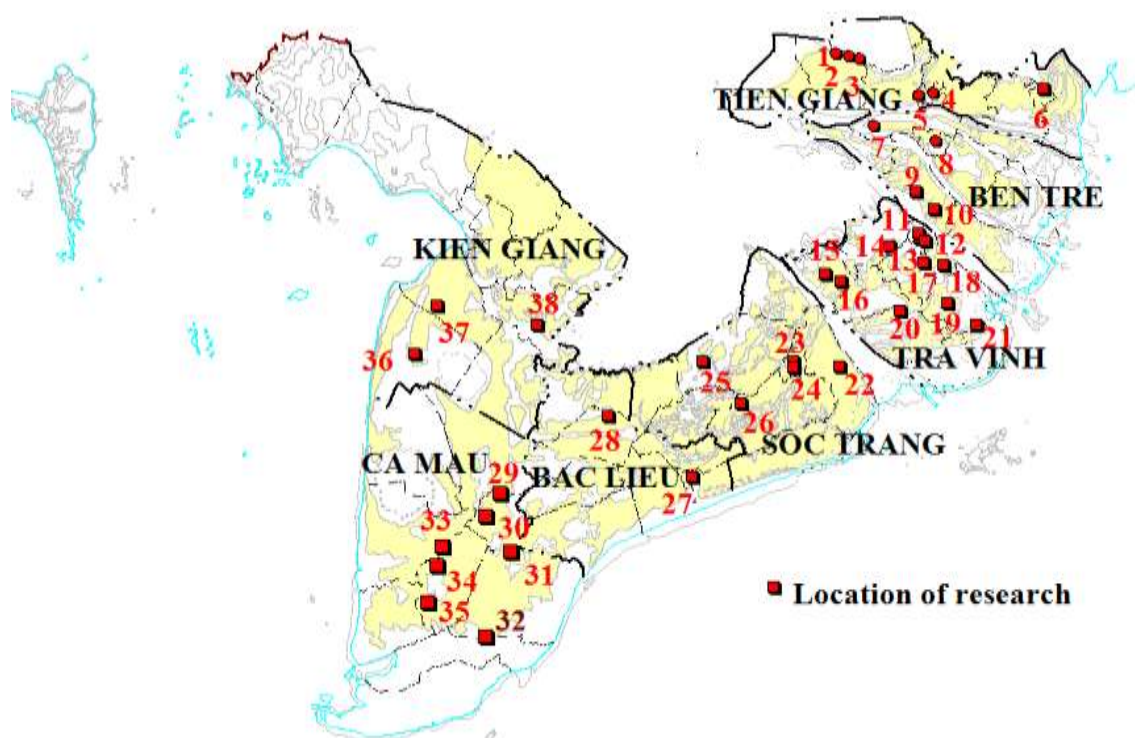


Figure 1- Location of the research area.

The study of soil components in the laboratory included mineral and chemical composition analysis, soluble salt content, pH, organic content, and ion-exchange. Particle size was determined according to the American standard ASTM D 422. The mineral composition was analyzed according to three methods, which were X-ray powder diffractometry, differential thermal analysis, and Scanning Electron Microscopy (SEM). The measurements of organic matter content, pH value, and cation exchange capacity were carried out according to the British standard BS 1377:part 3: 1990 and the American standard ASTM D 7503, respectively.

Results and Discussion

The composition characteristics of soft clay soil are described as follows:

Grain particle composition: The results of grain particle composition of soft clay soil are provided in Table-1. It could be observed that the ranges of the mean values were 37-50% of clay, 35-42% of silt, and 35-42% of sand in the soft clay soil. The results also showed that these range values were 24-27% of clay, 29- 36% of silt and 38 - 47% of sand in the soft sandy clay.

Table 1- Grain particle composition of soft clay soil

Sites	Number of samples	Size particle distribution, %		
		Sand	Silt	Clay
Soft clay				
1-6	364	19 ; 1 - 46	39 ; 18 - 67	42 ; 31 - 59
7-21	921	23 ; 5 - 57	40 ; 13 - 65	37 ; 30 - 55
22-26	474	16 ; 1 - 33	42 ; 18 - 62	44 ; 30 - 70
27- 38	2501	15; 0,5 - 38	35 ; 10 - 62	50 ; 30 - 79
Soft sandy clay				
1-6	91	47 ; 3 - 69	29; 14 - 56	24; 11 - 29
7-21	231	38 ; 9 - 69	36; 10 - 65	26; 13 - 29
22-26	81	39 ; 6 - 66	33; 17 - 57	27; 10 - 29
27- 38	74	38 ; 16 - 63	36; 16 - 62	26; 12 - 29
<i>Note: 19; 1 - 46 – Average, Min and Max value respectively</i>				

The predominance of the content of clay and silt particles in soft clay soil can reduce permeability, prolong the settlement time of the buildings and reduce the ability to mix inorganic adhesives into the soil.

Soluble salt and alum content: The composition of soft clay soil is provided in Table-2. It was found that soft clay soil had a different amount of salt, alum and organic content.

Table 2- Composition of soft clay soil.

Sites	pH value	SO ₃ ,%	Organic content, %			Salt content,%				
			Average	Max	Min	Average	Max	Min	Type of salt	
1-6	4.7-6.8	0.10-0.65	3.85	9.08	0.92	0.57	1.12	0.11	Cloru, Clorua -sunfat	Low salt or without salt
7-21	5.7-6.4	0.11-0.24	2.15	4.75	0.91	0.34	0.82	0.10		high salt, low salt
22-26	6.5-7.3	0.08-0.32	3.66	7.92	0.64	1.28	2.08	0.21		
27- 38	3.1-7.2	0.02-1.83	4.86	10.14	0.82	1.45	2.85	0.27		

In sites 1-6, there was low - saline soil (salt content ranges from 0.3 to 1%). But in some places, there were acid sulfate soils. The organic content of the soil was up to 9.08%. In the high terrain of the surface, the soil was not contaminated with salt-alum.

In sites 7-21, the soil belonged to low – saline soil. In the high terrain of the surface, the soil was not affected by alum - salt contamination. The organic content of the soil was less than 5%.

In sites 22-26, the soil belonged to high – saline soil. The organic content of the soil was less than 5%, but some places had up to 7.92% organic content.

In sites 27-38, there was high – saline soil (salt content of more than 1%) and low – saline soil, but in some places, there was acid sulfate soil or acid sulfate - contaminated salt soil. The organic content of soil ranged from 5 to 10.14%.

The results of the soluble salt content showed that:

- The high – saline soil and low – saline soil widely distributed in the Mekong Delta coastal provinces. This result can be explained by two reasons. The first reason is that the soil formed in a transitional environment (brackish water - saline water) with a certain amount of salt. Due to the existing condition, brackish water and saline water in the sediment could have washed salt – alum with different levels. The second reason might be that the terrain was low, the river system was intertwined with many estuaries to the East Sea and West Sea, and the tidal regime was complex (irregular tide regime, irregular semi-diurnal regime), caused saline intrusion in the groundwater and lead to salinize of soil.

- There were different salinity levels in the soft soil in the Mekong Delta coastal provinces. The clay soils in Ben Tre and Tra Vinh (sites 7-21) were classified as low– saline soils or soils without salt. This might be due to the fact that soft soils distributed in the high terrain areas, which were located before dunes and salts could wash out the soft soil because of the water river. In My Tho of Tien Giang (sites 4-5), the terrain was high and the sites located near the river, the saline level of clay soil was smaller than that in the areas of Dong Thap Muoi (sites 1-3) and Go Cong town (site 6). In Soc Trang province (sites 22-26), there were low– saline soils or high – saline soils. This can be explained that there was a little amount of freshwater in the dry season, and the seawater moved into groundwater and the saltwater intrusion happened. In the dry season, the water flow of the river was also smaller with the continuous and strong wind caused an increase in the saltwater intrusion. Moreover, human agriculture and fishery activities also promoted saltwater intrusion. In Bac Lieu, Ca Mau and Kien Giang (sites 27-38), the soils were classified as high – saline soils or low – saline soils. The main reason was that the terrain was the lowest and influenced by the East and West tides combined with the river system circulating with the sea. On the other hand, the level of washing of alum and saline in Bac Lieu, Ca Mau and Kien Giang (sites 27-38) is lower than that in Tien Giang and Ben Tre, Tra Vinh (sites 1-21) because of the low terrain and poor drainage conditions.

- In some sites, clay soils were alum or saline-alum soils (pH of less than 5.5 and SO₃ content of higher than 0.5%). There was SO₃ content in soils because of the bioaccumulation of sulfur in mangrove plants (black tiger and parrot). The death plants decomposed and accumulated alum content.

Mineral composition and cation exchange capacity: From the results of X-ray powder diffractometry, differential thermal analysis, and scanning electron microscopy (Figure 2), it can be observed that the mineral composition of clay soil included clay minerals such as illite, kaolinite, montmorillonite, and chlorite, in which the common clay mineral was illite or kaolinite, and the amount of montmorillonite was low. The higher content of illite and the presence of montmorillonite affected the plasticity, swelling, and compression of soil. These factors also adversely affected the ability of soft soil improvement by inorganic adhesives.

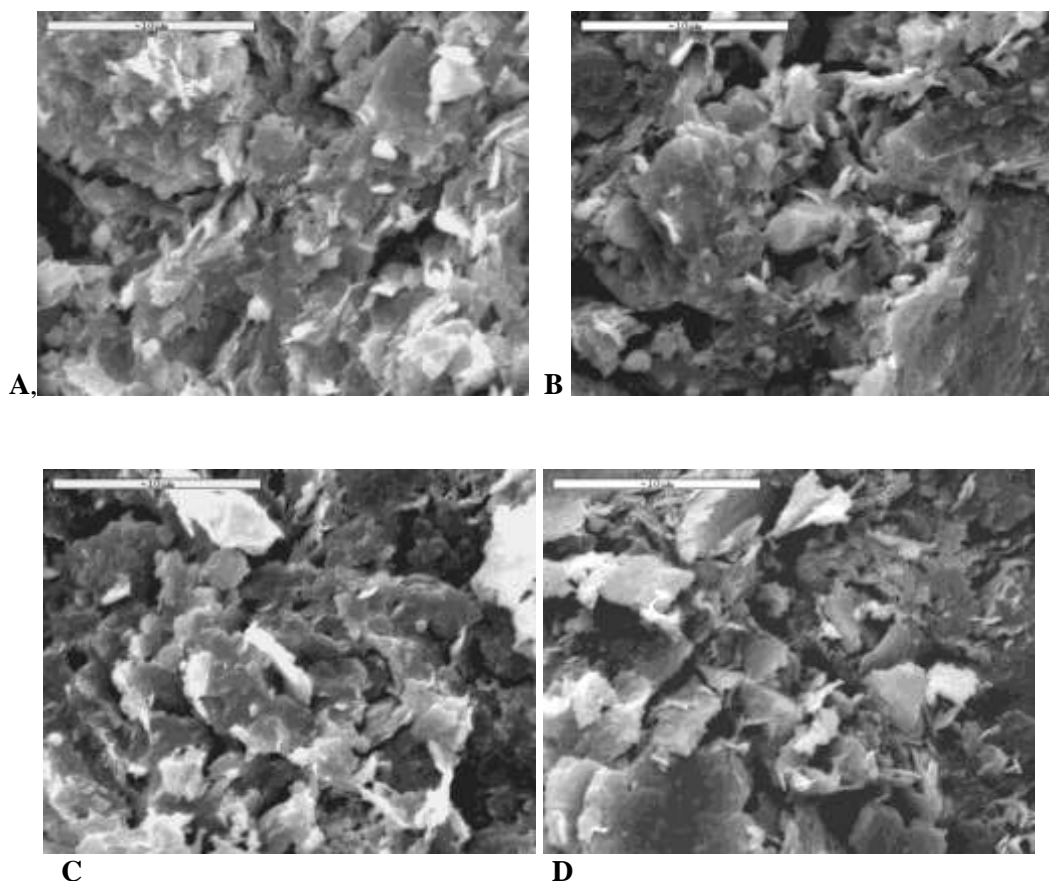


Figure 2- The SEM analysis at site 22. a, depth of 6.0-6.2m; b, depth of 8.0-8.2m; c, depth of 10.0-10.2m; d, depth of 14.0-14.2m.

The pH value of clay soil ranged between 3 and 7 and the environment of the pore water was neutral or weak acidic.

The cation exchange capacity of clay was classified medium to high [21] and ranged from 21.84 to 25.86 meq /100g dry soil. The cation exchange capacity of sandy clay was medium and varied from 16.90 and 20.74 me q/100g dry soil.

The predominant cations in clay soils were Ca^{2+} , Mg^{2+} , Na^+ , K^+ , and the cations of Al^{3+} ; Fe^{3+} , Fe^{2+} were very little content.

Groups of soft soil due to composition characteristics

Basis of soft soil groups

The type of soils and mineralogical properties of soils affected on physico - mechanical properties and the improvement of soft soil by inorganic adhesives stabilization. Based on the particle size, soft clay soils were divided into two types, namely soft clay (C) and soft sandy clay (SC). After that, based on the properties of salt and alum content, soft soils were classified into four types (Table-3).

Table 3 - Classification of soil types.

Types	Properties	
	Salt content, %	The pH value
Saline soil (S)	≥ 0.3	-
Acid sulphate soil (A)	-	< 5.5
Acid sulphate - Saline soil (A-S)	≥ 0.3	< 5.5
Soft soil has no salt and alum content (A0-S0)	< 0.3	≥ 5.5

Based on the degree of salt and alum contamination, soil type was divided into different subtypes, (Table-4).

Table 4 - Classification of soil subtypes

Subtypes	Properties	
	Salt content, %	The pH value
High- saline soil (S2)	≥ 1.0	-
Low - saline soil (S1)	0.3-1.0	-
Acid sulphate - saline soil (A-S)	≥ 0.3	< 5.5
Soft soil without alum and salt content (A0-S0)	< 0.3	≥ 5.5

Properties of soil groups

Based on the composition properties of soil, soft clay (C) and soft sandy clay (SC) were divided into types and subtypes as shown in Table-5. The physico – mechanical properties of the types and subtypes were also determined in the laboratory. These properties are shown in Table-5.

Table 5- Properties of types and subtypes of soft clay soil distributed in the Mekong Delta coastal province.

No	Properties of composition		Types and subtypes/ Area													
			C - A	C - S						C - A - S		C - A0 - S0		SC - S		SC - A0-P0
			C - A	C - S2			C - S1			C - A - S		C - A0 - S0		SC - S2	SC - S1	SC - A0-P0
			(1)	(27)	(29-31, 34-36)	(22,25,26)	(19-21)	(10)	(6)	(36-37)	(29)	(7-8)	(13-18)	(23-24)	(9)	(12)
1	Kaolinite	18	17	19	14	13	11	16	19	20	13	12	16	10	8	
		17	18	21	20	15	14	17	17	18	15	14	19	13	11	
		6	5	4	3	3	3	4	7	8	4	4	4	4	2	
2	pH	4.6-5.5	5.5-6.2	6.1-7.2	6.61-7.32	5.9-6.8	6.2-7.1	5.3-6.6	3.1-4.1	4.2 - 5.0	5.6-6.5	5.7-6.10	5.6-7.1	6.2 - 6.8	5.6-6.3	
3	Organic content,%	2.0-6.8	0.2- 2	1.6-10.4	0.64-5.31	0.4 - 1.6	2.1-5.4	2.3 5-4.0 5	2.0-10.6	2.2-8.5	0.2-2.1	0.0 - 2.1	0.2-3.5	2.8-5.0	0.2-2.2	
4	Salt content,%	0.06-0.4	0.87-1.94	0.32-2.85	0.21-2.08	0.30-0.73	0.24-0.82	0.1 1-0.9 8	0.35 - 2.48	0.27 - 1.86	0.03 - 0.28	0.10-0.25	0.11 - 1.50	0.34 - 0.82	0.08 - 0.27	
5	Cation exchange capacity, CEC,meq/100g	24.68	25.55	21.67	20.88	27.1	24.92	22.93	34.43	27.4 3	23.5 2	25.11	20.3 2	16.9 1	21.13	
6	Size particle distribution, P, %	Sand	19.2	14.2	12.5	19.2	25.4	18.3	20.4	20.4	7.8	6.1	22.6	37.0	33.3	29.1
		Silt	33.8	42.0	28.6	35.7	45.1	44.1	44.2	37.3	28.9	47.3	40.9	37.5	38.8	45.8
		Clay	47.3	43.8	58.9	45.1	47.7	37.5	39.7	43.3	63.7	46.2	36.5	26.0	27.5	25.1

Table 5- Properties of types and subtypes of soft clay soil distributed in the Mekong Delta coastal province (continued).

Group	Types	Sub -types	Soil composition properties	Distribution
Soft clay (C)	C - S	C – S2	pH value range from 5.5 to 7.32; salt content is almost more than 1%, up to 2.85%, in the upper of layer salt content is less than 1%; Organic content is less than 5%, At Ca Mau area there is more than 10%. The main clay mineral is illite, then kaolinite. The amount of montmorillonite is about 5%. Silt and clay content range from 80 to 90%.	Ca Mau peninsula, Soc Trang. Distributed small area in Ben Tre, Tra Vinh, and Tien Giang
		C – S1	pH value range from 5.9 to 7.1; salt content is less than 1%; Organic content is less than 5%, up to 10%; Silt and clay content range of 80 to 90%. The main clay mineral is illite, then kaolinite. The amount of montmorillonite is about 4%.	Ben Tre, Tra Vinh. Distributed small area in Tien Giang and Ca Mau peninsula
	C - A	C - A	pH value is less than 5.5; salt content is less than 0.3%, in some area, there is contaminated salt soil (salt content <1%); Silt and clay content range of 80 to 90%; Organic content is less than 5%, in some areas, there is 6 to 7% or up to 10% of organic content. Main mineral clay is kaolinite, then illite and montmorillonite	Distributed small area in Cai Lay, Cai Be, Chau Thanh of Tien Giang province; Ca Mau, Tan Hoi area of Kien Giang province
	C - A - S	C - A - S	pH value is less than 5, salt content changes of 0.3 to 2.5%; Silt and clay content range of 80 to 90%; Organic content is more than 5% (up to 10%). Main clay mineral kaolinite, then illite. The amount of montmorillonite is about 10%.	An Bien, An Minh, Go Quao of Kien Giang province; Ca Mau; Bac Lieu và small area in Tien Giang; My Tu of Soc Trang province.
	C – A0 - S0	C – A0 -S0	pH value ranges from 5.6 to 6.5; salt content is less than 0.3%; Organic content is less than -2%; Silt and clay content range of 70 to 80%. Clay minerals are respectively illite, kaolinite and montmorillonite;	Tra Vinh, Ben Tre; Tien Giang; the small area in Chau Thanh of Kien Giang province; Ke Sach - Soc Trang
Soft sandy clay (SC)	SC - S	SC – S2	pH value range of 5.6 to 7.1; salt content is more than 1.0%, the upper of layer salt content is less than 1%; Organic content is less than 5%. Main mineral clay is illite, then kaolinite. The amount of montmorillonite is less than 4%, Silt and clay content range of 50 - 60%.	Distributed small area in Ca Mau, Kien Giang và Soc Trang.
		SC – S1	pH value range of 6.2 to 6.8; salt content is less than 1%; Organic content is less than 5%; Silt and clay content range of 60 to 70%. Main mineral clay is illite, then kaolinite. Amount of montmorillonite is about 4%	Tra Vinh, Ben Tre. Tien Giang
	SC – A0 - S0	SC – A0 -S0	pH value range of 5.6 to 6.3; salt content is less than 0.3%; Organic content is less than 2%; Silt and clay content range of 60 to 70%. Clay minerals are illite, kaolinite, and montmorillonite.	Tra Vinh, Ben Tre; My Tho city - Tien Giang province

Table 5- Properties of types and subtypes of soft clay soil distributed in the Mekong Delta coastal province (continued).

No	Physico – mechanical properties	Types and subtypes/ area							
		C - A	C - S		C - A - S	C - A0 - S0	SC-S		SC – A0 -S0
		C - A	C – S2	C – S1	C - A - S	C - A0 - S0	SC- S2	SC-S1	SC – A0 -S0

		(1)	(27)	(29-31,34-36)	(22,25,26)	(19-21)	(10)	(6)	(36-37)	(29)	(7-8)	(13-18)	(23-24)	(9)	(12)	
1	Water content, W, %	67.4	68.6	73.2	61.1	58.4	58.6	70.8	75.8	75.90	63.0	54.2	40.6	41.8	41.9	
2	Unit weight, γ_w , g/cm ³	1.57	1.56	1.55	1.62	1.61	1.63	1.56	1.54	1.54	1.59	1.63	1.80	1.73	1.74	
3	Dry unit weight, γ_c , g/cm ³	0.94	0.93	0.89	1.01	1.02	1.03	0.91	0.88	0.88	0.98	1.06	1.28	1.22	1.23	
4	Specific gravity, γ_s , g/cm ³	2.66	2.60	2.67	2.68	2.65	2.70	2.67	2.65	2.69	2.63	2.67	2.68	2.68	2.64	
5	Void ratio, e	1.836	1.810	1.984	1.665	1.607	1.627	1.923	2.025	2.073	1.696	1.526	1.093	1.197	1.153	
6	Porosity, n, %	64.7	64.4	66.5	62.5	61.6	61.9	65.8	66.9	67.5	62.9	60.4	52.2	54.5	53.6	
7	Saturation ratio, G, %	97.6	98.5	98.5	98.3	96.3	97.2	98.3	99.2	98.5	97.7	94.8	99.5	93.6	95.9	
8	Liquid limit, WL, %	58.9	56.5	66.4	60.7	54.0	54.2	64.3	73.5	68.2	58.8	50.7	36.5	39.4	40.2	
9	Plastic limit, Wp, %	33.7	26.1	30.8	28.9	27.6	29.3	31.3	38.3	39.1	31.4	31.2	25.7	24.4	25.6	
10	Plasticity index, Ip, %	25.2	30.4	35.6	31.8	26.4	24.9	33.0	35.2	29.1	27.4	19.5	10.8	15.0	14.6	
11	Liquidity index, Is	1.34	1.40	1.19	1.01	1.17	1.18	1.20	1.07	1.27	1.15	1.18	1.38	1.16	1.12	
12	Preconsolidation pressure, σ'_p , kPa	46	44	52	54	46	61	52	47	51	45	65	62	59	52	
13	Recompression Index, Cc	0.592	0.640	0.777	0.576	0.497	0.537	0.738	0.768	0.827	0.576	0.415	0.300	0.288	0.314	
14	Swell index, Cr	0.096	0.071	0.153	0.097	0.069	0.062	0.079	0.129	0.122	0.078	0.074	0.052	0.038	0.053	
15	The ratio of $C\alpha/Cc$	0.036	0.035	0.035	0.037	0.035	0.035	0.036	0.035	0.035	0.035	0.035	0.034	0.034	0.034	
16	The coefficient vertical of consolidation of soil, Cv(NC), 10 ⁻³ x cm ² /s	0.57	0.15	0.28	0.49	0.50	1.28	0.49	0.21	0.25	0.56	0.75	1.02	1.51	0.93	
17	The ratio of Ch/Cv	Max	4.07	5.89	6.49	6.06	5.73	6.00	2.94	4.66	5.15	6.40	5.36	4.69	3.50	3.30
		TB	2.97	3.56	4.01	3.75	3.02	3.19	2.62	3.41	3.32	3.04	2.93	3.79	2.83	2.61
		Min	2.34	2.06	2.02	1.81	1.84	1.72	2.31	2.81	2.41	1.87	2.04	3.13	2.13	1.88
18	Undrained shear strength (UU test)	Cu, kPa	12.9	10.7	11.4	15.3	14.6	10.5	13.7	11.4	12.8	14.6	14.8	19.0	19.2	13.3
		ϕ_u , degree	0°10'	1°00'	0°56'	1°11'	0°46'	1°38'	0°36'	0°07'	1°34'	0°39'	1°04'	1°18'	1°19'	1°14'
19	CU test	Ccu, kPa	10.5	9.2	12.1	12.8	11.3	13.3	17.3	11.5	12.0	17.3	12.2	14.6	11.5	12.9
		ϕ_{cu} , degree	14°28'	12°33'	13°02'	12°86'	12°82'	11°96'	11°30'	12°49'	14°64'	10°33'	14°33'	13°80'	23°51'	14°50'
		C', kPa	8.8	8.1	10.5	10.9	8.4	11.0	16.1	9.0	10.5	12.0	9.4	11.6	5.6	10.1
		ϕ' , degree	25°57'	21°08'	22°59'	22°46'	23°47'	22°15'	21°53'	22°13'	23°10'	23°58'	24°43'	24°06'	31°48'	26°07'

Initial laboratory results of improvement by cement stabilization and deep mixing method for soft clay soil

In order to study the influence of the composition of clay soil on the improvement by cement, the initial experiments on the mixture of soil and cement (the shallow stabilization and deep mixing methods) were performed in the laboratory. For the shallow stabilization method, compaction characteristics of soil, the compressive strength and elastic modulus of the mixed soil-cement were determined (Tables- 6 - 7, Figure 3). Portland PC30 cement was used for mixing with the soil. For the deep mixing method, a metal mold of 50mm in inner diameter and 100 mm length was used for the preparation of mixture samples. All the mixed samples were subjected to a cure at room humidity and temperature for 28 days before testing. The unconfined compressive strength was tested according to ASTM D2166. Experimental results are shown in Table-8 and Figure-4.

Figure-3a and Table-7 show that the compressive strength and saturated elastic modulus values of the mixture of cement with the non-saline and alum soil types (C-A0-S0) in site 11 were the highest, while those values in the mixture of cement with high - saline soil (C-S2) in site 29 was decreased by 50 to 60%. The values of these two parameters in the mixed acid sulfate soil-cement sample were decreased by 57 to 65% in site 37. These results can be explained that the compressive strength of the soil-cement mixture was affected by pH value, organic content and salt content. If the salt content was higher than 1%, or pH value was lower than 5.5, or organic content was higher than 5%, and silt and clay content were high, the compressive strength and elastic modulus of the soil-cement mixture decreased. This is consistent with the results of Bell [22] and Moseley et al. [23]. Kazemian et al. [19] and Zhu et al. [20] explained that the low pH value (in a range of 3-5) inhibited the hydration and the pozzolanic reactions resulted in low compressive strength and low elastic modulus of the mixed soil – cement.

The results of the improvement of the soft sandy soil with cement were better than those of using soft clay. The soil-cement mixture of the type SC-A0-S0 in site 12 had the highest values of compressive strength and elastic modulus (Figure-3b).

Table 6- Compaction characteristics of some soft soils in the Mekong Delta coastal province.

Site	Types of soil	Subtypes of soil	Optimum water content $W_{tur}, \%$	Maximum dry unit weight, $\rho_{c \max}, \text{g/cm}^3$
1	C-A	C-A	34.9	1.30
37	C-A-S	C-A-S	33.2	1.34
33	C-S	C-S2	32.5	1.40
29	C-S	C-S1	30.1	1.43
11	C-A0-S0	C-A0-S0	28.0	1.46
23	SC-S	SC-S2	30.5	1.39
31	SC-S	SC-S1	33.1	1.39
12	CS- A0 - S0	CS- A0 - S0	24.5	1.55

Table 7- Compressive strength and elastic modulus of the mixed soil-cement sample.

Site	Types of soil	Subtypes of soil	Mixed soil + % cement (C+%CM, SC+%CM)	Optimum water content $W_{tu}, \%$	Maximum dry unit weight, $\rho_{c \max}, \text{g/cm}^3$	Compressive strength, kPa		Saturated elastic modulus E, kPa
						Compressive strength	Saturated Compressive strength	
1	C-A	C-A	C+9 CM	32.1	1.34	702	423	66690
			C+12 CM	32.3	1.35	1044	567	101160
			C+15 CM	33.9	1.36	1368	630	106920
37	C-A-S	C-A-S	C+3 CM	31.1	1.31	221	133	23452
			C+6 CM	32.2	1.32	310	186	32843
			C+9 CM	32.5	1.32	432	277	46687
			C+12 CM	32.7	1.33	607	418	66861
			C+15 CM	34.1	1.34	800	565	89718

33	C-S	C-S2	C+3 CM	21.7	1.41	270	160	27270
			C+6 CM	23.5	1.42	378	224	38190
			C+9 CM	25.0	1.43	527	334	54287
			C+12 CM	26.0	1.44	740	504	77745
			C+15 CM	27.6	1.45	975	681	104323
29	C-S	C-S1	C+3 CM	28.9	1.44	375	222	37905
			C+6 CM	29.5	1.45	525	311	53084
			C+9 CM	31.2	1.46	733	464	75459
			C+12 CM	32.1	1.47	1029	701	108066
			C+15 CM	33.5	1.48	1355	947	145009
11	C- A0-S0	C- A0-S0	C+3 CM	30.0	1.47	679	250	57715
			C+6 CM	31.2	1.48	909	575	79083
			C+9 CM	32.1	1.49	1232	809	109648
			C+12 CM	33.5	1.51	1403	906	127673
			C+15 CM	33.9	1.52	1754	1133	159598
23	SC-S	SC-S2	SC+3 CM	29.0	1.40	415	271	32900
			SC+6 CM	30.0	1.41	598	390	50192
			SC+9 CM	34.0	1.42	838	498	72866
			SC+12 CM	23.2	1.56	1257	797	123872
31	SC-S	SC-S1	SC+3 CM	21.7	1.41	543	200	46172
			SC+6 CM	23.5	1.42	782	523	71175
			SC+9 CM	25.0	1.43	1072	728	100876
			SC+12 CM	26.0	1.44	1193	1031	114840
			SC+15 CM	27.6	1.45	1438	929	132466
12	SC- A0-S0	SC- A0-S0	SC+3 CM	23.2	1.56	760	357	70680
			SC+6 CM	25.0	1.57	1053	610	100035
			SC+9 CM	27.0	1.59	1382	864	134054
			SC+12 CM	28.8	1.59	1604	1102	158796

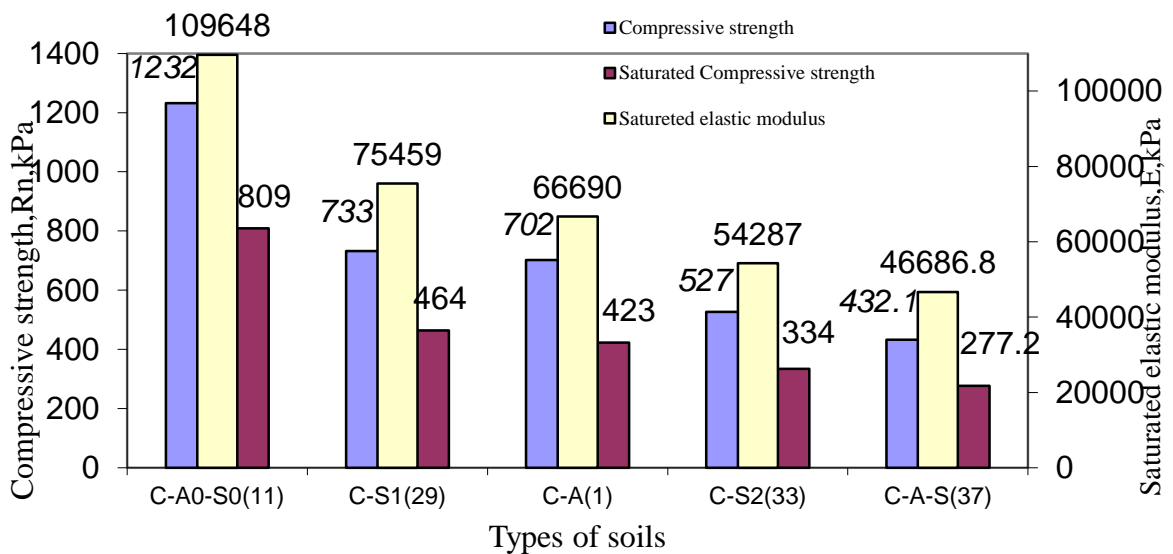


Figure 3a - Compressive strength and saturated elastic modulus of the mixed soil-cement sample (mixing soil with 9% cement).

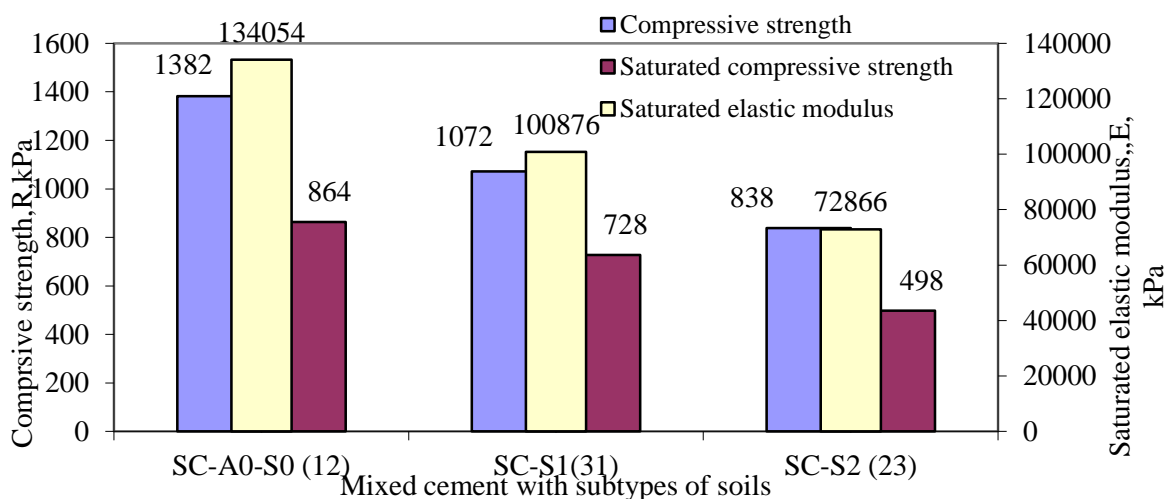


Figure 3b- Compressive strength and saturated elastic modulus of the mixed soil-cement sample (mixing soil with 9% cement).

The compressive strength and secant modulus of the soil-cement mixture in deep mixing method are shown in Table- 8 and Figure-4. It can be seen that the compressive strength and secant modulus of mixed cement with non-salt - alum soil types (C-A0-S0, SC-A0-S0), mixed cement with low- saline soil types (C-S1, SC-S1) were highest.

Table 8- Compressive strength and secant modulus of the soil-cement mixture.

Site	Types of soils	Subtypes of soils	Cement content (% or kg/m ³)	Unconfined compressive strength q _u , kPa		Secant modulus E ₅₀ , kPa
				7 days	28 days	
1	C-A	C-A	9%	9.0	11.3	540
			12%	19.0	25.0	2510
			16%	70.0	90.0	3660
			200kg/m ³	100.0	128.0	5230
3	C-S	C-S2	200kg/m ³	449.0	548.0	45109
			220kg/m ³	610.6	756.2	75624
			250kg/m ³	690.0	877.2	96496
4	C-S	C-S2	200kg/m ³	575.5	638.0	61682
			220kg/m ³	661.8	752.8	73025
			250kg/m ³	814.0	948.6	93909
30	C-S	C-S2	200kg/m ³	265.0	564.0	50357
			220kg/m ³	303.0	638.0	82073
			250kg/m ³	391.0	766.0	90667
34	C-S	C-S2	6%	197.1	274.3	28212
			9%	279.0	347.4	31718
			12%	397.0	442.0	43441
			16%	439.0	560.0	75505
			19%	542.0	650.0	96500
			200kg/m ³	439.0	560.0	75505
4	C-S	C-S1	9%	156.4	249.8	18293
			12%	295.0	485.0	33920
			16%	493.0	864.0	75930
			200kg/m ³	635.0	1080.0	111970

29	C-S	C-S1	200kg/m ³	598.0	726.0	96100
			220kg/m ³	687.7	827.6	120008
			250kg/m ³	852.7	993.2	146989
37	C-A-S	C-A-S	200kg/m ³	326.0	491.0	71833
			220kg/m ³	490.0	688.0	109455
			250kg/m ³	573.0	831.0	125909
11	C-A0-S0	C-A0-S0	6%	43.0	55.0	5022
			9%	103.0	142.0	13419
			12%	360.0	550.0	53185
			200kg/m ³	588.0	898.0	106800
31	SC-S	SC-S2	12%	404.3	452.3	39730
			16%	520.0	635.0	68100
			19%	617.0	926.0	92550
			200kg/m ³	520.0	635.0	68100
23	SC-S	SC-S2	200kg/m ³	794.0	932.0	111300
			220kg/m ³	1111.6	1351.4	151985
			250kg/m ³	1300.6	1608.2	182048
9	SC-S	SC-S1	9%	133.9	263.3	18518
			12%	242.0	480.0	31720
			16%	422.0	854.0	60330
			200kg/m ³	774.0	1090.0	123400
12	SC-A0-S0	SC-A0-S0	6%	52.0	76.0	7471
			9%	124.0	164.0	16252
			12%	480.0	616.0	61538
			200kg/m ³	880.0	1170.0	134200

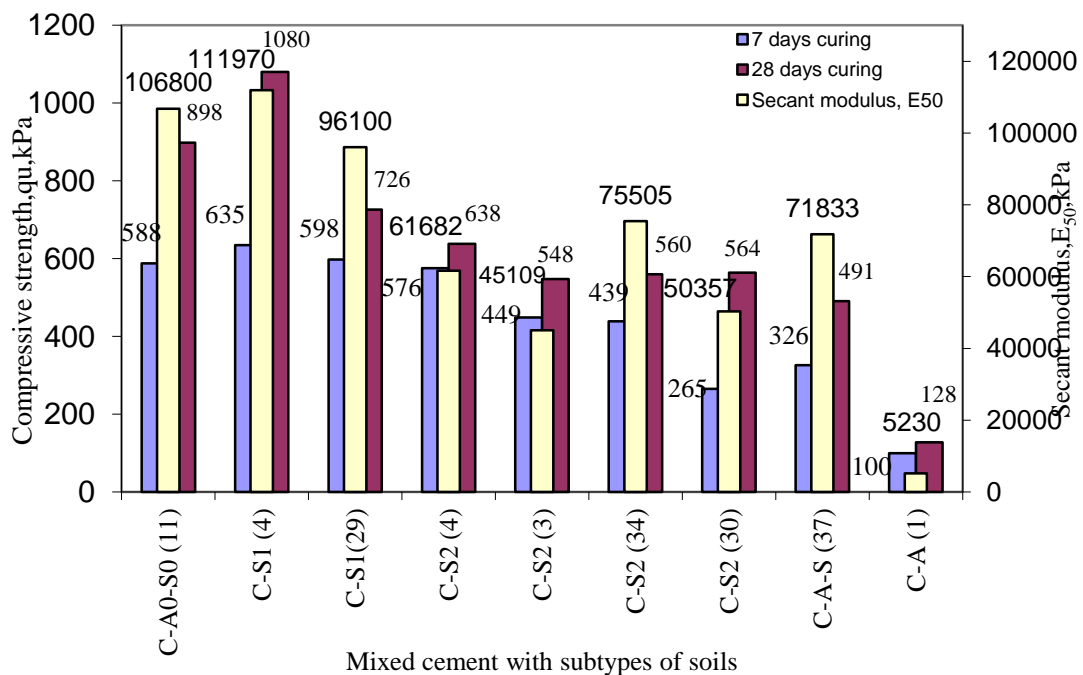


Figure 4a- Compressive strength and secant modulus of the soft clay mixed with cement (200kg cement/1m³soil).

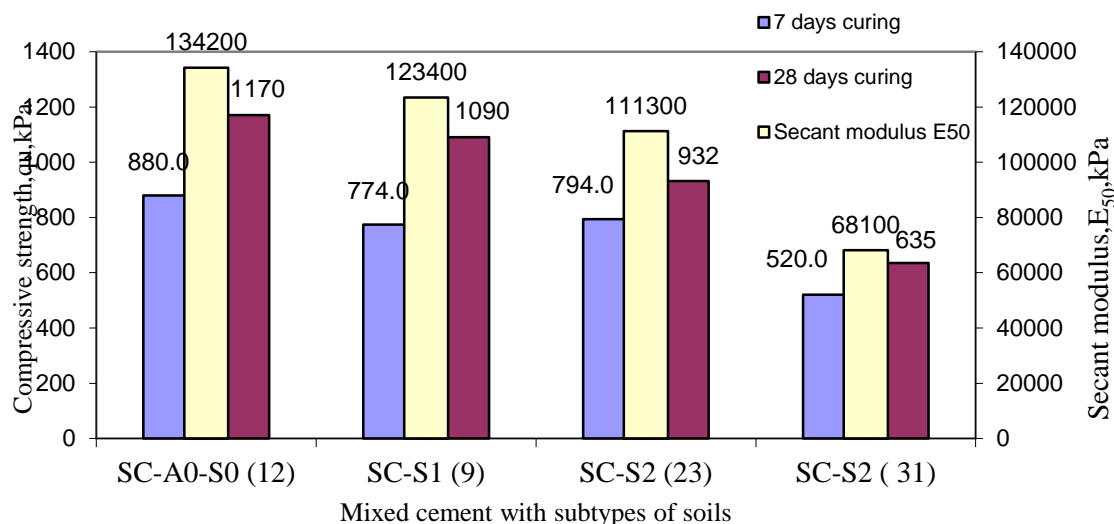


Figure 4b - Compressive strength and secant modulus of the soft sandy clay mixed with cement (200kg cement/1m³ soil).

Conclusions

Based on the analysis of the results, the following conclusions can be drawn as follows:

The soft clay soil with high silt - clay content (> 90%) had the disadvantage to improve soft soil by adhesives (lime and cement). The mixing of the binder with the soil was difficult and it may use a large amount of binder to mix with soil. Soft sandy clay soil can be improved by adhesives because of the low silt – clay content.

The high amount of montmorillonite and illite in clay soil was the disadvantage to stabilize soil due to preventing the hydration process of cement and lime.

The organic content, soluble salt content and the low pH value are the disadvantages to improve soil with lime and cement. If the organics content is lower than 5% and soluble salts content is higher than 1%, the soil can still be improved by these adhesives. But, The improvement of soft soil with lime and cement was not effective if the organics, salt content was high or the pH value was lower than 5.5.

Soft clay soil included the types of C – S2, C – S1, C-A, C-A-S, C-A0-S0. The stabilization of high - saline clay soil (C- S2), acid sulfate clay soil (C-A), and acid sulfate - saline soil (C-A-S) with cement was inefficient. The amount of cement to mix these soils was higher than that in the low - saline clay soil (C-S1) or non-saline- alum soil (C-A0-S0).

Soft sandy clay soil included the types of SC-S2, SC-S1 or SC-A0 – S0. The type of soft sandy soil (SC-S2) was effective for stabilization by cement.

To overcome the above disadvantages, it is possible to study the use of additives in soil improvement methods by lime and cement to reduce dispersion and improve low pH value.

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