



A comparative study on the effect of different additives on the strength of cement-treated soil in Mekong Delta, Vietnam

Vu Ngoc Binh¹ · Nguyen Thanh Duong^{2,3} · Do Minh Toan⁴

Received: 8 May 2024 / Accepted: 9 October 2025
© Springer Nature Switzerland AG 2025

Abstract

Mekong Delta is the biggest Delta in Vietnam where distributes different types of soft soil with considerable thickness. Thus, soft soil improvement for engineering purposes in this area is very popular. In which, cement is one of the most common binders for soft soil stabilization. However, many areas in Mekong Delta distribute organic soil and salt-contaminated soil, especially along the coastline. Organic matter and soluble salt in soil are unfavourable for soft soil improvement by cement. Therefore, additives should be used in combination with cement for soil stabilization. In this study, a comparative study on the effect of different additives (lime, gypsum, RoadCem, and sodium silicate) on the unconfined compressive strength of cement-treated soil in Mekong Delta will be investigated. Two types of soil, including organic soil (OH soil) and salt-contaminated soil (MH soil), were used for this investigation. The research results showed that the additives used have significantly improved the strength of organic soil both in strength magnitude and strength development. The optimum contents of additives are 4%, 2%, 1%, and 0.5% for lime, gypsum, RoadCem, and sodium silicate, respectively. In which, sodium silicate is the best additive for the improvement of organic soil (strength increase by 702.0%), followed by the descending orders: RoadCem (547.8%), gypsum (418.2%), and lime (346.0%). The research results also indicate that different from organic soil, the addition of RoadCem additive to cement-stabilized salt-contaminated soil resulted in an insignificant increase in strength.

Keywords Soft soil improvement · Cement-stabilized soil · Additive · Organic soil · Salt-contaminated soil · Mekong delta

Introduction

Soft soil improvement is a common practice in geotechnical engineering to increase the strength and bearing capacity of the ground to meet engineering purposes. Cement and lime are the most common chemical stabilizers for the improvement of soil. In terms of strength enhancement, cement is

better than lime. However, the mechanical characteristics of soil-cement mixture depend on various factors such as moulding water content, water/cement ratio, clay-water/cement ratio, cement type, cement content, and curing conditions [1–8]. In addition, some environmental factors such as organic matter, and chemical solution (salt solution types, salt content, pH value) also significantly affect the strength of cement-stabilized soil.

With organic soils, the organic matter will impede the hydration process of cement and also prevent the interaction of soil particles with the hydration products. This action leads to a low unconfined compressive strength (UCS) of stabilized soil [9–11]. On the other hand, organic soils have a high content of humic acid and a low pH value which also affects the cementation process and formation of cementitious products. The increase in the content of organic matter or humic acid will result in a decrease in the strength of stabilized soil [10–14]. Xun [15] indicated that for improvement of peaty soil using cement deep mixing, the UCS could

✉ Nguyen Thanh Duong
nguyenthanhduong@humg.edu.vn

¹ Hydraulic Construction Institute, Viet Nam Academy for Water Resources, Hanoi, Vietnam

² Hanoi University of Mining and Geology (HUMG), Hanoi, Vietnam

³ Research Group of Engineering and Geoenvironment (EEG)-HUMG, Hanoi, Vietnam

⁴ Vietnam Association of Engineering Geology and Environment (VAEGE), Hanoi, Vietnam

not reach 300 kPa even when the cement content was used up to 30%. The research of Chen and Wang [9] reported that the strength of organic soils mixed with cement only was significantly low at 63.7 kPa. They concluded that it should not use only cement for the improvement of organic soils. One of the main problems of organic soils is low pH value due to containing humic and fulvic acid. Thus, the use of additives to increase the pH value of the environment is necessary.

Regarding chemical solutions, Xing et al. [16] reported that Mg^{2+} , Cl^- , and SO_4^{2-} negatively affect the strength of cement-stabilized soil, especially Cl^- . Cl^- affects both early and long-term strength of soil-cement admixture. They suggested that additives should be used to mitigate the negative effect of Mg^{2+} , Cl^- , and SO_4^{2-} on the strength of stabilized soil. Similarly to Xing et al. [16], Zhang et al. [17] showed that soluble salt ions of Mg^{2+} , Cl^- , and SO_4^{2-} have an adverse effect on the strength of soil-cement mixtures, especially when increasing the content of these salt ions. Some other authors also indicated that sodium chloride salt has a significant effect on the strength and stiffness of soil-cement admixture. Since the salt can impede the hardening process of cement, the increase in salt concentration will lead to a decrease in the strength of stabilized soil. The high cement content used will eliminate the negative effect of sodium chloride salt [18, 19]. When exposed to NaCl, the research result of Chegenizadeh et al. [20] showed that the NaCl damaged the formation of cement hydration products such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), resulting in a decrease in strength. Some previous studies implied that seawater can increase the strength of cement-stabilized soil [21]. Whereas $MgSO_4$ solution often exhibits a negative effect on the strength properties of the soil + cement mixtures [22, 23]. According to Hara et al. [23], the strength of cement-treated soil was significantly decreased by up to 80% after immersion in the Mg solution. After immersion in the Mg solution, the magnesium silicate hydrate (MSH) gel was formed instead of CSH gel which led to a reduction in strength.

Mekong Delta is the biggest Delta in Vietnam with an area of about 40 thousand km^2 . This Delta is a low area with 0 to 4 m above sea level. This is a young Delta with an age from 20,000 to 40,000 years [24]. Due to young age, soft soils are popular and distributed from the ground surface to a depth of tens meters. Types of soft soils are various from very soft clay, soft clay to mud soils [25]. In which, in some areas of the Mekong Delta, the soils contain a high content of organic matter or are contaminated with salt and alum, especially along the coastline [26–28]. As mentioned above, the strength of soil-cement mixtures is significantly affected by the chemical solution and organic matter. To meet engineering purposes, the content of cement must be increased

to eliminate the effect of salt [18]. However, the increase in cement content will lead to an increase in the construction cost. In addition, Chen and Wang [9] concluded that organic soils cannot be improved by using only cement. Thus, adding additives to soil-cement mixtures is necessary and more effective than increasing the cement content. This action not only increases the strength properties but also saves the construction cost.

In the literature, different types of additives have been used for cement-treated soil. Ali et al. [29] indicated that 1% NaOH and 1.5% Na_2CO_3 were optimal additive contents to obtain the highest values of UCS and CBR. Chen and Wang [9] suggested that some additives such as crystal calcium sulfate, aluminum sulfate, accelerator admixtures of sodium sulfate 2%, sodium chloride 0.5%, and triethanolamine 0.05% can be used for the stabilization of organic soils. Moayedi et al. [30] also indicated that the use of Na_2SiO_3 , $CaCl_2/Al_2(SO_4)_3$ additives can increase the strength of organic soil up to 220% and 270%, respectively. Kulanthaivel et al. [31] indicated that sodium silicate (SS) and sodium hydroxide (SH) can increase the strength of soil-cement mixtures. The strength of stabilized soil reached the highest value of 215.22 kPa for the mixture of 10% cement + 4%SS + 8 molarity of SH. Recently, Kiuna and Kaya [12] indicated that a mixture of 6% sodium silicate and 20% cement gave the best stabilization for organic soil in terms of strength. Gypsum is also an additive which can increase the strength of soil-cement mixture or partially replace cement content [32–35]. In particular, Kuno et al. [35] revealed that a mixture of cement and 10% gypsum was suitable for the stabilization of organic soil. Abbey et al. [36] used RoadCem which is a nanotechnology-based additive for soil stabilization. They reported that the addition of RoadCem increased the shear strength and decreased the swelling potential of treated soil. Quick lime can be used as an additive for soil improvement since the addition of quick lime will increase pH value of the environment which enhances the pozzolanic reactions and formation of cementitious products [37].

It can be seen that the use of additives for cement-stabilized soil has been widely investigated. In the Mekong Delta, some investigations regarding the use of additives for cement-treated soil have been conducted [38–40]. However, the comparison of the effectiveness of different additives used for cement-treated soil has not been researched and evaluated sufficiently. In this study, the effect of various additives, including gypsum, lime, RoadCem, and sodium silicate on the unconfined compressive strength of cement-stabilized organic soil and salt-contaminated soil in the Mekong Delta will be reviewed and thoroughly investigated.

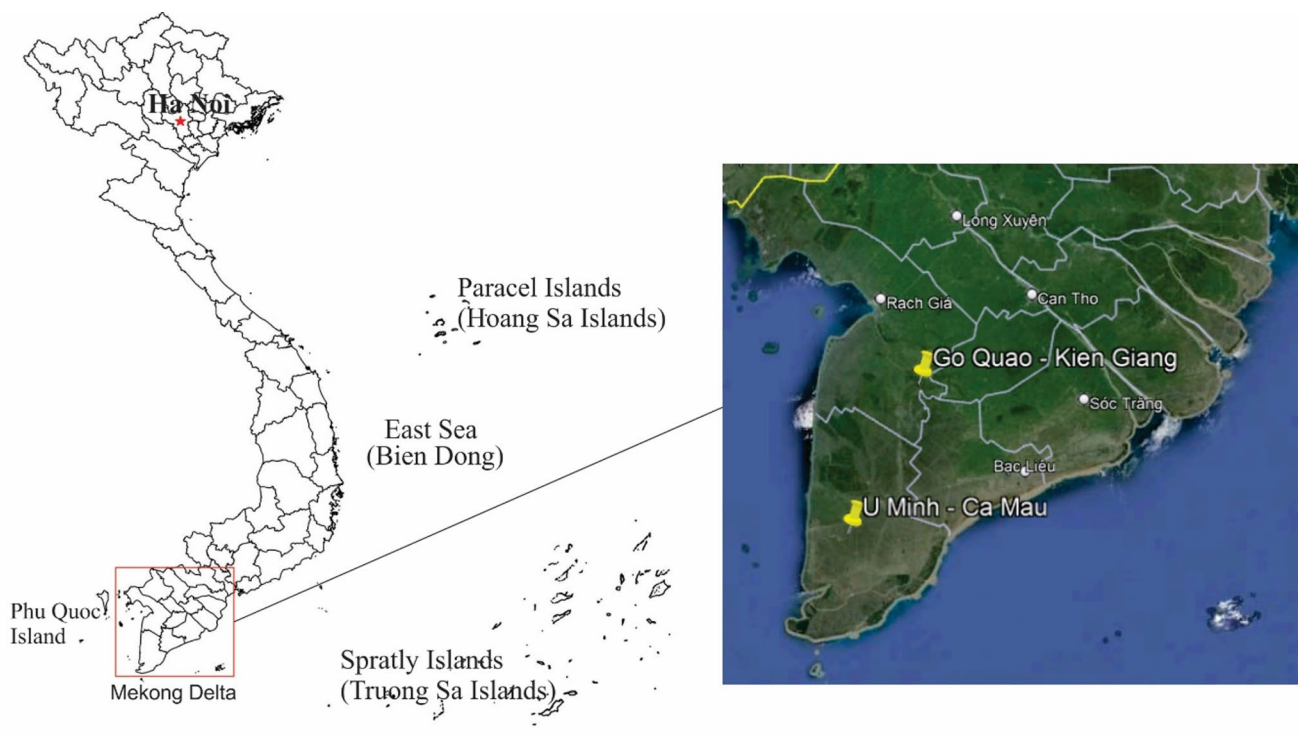


Fig. 1 Location of soil samples

Table 1 Physical properties of soil samples [41]

Properties		Soil sample at Go Quao, Kien Giang	Sample at U Minh, Ca Mau
Soil particles	Sand (%)	36.5	1.2
	Dust (%)	45.2	60.4
	Clay (%)	18.3	38.4
Natural water content (%)		285.0	80.3
Wet unit weight, γ_w (g/cm ³)		1.13	1.52
Specific density, ρ (g/cm ³)		1.90	2.64
Liquid limit, W_L (%)		235.8	73.6
Plasticity index, PI (%)		64.2	35.6
Organic content (%)		44.3	7.3
pH		2.1	3.5
Salt contamination	Salt content (%)	0.29	4.5
	Cl ⁻ (mg/100 g)	38.99	962.46
	SO ₄ ²⁻ (mg/100 g)	397.2	327
	Cl ⁻ / SO ₄ ²⁻	0.1	2.94
	Salt-affected type	Sulfate soils	Chloride soils
Soil classification		OH (Organic soil)	MH (Salt-contaminated soil)

Table 2 Mineralogical compositions of soil samples [41]

Mineralogical compositions	Value (%)	
	Soil sample at Go Quao, Kien Giang	Soil sample at U Minh, Ca Mau
Montmorillonite	5	6
Illit	13	23
Kaolinite	7	31.5
Chlorite	5	5
Quartz	24	21
Felspat	4	-
Goethite	15	5
Pyrite	6	4
Other	Amphibole, Gibbsit	Amphibole, Gibbsit

Materials and methods

Soil samples

The soil samples were taken from two locations in the Mekong Delta, namely: Go Quao district, Kien Giang province and U Minh district, Ca Mau province as shown in Fig. 1.

The physical properties and mineral compositions of soil samples are listed in Tables 1 and 2 respectively [41]. As shown in Table 1, the soil sample at Go Quao is classified as OH soil whereas the soil sample at U Minh is MH soil. The

soil sample at Go Quao has some special physical properties such as high natural water content (285.0%), high plasticity properties ($W_L=235.8\%$, $W_p = 171.6\%$), high organic content (44.3%), low pH value ($pH = 2.1$), low salt content (0.29%). The low pH value of OH soil is due to the existence of fulvic acid and humic acid [10]. Different from the soil at Go Quao, the soil sample at U Minh has a high salt content (4.5%). Based on the anion ratios (Cl^-/SO_4^{2-}), the soil sample at Go Quao, Kien Giang is classified as sulfate soil while the soil sample at U Minh, Ca Mau is chloride soil [42]. The mineralogical and chemical compositions of soil samples are shown in Table 3. As shown in Table 3, the SiO_2 content in the soil sample at Go Quao is significantly lower than that in the soil at U Minh. The LOI (loss of ignition) of the soil sample at Go Quao is significantly higher than that of the soil at U Minh.

Cement

Portland cement PCB40 Ha Tien was employed in this study. This is a product of Ha Tien cement company in Kien Luong district, Kien Giang province in the Mekong Delta. The chemical compositions of PCB40 cement are listed in Table 4. In this study, cement contents of 350 kg/m^3 and 250 kg/m^3 were used for soil at Go Quao, Kien Giang province and soil at U Minh, Ca Mau province, respectively. The soil at Go Quao has a very high content of organic matter, so the cement content used for improving this soil is higher than that used for soil at U Minh.

Additives

a. Lime

In this study, white quicklime (CaO) in the form of powder was used. The quicklime has a pH of 12.4 and a specific density of 2.78 g/cm^3 .

b. Gypsum ($CaSO_4 \cdot 0.2 H_2O$)

Gypsum ($CaSO_4 \cdot 2H_2O$) is a soluble salt that contains 32.6% calcium oxide (CaO), 46.5% sulfur trioxide (SO_3), and 20.9% combined water (H_2O). Gypsum can be massive or powder form and has various colours: white, gray, red, brown, or shades of yellow [43]. When using a combination of gypsum and lime or cement in soil improvement, the sulfate ions from the dissolution of gypsum in water will react with alumina and calcium to form ettringite [44]. The formation of ettringite will reduce the porosity, interlock, and dewatering of the system which results in an increase in the strength of stabilized soil [45].

Table 3 Chemical compositions of soil samples [41]

Chemical compositions	Value (%)	
	OH soil, Kien Giang	MH soil, Ca Mau
SiO_2	27.87	52.41
TiO_2	0.37	0.71
Al_2O_3	9.23	18.10
Fe_2O_3	6.67	5.77
K_2O	1.75	2.84
Na_2O	0.27	1.75
P_2O_5	0.11	0.07
FeO	0.15	1.22
MnO	0.12	0.05
CaO	1.30	0.60
MgO	1.38	1.89
SO_3	10.80	7.22
LOI (Loss of Ignition)	44.3	7.3

Table 4 Chemical compositions of PCB40 cement [41]

Chemical compositions	Values (%)	Chemical compositions	Values (%)
SiO_2	23.77	MgO	2.53
TiO_2	0.52	K_2O	0.88
Al_2O_3	5.83	Na_2O	1.04
Fe_2O_3	3.94	P_2O_5	0.33
FeO	0.22	SO_3	2.25
MnO	2.53	Cr_2O_3	0.016
CaO	51.66	Loss of Ignition (%)	8.26

In this study, white gypsum in the form of powder was employed. The solubility of gypsum in water at 20°C is 0.24 g/100 ml . The specific density of gypsum used in this study is 2.96 g/cm^3 .

c. Sodium silicate (Na_2SiO_3)

Sodium silicate is one of the most common grouts because it is safe and environmentally friendly [46]. Based on the ratio of SiO_2 to Na_2O , sodium silicate has different types (Sodium orthosilicate, Na_4SiO_4 ; Sodium sesquisilicate, $Na_6Si_2O_7$; Sodium metasilicate, Na_2SiO_3 ; Sodium disilicate, $Na_2Si_2O_5$) and can be developed into different grout systems [47]. Sodium silicate is a white powder or colorless solution which easily dissolves in water. The colloid can be formed based on the reaction of silicate solution, it then polymerizes to form a gel which fills voids and enhances the soil strength. In addition, the dissolution of sodium silicate in water will produce an alkaline solution and increase the pH value which is an advantageous environment for the formation of cementitious products [30].

In this study, sodium silicate (Sodium metasilicate, Na_2SiO_3) in the form of the solution was bought from Vietchem company. As reported by the manufacturer, the density of sodium silicate is 1.40 g/cm^3 ; the pH value of 11.

d. RoadCem

RoadCem is the main product of Powercem Technologies in Moerdijk, Netherlands. It is a nanotechnology-based additive which mainly composes of synthetic zeolites and alkali substances (NaCl, KCl, CaCl₂, MgCl₂). This additive is often used in a small quantity in combination with cement to improve the strength characteristics [48]–[49]. RoadCem can be also used to enhance the strength of cement-treated soil [36, 50]. Using RoadCem in soil stabilization can produce the highest values of compressive, flexural, and durability properties. Thus, it has been widely used for road construction [51]. In this study, RoadCem was used from the pilot project of Powercem Technologies conducted in Vietnam (project code: RC.20140607.VN.0987).

The content of different types of additives used in this study for two types of studied soil is presented in Table 5. For the RoadCem additive, this is still a new additive and not popular in Vietnam. Thus, in this study, this additive will be applied to both types of soil (organic soil and salt-contaminated soil) to investigate its effectiveness in soft soil improvement.

Methods

In this study, a laboratory testing program was conducted to evaluate the effect of different additives on the strength of soil-cement mixtures. The tested samples were prepared at the natural water content and the ratio of water to cement of 1 according to Vietnamese standard TCVN 9403:2012 [52]. The sample has a diameter of 4.6 cm and a height of 9.2 cm. All tested samples were cured at 7, 14, 28, 56, 91, and 180 days at the moisture condition (room temperature of 25±2 °C, humidity of 95%). The procedure of sample preparation was described in previous studies [38, 40]. Various unconfined compressive tests were conducted on cylindrical samples to determine the unconfined compressive strength (UCS) according to ASTM standard D2166 with a loading rate of 1 mm/min [53].

Test results and discussions

The test results of unconfined compressive strength of soil+cement mixtures with different types and contents of additives are presented in Table 6.

The comparison of strength and its development of organic (OH) and salt-contaminated (MH) soils treated by cement only is plotted in Fig. 2. It can be seen that the strength of treated OH soil (organic soil) is low and significantly lower than that of treated MH soil, even using higher cement content. This is because the organic matter in OH soil considerably affects the strength of treated soil [9, 11]. According to Kitazume and Terashi [54], the strength of stabilized soil with the ignition loss of higher than 15% was still low even when the content of cement exceeded 20%. In addition, the low pH value in organic soil may impede the dissolution of clay minerals, pozzolanic reaction and prevent the formation of cementitious products [13, 55]. The strength of cement-treated OH soil in this study is almost similar to that reported by Chen and Wang [9] with a UCS value of about 60 kPa. Additionally, regarding the strength development, the strength of treated MH soil significantly increases while it of treated OH soil gradually decreases with the curing time. The tendency of strength development of cement-treated OH soil is similar to that of lime-treated soil which was reported in Yunus et al. [13]. This phenomenon can be explained based on the effect of humic acid in organic soil. According to Yunus et al. [13], the pH value of treated soil decreased with the increasing of curing time due to the decomposition of organic matter. The decrease in pH value may be one of the main causes resulting in a decrease in the strength of treated soil. The low strength and decrease in long-term strength prove that the organic soil cannot be treated by using cement only. Therefore, the use of additives for cement-treated organic soil is crucial.

The UCS values of cement-treated OH soil using different types and contents of additives at different curing times from 7 days to 180 days are plotted in Figs. 3, 4, 5 and 6.

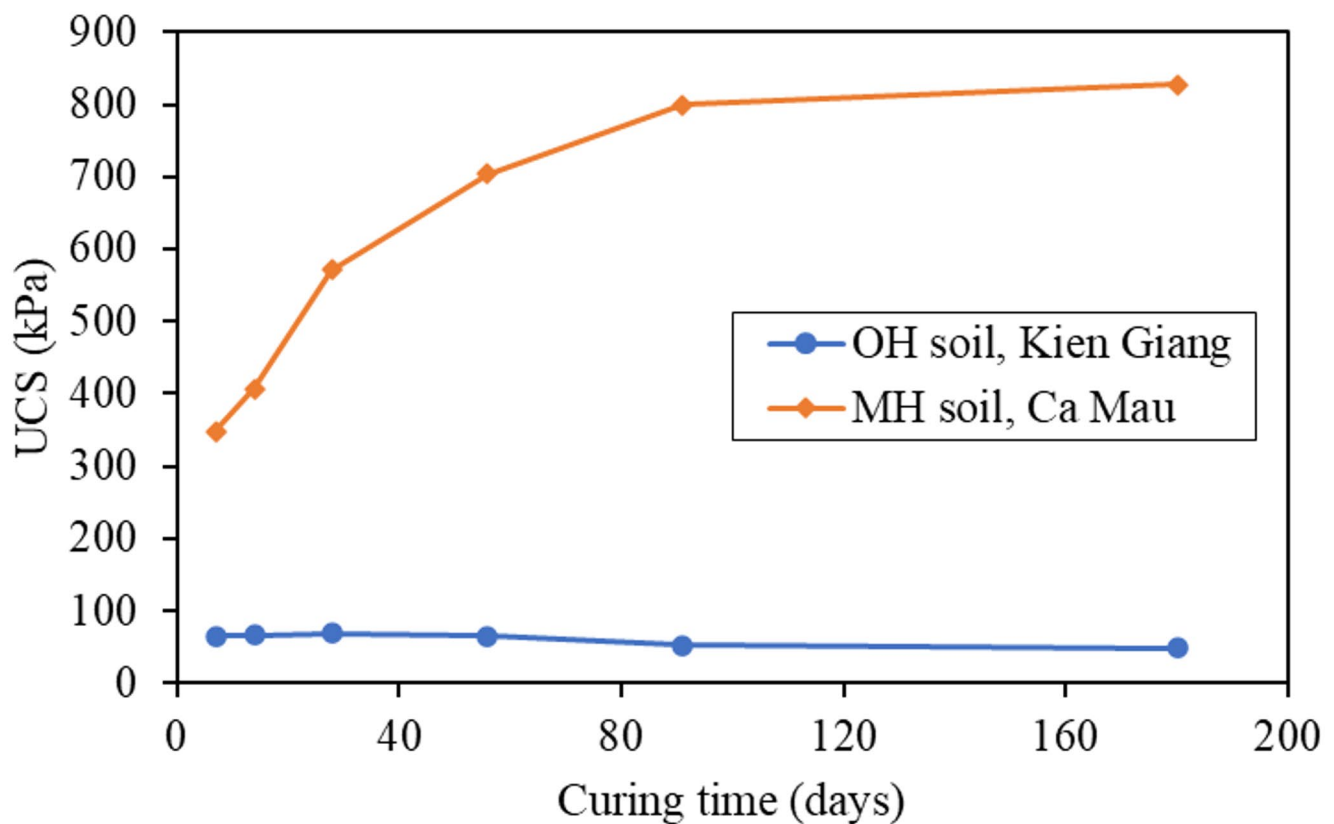
Table 5 Content of additives used for cement-treated soil

Additives	RoadCem	RoadCem	Gypsum	Lime	Sodium Silicate
Soil	Salt-contaminated soil (MH)	Organic soil (OH)			
Content (%) (by wet soil weight)	1, 1.5, 2	1, 1.5, 2	1, 2, 3	1, 2, 4, 6	0.5, 1, 1.5, 2
Denoted as	R1, R1.5, R2	R1, R1.5, R2	G1, G2, G3	L1, L2, L4, L6	SD0.5, SD1, SD1.5, SD2
Cement content (C) (kg/m ³)	250	350			
Sample name	C250R1, C250R1.5, C250R2	C350R1, C350R1.5, C350R2	C350G1, C350G2, C350G3	C350L1, C350L2, C350L4, C350L6	C350SD0.5, C350SD1, C350SD1.5, C350SD2

Table 6 Unconfined compressive strength (UCS) of soil + cement mixtures with different types and additive contents [41]

Soil type	Sample mixture	Sample name	Unconfined compressive strength (UCS), kPa					
			Curing period (days)					
			7	14	28	56	91	180
OH soil (at Go Quao)	Controlled sample ^(*)	C350	64.7	66.0	69.5	64.9	51.8	49.0
	Soil+	C350L1	111.9	128.2	134.3	143.2	148.1	153.4
	Cement+	C350L2	117.0	124.0	155.5	155.9	175.6	210.8
	Lime ^(*)	C350L4	134.9	139.8	148.6	186.3	200.1	218.7
		C350L6	44.3	64.3	80.5	96.1	103.0	113.8
	Soil+	C350G1	70.2	114.9	116.7	119.6	133.6	140.7
	Cement+	C350G2	103.0	117.6	119.3	136.7	224.7	254.1
	Gypsum	C350G3	144.7	146.1	150.0	151.8	162.4	212.0
	Soil+	C350SD0.5	285.3	299.2	315.4	331.5	363.3	393.2
	Cement+	C350SD1	194.1	231.9	245.7	251.2	276.2	322.6
	Sodium Silicate ^(*)	C350SD1.5	189.3	209.5	215.1	239.3	269.8	283.4
		C350SD2	176.4	198.4	215.8	232.3	259.4	267.7
	Soil+	C350R1	185.6	241.6	254.5	275.9	295.2	317.6
	Cement+	C350R1.5	97.8	113.5	127.5	133.4	162.8	184.4
	RoadCem	C350R2	74.7	80.1	93.4	126.0	143.2	157.9
MH soil (at U Minh)	Controlled sample	C250	348.1	406.2	570.6	-	799.3	827.4
	Soil+	C250R1	387.2	430.5	522.9	-	632.1	642.6
	Cement+	C250R1.5	459.6	518.6	636.3	-	805	896.3
	RoadCem	C250R2	318.1	373.8	456.3	-	736.7	740.4

(*)These results have been used in Vu et al. [40]

**Fig. 2** Strength development of soil + cement mixtures without additives

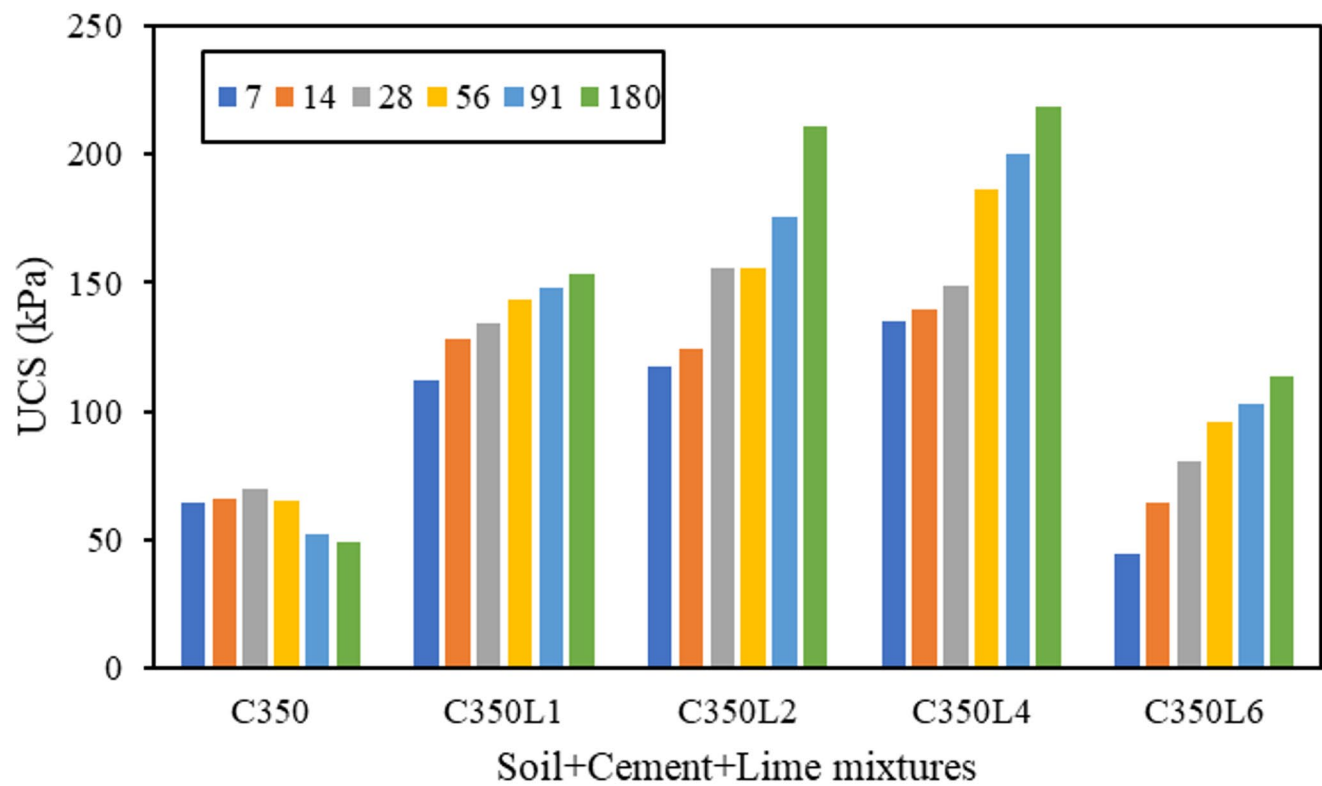


Fig. 3 Strength of soil + cement mixtures with lime additive (for organic soil-OH soil)

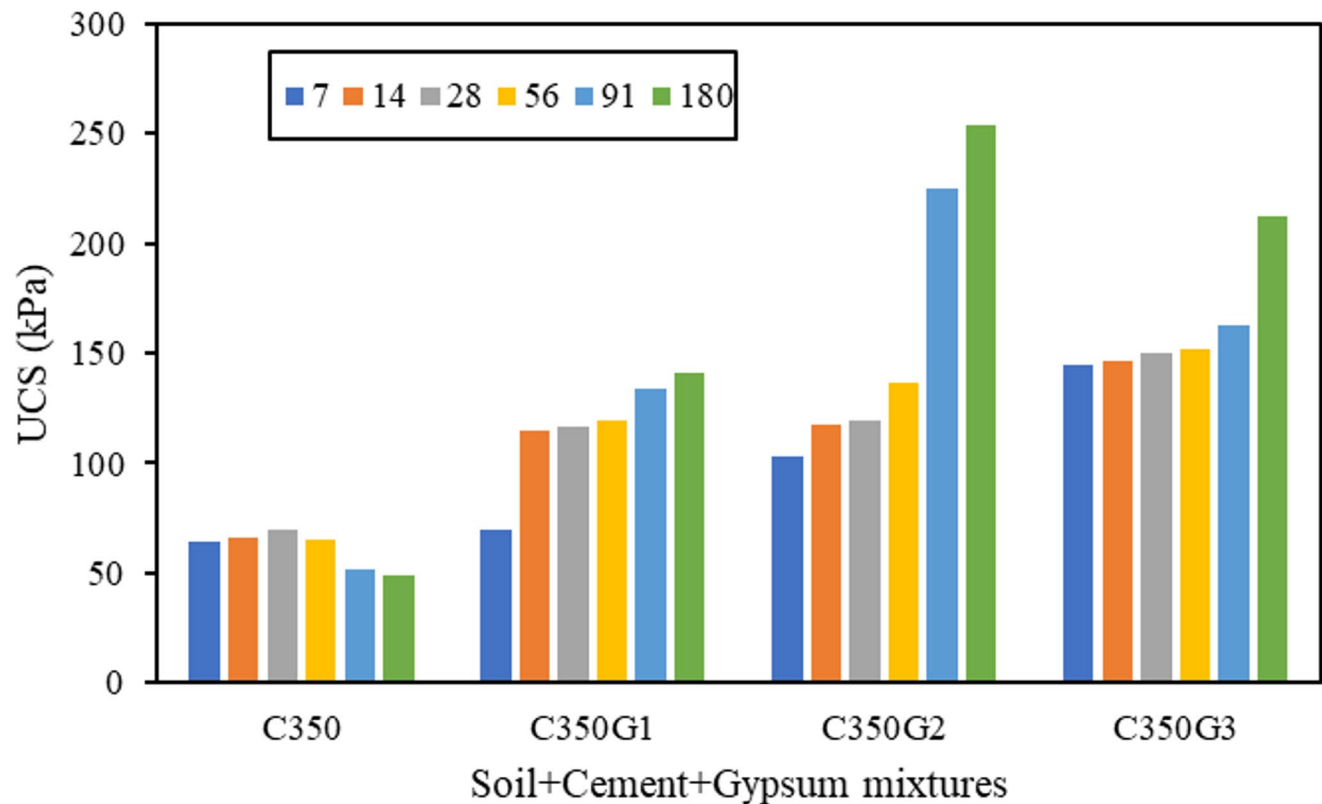


Fig. 4 Strength of soil + cement mixtures with gypsum additive (for organic soil-OH soil)

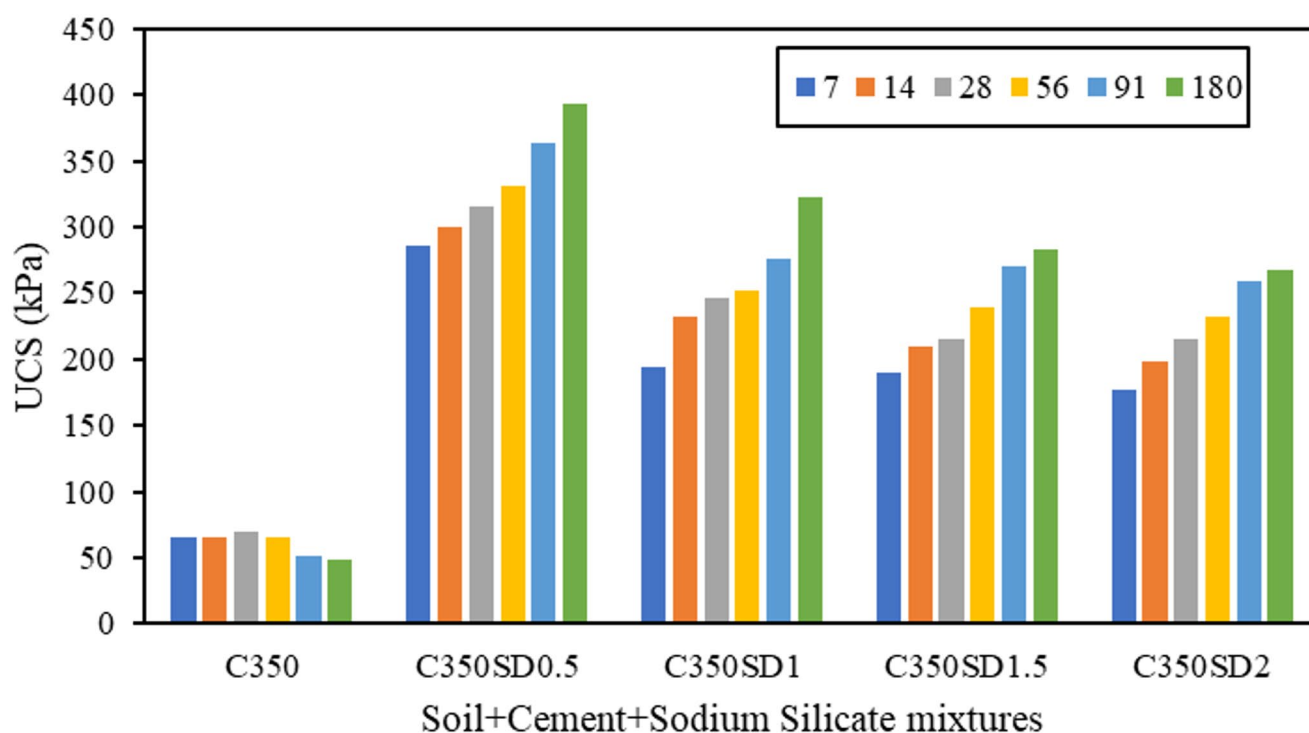


Fig. 5 Strength of soil + cement mixtures with sodium silicate additive (for organic soil-OH soil)

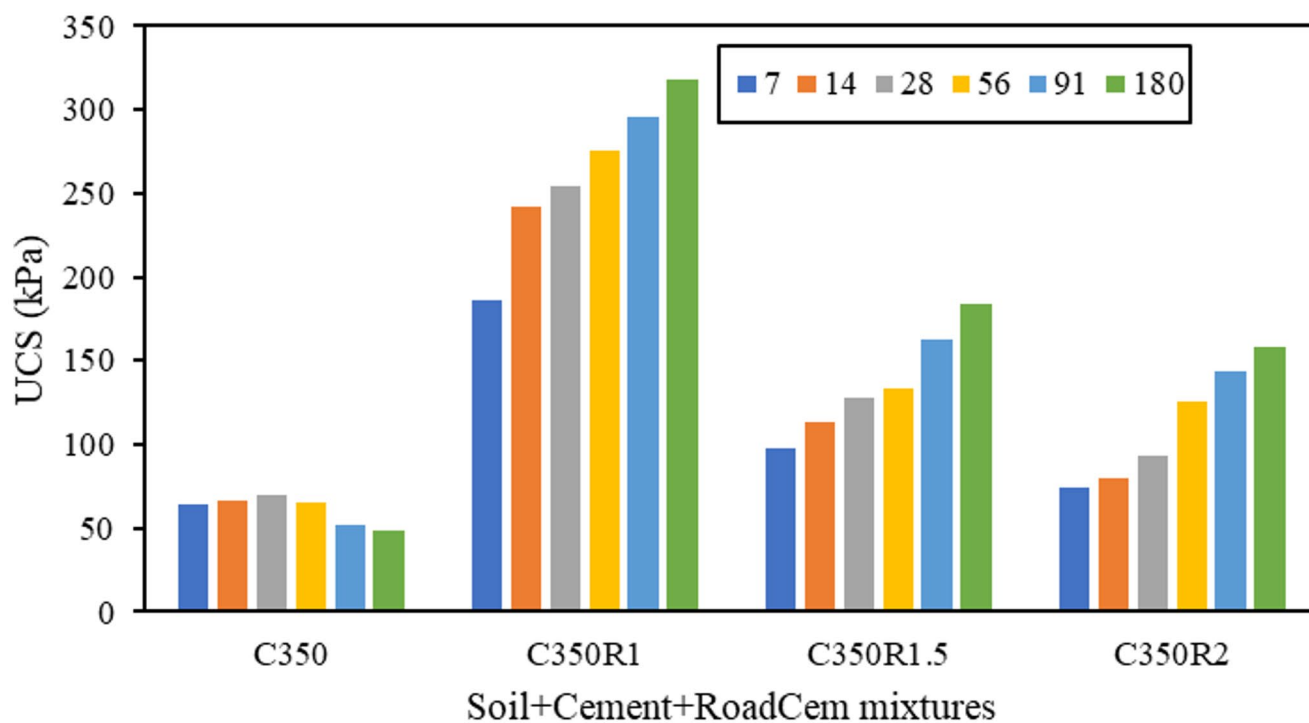


Fig. 6 Strength of soil + cement mixtures with RoadCem additive (for organic soil-OH soil)

As shown in these Figs., different from controlled sample C350 (without additive), the UCS values of treated soil with additives increase with the increase of curing time. This indicates the effectiveness of additives in increasing the long-term strength of treated OH soil.

In Fig. 3, the UCS values of soil + cement + lime mixtures at all curing times increase as the lime content increases from 0 to 4%. When the lime content exceeds 4%, the UCS value of treated soil tends to decrease. Thus, 4% of lime is the optimum content for cement-treated OH soil (mixture sample C350L4). The addition of lime to the soil + cement mixture will increase the pH of the environment due to the reaction of lime with water to form $\text{Ca}(\text{OH})_2$ [37]. The high pH environment creates a favourable condition for the hydration process and the formation of cementitious products such as calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and calcium aluminosilicate hydrates (CASH) [56]. The high pH value from 12 to 13 is sufficient for the hydration process [57, 58]. In particular, the environment with a pH of 12.4 is optimum for activating the pozzolanic reaction [59]. According to Bessaim et al. [37], the addition of 4% lime increased the pH value to about 12.4 and this content was an optimum amount to reach the fixation point of lime. In addition, the cation Ca^{2+} released from the dissolution of lime can enhance the pozzolanic reaction between the composition of cement and clay mineral, then increases the strength of treated soil [55, 60].

Figure 4 shows the strength of cement-treated OH soil using gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) as an additive. It can be seen that at curing times of 7, 14, 28, and 56 days, the mixture sample C350G3 (3% of gypsum) shows the highest UCS values. However, at the long-term curing of 90 and 180 days, the highest UCS values are obtained for mixture sample C350G2 (2% of gypsum). Thus, the optimum content of gypsum used for cement-treated OH soil in this study is 2%. The addition of gypsum can increase the pH value of the environment due to its dissolution in water. Similarly to the role of lime, the high pH environment will enhance the pozzolanic reaction, and then increase the strength degree [40]. Besides, the dissolution of gypsum will release sulfate ions which can react with calcium aluminate to form ettringite crystals. The formation of ettringite will fill the void, reduce the porosity, increase the soil density, and interlock the soil matrix, all of which will contribute to enhancing the strength of stabilized soil [34, 61].

The strength of cement-treated OH soil with sodium silicate additive is plotted in Fig. 5. As shown in this Fig. 6, the strength of treated soil sharply increases with the addition of 0.5% of sodium silicate (mixture sample C350D0.5). When the content of sodium silicate is higher than 0.5%,

the strength of the treated soil gradually decreases. Thus, the optimum content of sodium silicate additive is 0.5% for cement-stabilized OH soil in this study. With this content of sodium silicate, the strength of treated soil (C350SD0.5 mixture) at 180 days of curing is increased by about 702% compared to that of the controlled sample (C350). The mechanism of sodium silicate in increasing the strength of the soil mixture is similar to that of lime and gypsum. That is the addition of sodium silicate to the soil + cement mixture will increase the pH value and create a favourable environment for the hydration process of cement, accelerating cementitious compounds, then resulting in an increase in strength [62]. According to Suganya and Sivapullaiah [62], the addition of sodium silicate to the soil mixture also changes the pore water chemistry, induces more repulsive force, and increases interparticle forces. Besides, when adding sodium silicate to the soil, the silicate ions will be adsorbed on the clay particle surface, then it reacts with liberated calcium ions to form more cementitious products that bond the soil particles.

Similarly to sodium silicate additive, the addition of 1% RoadCem additive to the cement-treated OH soil suddenly increases the strength of the treated soil (Fig. 6). However, when the content of RoadCem is higher than 1%, there is a significant decrease in the strength of treated soil. This indicates that 1% of RoadCem is the most effective amount for increasing the strength of cement-treated OH soil in this study. Previous studies also mentioned that RoadCem was mostly used in a small quantity of 1.0 to 1.5% for soil stabilization [36, 50]. At 180 days of curing, the strength of mixture sample C350R1 rose by 547.8% compared to that of the controlled sample (C350). Different from lime, gypsum and sodium silicate additives, the addition of RoadCem to the soil + cement mixture will decrease the amount of free water, increase the crystals in the empty void ratio, and then reduce the porosity. These actions lead to an increase in compressive and flexural strength. When using RoadCem, the binding mechanism transforms from “glueing” to “wrapping” effect. The “wrapping” effect is associated with the formation of needle crystalline products and soil matrix with interlocking string (Fig. 7). These products are responsible for strength enhancement [36, 63].

In this study, the RoadCem additive was also used for cement-treated salt-contaminated soil. The strength of this soil + cement mixture with different contents of RoadCem additive is depicted in Fig. 8. Different from organic soil, for salt-contaminated soil, the increase of RoadCem content gives a slight decrease (at 1% of RoadCem), followed by an increase in the strength of treated soil and reaches the highest value of strength at 1.5% RoadCem. However,

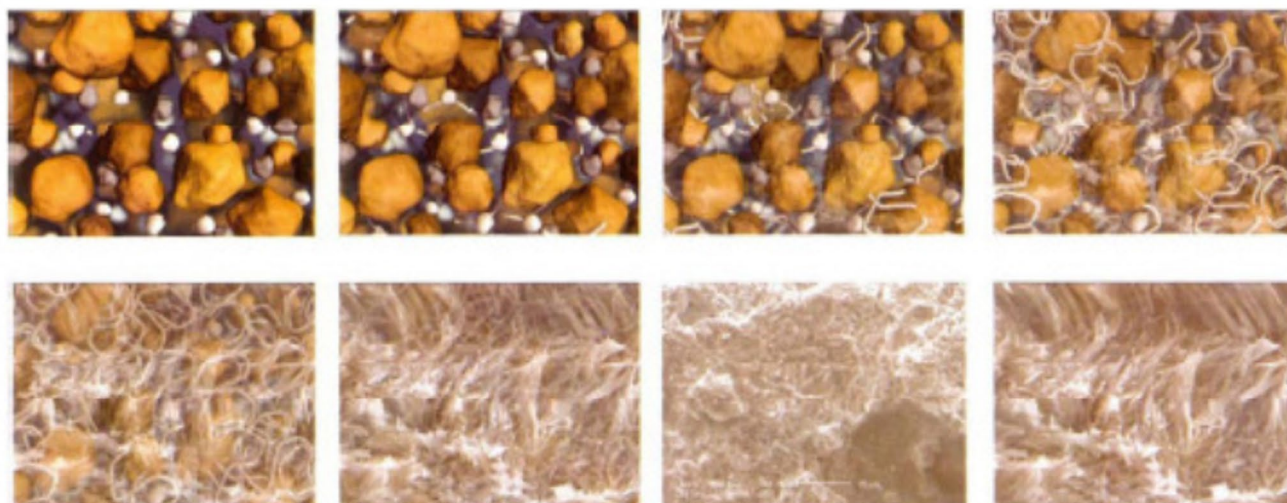


Fig. 7 The “wrapping” effect associated with crystalline products and soil matrix [63]

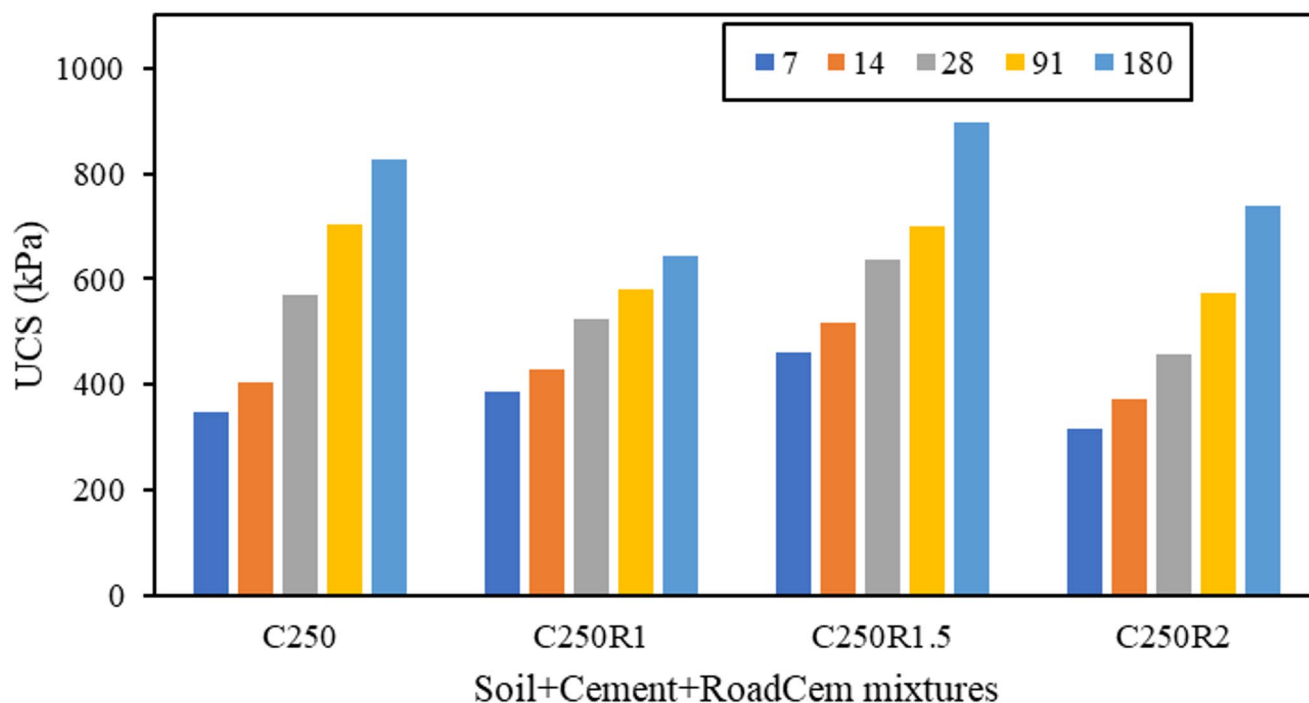


Fig. 8 Strength of soil + cement mixtures with different RoadCem additive contents (for salt-contaminated soil-MH soil)

the addition of more RoadCem will lead to a decrease in the strength of treated soil. In general, the change in the strength of treated MH soil with the addition of RoadCem is insignificant. In particular, with the optimum content of 1.5% RoadCem, the strength of the treated soil mixture (C250R1.5) just increases by about 8% compared to that of the controlled sample (C250) at the curing time of 180 days. This result reveals that the RoadCem additive shows a low effectiveness for cement-treated MH soil and its effectiveness is significantly lower than that for cement-treated OH soil.

The results above indicate that the addition of additives exceeding the optimum contents will lead to a decrease in the strength. This is due to adding more lime, gypsum, and sodium silicate additives to the soil + cement mixture can increase the pH value of the environment to 13, 14 and the very high pH value will damage the concrete structure and lead to a decrease in the strength of stabilized soil [58]. Besides, additives used in this study have no or little cementitious properties, so exceeding the optimum contents will result in a low strength. Vakili et al. [64] revealed that

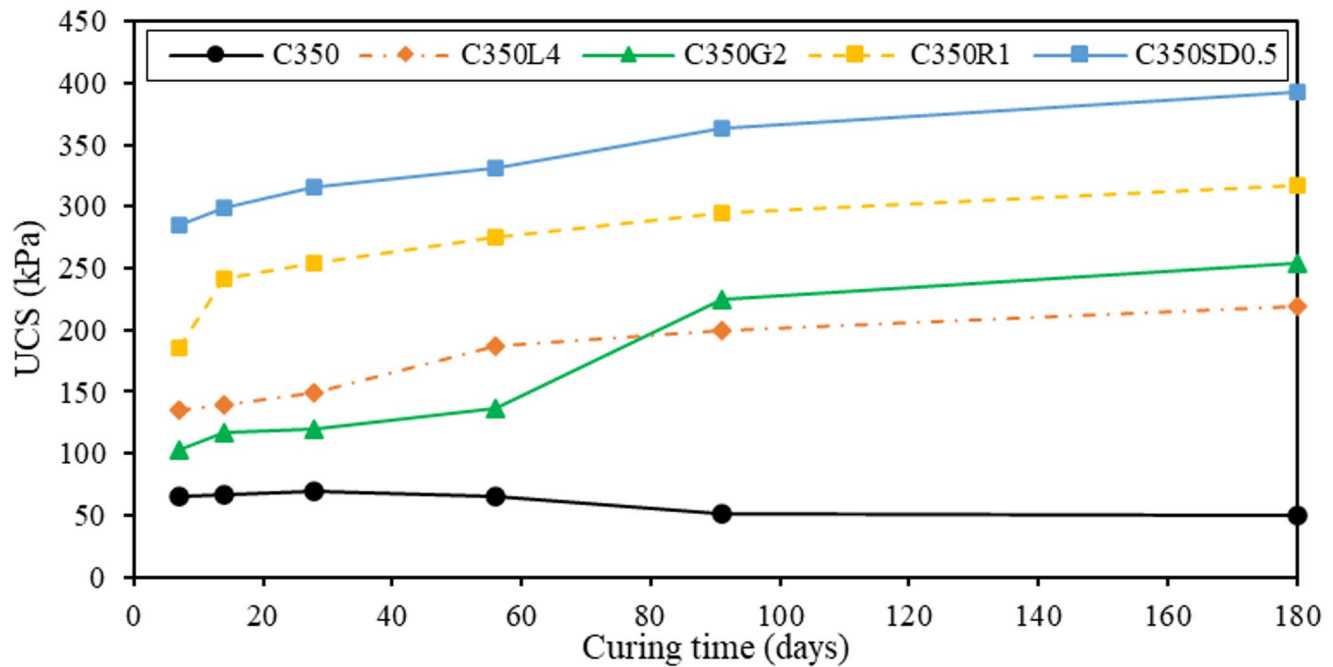


Fig. 9 Strength development of soil + cement mixtures with optimum additive contents (for organic soil-OH soil)

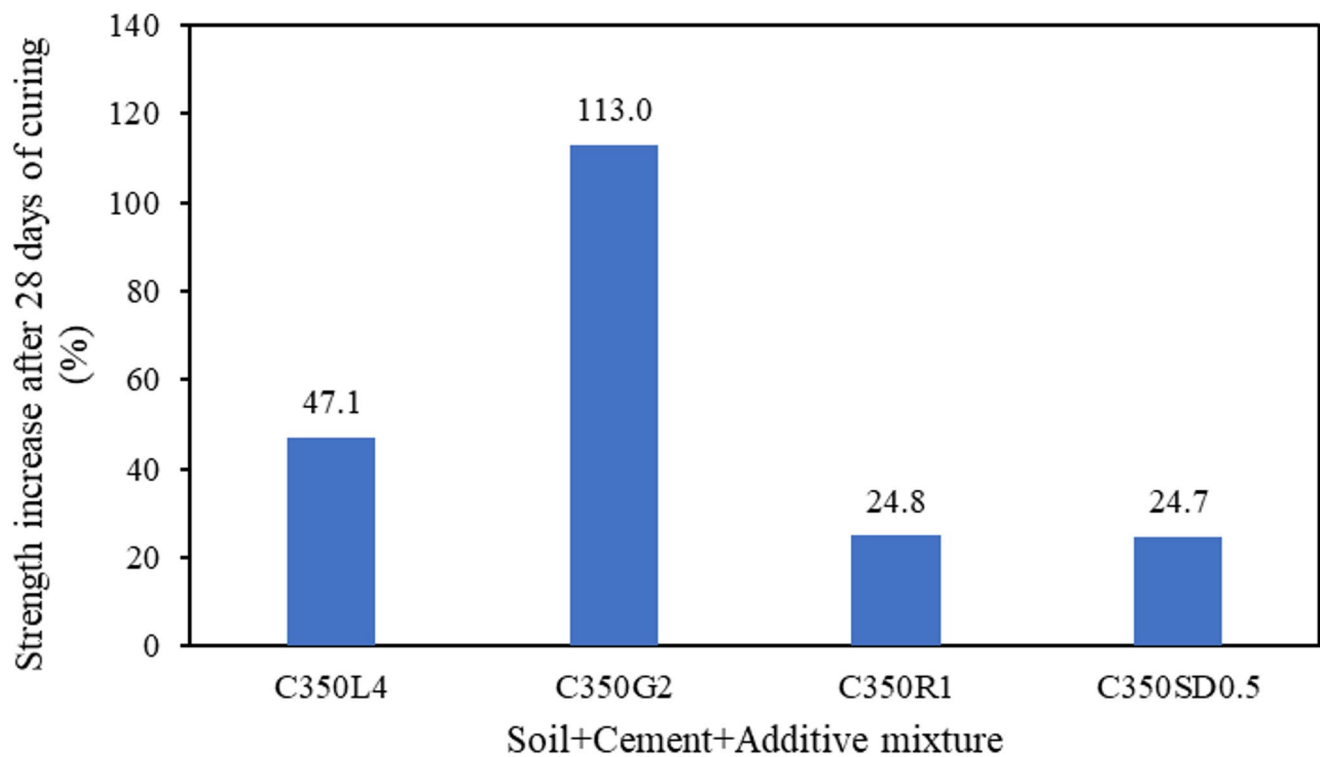


Fig. 10 The increase in strength after 28 days of curing for soil + cement mixtures with the optimum additive contents (for organic soil-OH soil)

the excessive amount of sodium silicate will prevent the reaction of other additives and the bonding of soil particles.

The strength development of OH soil + cement mixtures with the optimum additive contents is shown in Fig. 9. The increase in strength after 28 days of curing is plotted in

Fig. 10. As described in this Fig., the strength of the soil + cement mixture with 2% of gypsum (C350G2) significantly increases after 28 days of curing (increase by 113%). For other additives, the strength after 28 days of curing is increased by 24.7% to 47.1%. These results show that the

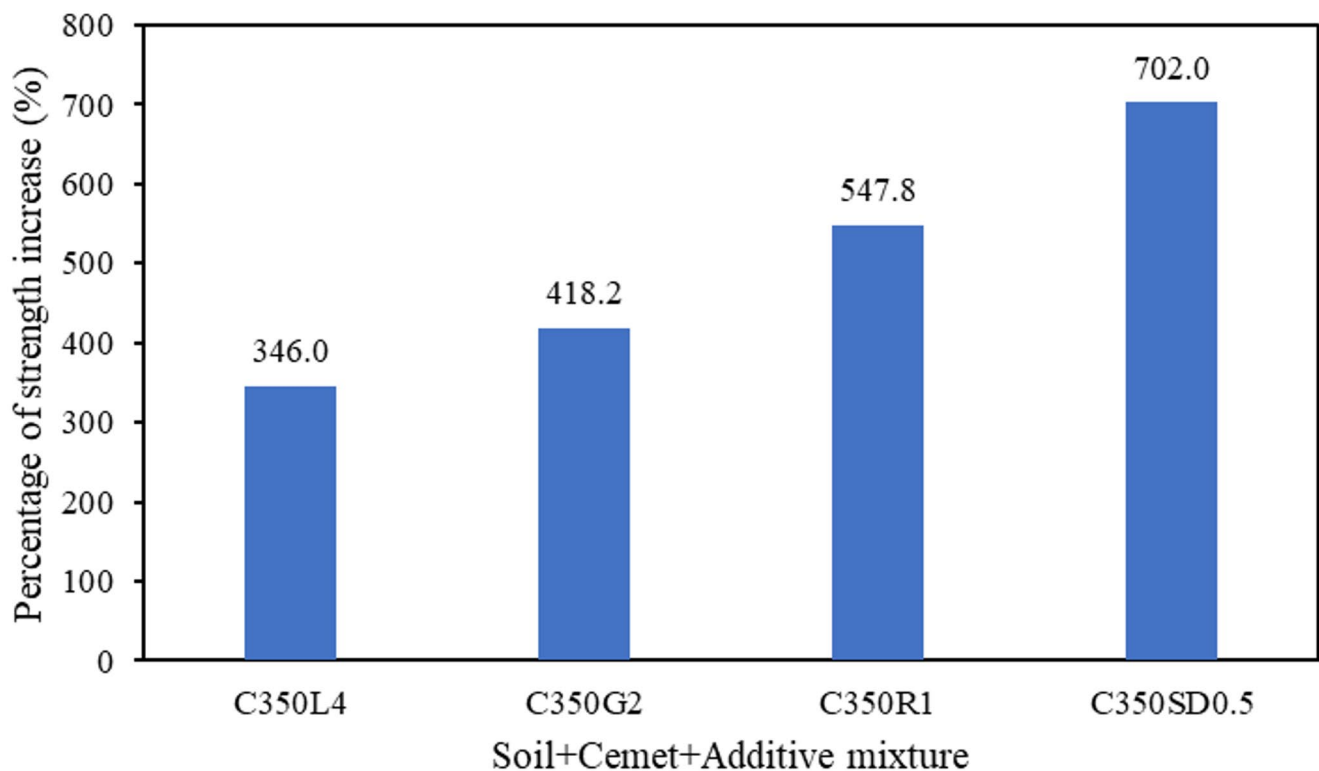


Fig. 11 The increase in strength of organic soil+cement mixtures with the optimum additive contents compared to controlled samples (without additives)

gypsum additive is more effective in the long-term period of curing.

To evaluate the effectiveness of different types of additives, the increase in strength after 180 curing days of soil + cement samples with the optimum additive contents compared to the controlled sample (without additive) is calculated and plotted in Fig. 11. It can be seen that the sodium silicate additive shows the most effectiveness in strength enhancement for organic soil with an increase in strength of 702%, followed by the descending orders: Road-Cem (547.8%), gypsum (418.2%) and lime (346%). This research result is consistent with that of some previous studies. According to Suganya and Sivapullaiah [62], since different bonding mechanisms occurred when adding sodium silicate additive to the soil mixture, this additive considerably increases the strength of cement-treated soil. Recently, the research results of Kiuna and Kaya [12] also indicated that the mixture of cement and sodium silicate was very effective in improving the strength of organic soil. Accordingly, the UCS value of organic soil + 20% cement + 6% sodium silicate mixture at 28 days of curing increased about 6 times compared to that of the untreated sample.

Conclusions

In this research, a comparative study regarding the effect of different types of additives on the UCS strength of cement-treated organic soil and salt-contaminated soil in the Mekong Delta has been conducted. Some conclusions can be drawn as follows:

- (1) The UCS value of cement-treated organic soil is significantly low, even with the cement content used of 350 kg/m³ and it tends to decrease with the increasing of curing time. This is because the low pH value and the decomposition of organic matter in organic soils during curing lead to a low and decrease in the strength of the soil+cement mixture. Thus, the use of cement only for the stabilization of organic soil is not effective.
- (2) The use of different additive types (lime, gypsum, Road-Cem, sodium silicate) for cement-treated organic soil has made a significant improvement. Accordingly, the strength of stabilized organic soil (OH soil) with additives is considerably higher than that of the controlled sample (without additives) and it shows an increasing trend as the curing time increases. Additionally, among different additives used, the gypsum mostly increases the UCS value of treated organic soil at the long-term curing.

- (3) For organic soil (OH soil), the research results indicated the optimum contents of additives for cement-treated soil as follows: 4% lime, 2% gypsum, 1% RoadCem, and 0.5% sodium silicate. For soil containing a high salt content (MH soil), 1.5% of RoadCem is the most effective amount. However, the effectiveness of RoadCem for the improvement of salt-contaminated soil is considerably lower than that for the improvement of organic soil.
- (4) The research results revealed that sodium silicate (Na_2SiO_3) is the most effective additive for cement-treated organic soil, followed by the descending order: RoadCem, gypsum, and lime.

Acknowledgements This research is funded by project code B2024-MDA-07 under the Ministry of Education and Training, Vietnam.

Declarations

Conflict of interest The authors declare that they are not aware of any conflict of interest.

Ethical approval Presented results do not contain studies with human or animal subjects.

Informed consent For this type of study, formal consent is not required.

References

1. Horpibulsuk S, Miura N, Nagaraj TS (2005) Clay–water/cement ratio identity for cement admixed soft clays. *J Geotech Geoenviron Eng* 131(2):187–192
2. Ribeiro D, Néri R, Cardoso R (2016) Influence of water content in the UCS of soil-cement mixtures for different cement dosages. *Procedia Eng* 143:59–66
3. Suksiripattanapong C, Tesanasin T, Tiyasangthong S, Tabyang W, Sukontasukkul P, Chindaprasit P (2023) Use of cement and bottom Ash in deep mixing application for stabilization of soft Bangkok clay. *Arab J Sci Eng* 48(4):4583–4593
4. Vo BH, Dinh HL, Dang NL (2024) Materials Characteristics of Soil-cement Samples under Various Maintenance Conditions. In *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2023, p. 012063
5. Vu TB, Dang VQ, Ngo QA, Ho LS (2023) Influence of some factors on the mechanical properties of cement-treated clay for shallow mixing in vietnam: A comparative study. *Results Eng* 17:101011
6. Wang F, Li K, Liu Y (2022) Optimal water-cement ratio of cement-stabilized soil. *Constr Build Mater* 320:126211
7. Gupta S, Kumar S (2023) A state-of-the-art review of the deep soil mixing technique for ground improvement. *Innov Infrastruct Solut* 8(4):129
8. Chamling PK, Biswal DR, Sahoo UC (2021) Effect of moulding water content on strength characteristics of a cement-stabilized granular lateritic soil. *Innov Infrastruct Solut* 6(2):82
9. Chen H, Wang Q (2006) The behaviour of organic matter in the process of soft soil stabilization using cement. *Bull Eng Geol Environ* 65(4):445–448
10. Du C, Zhang J, Yang G, Yang Q (2021) The influence of organic matter on the strength development of cement-stabilized marine soft clay. *Mar Georesources Geotechnol* 39(8):983–993
11. Kazemian S, Huat BB, Prasad A, Barghchi M (2011) Effect of peat media on stabilization of peat by traditional binders. *Int J Phys Sci* 6(3):476–481
12. Kiuna VG, Kaya Z (2023) Effect of sodium silicate and cement on the improvement of engineering properties of organic soil. *Revista De La construcción* 22(3):632–645
13. Yunus NM, Wanatowski D, Stace LR (2013) Lime stabilisation of organic clay and the effects of humic acid content. *Geotech Eng J SEAGS AGSSEA* 44(1):19–25
14. Zhu W, Chiu CF, Zhang CL, Zeng KL (2009) Effect of humic acid on the behaviour of solidified dredged material. *Can Geotech J* 46(9):1093–1099
15. Xun Y (2000) The anti-influences and influences of containing organic matter on cement soil strength. *Build Sci Res Sichuan* 3:58–59
16. Xing H, Yang X, Xu C, Ye G (2009) Strength characteristics and mechanisms of salt-rich soil–cement. *Eng Geol* 103(1–2):33–38
17. Zhang H, Xing H, Li H (2022) Mechanical characteristic and microstructure of salt-rich cement soil. *Bull Eng Geol Environ* 81(3):92
18. Dingwen Z, Libin F, Songyu L, Yongfeng D (2013) Experimental investigation of unconfined compression strength and stiffness of cement treated Salt-Rich clay. *Mar Georesources Geotechnol* 31(4):360–374
19. Yin J, Han W, Xu G, Hu M, Miao Y (2019) Effect of salinity on strength behavior of Cement-treated dredged clay at high initial water contents. *KSCE J Civ Eng* 23(10):4288–4296
20. Chegenizadeh A, Kanagaratnam A, Nikraz H, Keramatikerman M (2021) Sodium chloride impact on cemented clay. *Results Eng* 11:100256
21. Samadi P, Ghodrati A, Ghadir P, Javadi AA (2023) Effect of seawater on the mechanical strength of geopolymer/cement stabilized sandy soils. In *Proceedings of the TMIC 2022 slope stability conference (TMIC 2022)*, Atlantis Press International BV Dordrecht, 121–129
22. Hasan MF, Canakci H (2022) Assessing the effect of seawater and magnesium sulfate on the durability and strength properties of Cement-Stabilized Full-Scale soilcrete column constructed in clayey soil. *Arab J Sci Eng* 47(10):13171–13185
23. Hara H, Ikeda H, Yoshimoto N (2024) Strength reduction mechanism of cement-treated soil under seawater environment. *Soils Found* 64(1):101425
24. Ta TKO, Nguyen VL, Tateishi M, Kobayashi I, Tanabe S, Saito Y (2002) Holocene delta evolution and sediment discharge of the Mekong River, Southern Vietnam. *Q Sci Rev* 21(16–17):1807–1819
25. Giao PH, Dung NT, Long PV (2008) An integrated geotechnical–geophysical investigation of soft clay at a coastal site in the Mekong delta for oil and gas infrastructure development. *Can Geotech J* 45(11):1514–1524
26. Ngoc BV (2022) Characteristics of clay soft soil in the Mekong delta of Vietnam and improvement result with cement. *Iraqi Geol J* : 64–73
27. Nu NT, Duong NT, Son BT, Thinh PH (2020) Investigation of salt, alum content in soft soils and their effects on soil properties: case study in coastal areas of Vietnam. *Iraqi Geol J* : 19–34
28. Tan TS, Goh TL, Yong KY (2002) Properties of Singapore marine clays improved by cement mixing. *Geotech Test J* 25(4):422–433
29. Ali HE, Asmel NK, Ganiyu AA, Tijani H (2020) Effect of sodium compounds additives on the strength of cement-stabilized soils. *Eng Appl Sci Res* 47(3)

30. Moayedi H, Huat BB, Kazemian S, Daneshmand S (2012) Stabilization of organic soil using sodium silicate system Grout. *Int J Phys Sci* 7(9):1395–1402
31. Kulanthaivel P, Selvakumar S, Soundara B, Krishnaraja AR (2023) Strength enhancement of clay soil stabilized with ordinary portland cement, sodium silicate and sodium hydroxide. *Int J Pavement Res Technol* 16(5):1297–1310
32. Hughes PN, Glendinning S, Manning DAC, White ML (2011) Use of red gypsum in soil mixing engineering applications. *Proc. Inst. Civ. Eng. Geotech. Eng.* 164(3): 223–234
33. Janbaz M, Iacobucci L, Francisco K, Miskewitz R, Kitazume M, Maher A (2021) Effect of gypsum and cement content on unconfined compressive strength of soft sediment. *Int J Geotech Eng* 15(3):373–378
34. Wu J, Liu L, Deng Y, Zhang G, Zhou A, Xiao H (2022) Use of recycled gypsum in the cement-based stabilization of very soft clays and its micro-mechanism. *J Rock Mech Geotech Eng* 14(3):909–921
35. Kuno G, Kutara K, Miki H (1989) Chemical stabilization of soft soils containing humic acid. *Proc. 12th International Conf. on Soil Mechanics and Foundation Engineering, Rio de Janeiro. 2: 1381–1384*
36. Abbey SJ, Eyo EU, Okeke CA, Ngambi S (2021) Experimental study on the use of roadcem blended with by-product cementitious materials for stabilisation of clay soils. *Constr Build Mater* 280:122476
37. Bessaim MM, Bessaim A, Missoum H, Bendani K (2018) Effect of quick lime on physicochemical properties of clay soil. In *MATEC Web of Conferences, EDP Sciences*, p. 02065
38. Binh VN (2015) Research on improving clayey soil at Ca Mau using cement combined with Rovo additives in laboratory. *J Water Resour* 3:45–51 (In Vietnamese)
39. Binh VN, Công NT (2016) Research improve peat soil at Kien Giang and Hau Giang by cement with additives in laboratory. *Geotech J* 2:21–26 (In Vietnamese)
40. Vu NB, Do MN, Thi NN, Ho LS (2021) Effects of additives on the results of improving peat soil: A case study at Mekong delta in Vietnam. *J Appl Sci Eng* 25(5):951–959
41. Binh VN (2018) Effect of soil geotechnical properties on the soft soil improvement by cement combined with additives in the Mekong Delta. *Doctoral Thesis (In Vietnamese)*
42. Metternicht G, Zinck JA (2008) Remote sensing of soil salinization: impact on land management, chap, vol 2. *Spectral behavior of salt types*
43. Kuttah D, Sat K (2015) Review on the effect of gypsum content on soil behavior. *Transp Geotech* 4:28–37
44. Beetham P, Dijkstra T, Dixon N, Fleming P, Hutchison R, Bate-man J (2015) Lime stabilisation for earthworks: a UK perspective. *Proc Inst Civ Eng - Ground Improv* 168(2):81–95
45. Jha AK, Sivapullaiah PV (2016) Role of gypsum on microstructure and strength of soil. *Environ Geotech* 3(2):78–89
46. Lindh P (2001) Optimising binder blends for shallow stabilisation of fine-grained soils. *Proc Inst Civ Eng - Ground Improv* 5(1):23–34
47. Hurley CH, Thornburn TH (1972) Sodium silicate stabilization of soils: A review of the literature. *Highway Res Rec* 381:46–79
48. Holmes N (2015) Structural properties of concrete materials containing RoadCem. *J Constr Eng* 2015:1–8
49. Ventura D, Koloane T (2005) Laboratory evaluation of powercem blend to determine its suitability as a road Building material stabilizer. *Zwijndrecht, The Netherlands*
50. Eyo EU, Abbey SJ, Ngambi S, Ganjian E, Coakley E (2021) Incorporation of a nanotechnology-based product in cementitious binders for sustainable mitigation of sulphate-induced heaving of stabilised soils. *Eng Sci Technol Int J* 24(2):436–448
51. RoadCem solves soil (2024) stabilisation problems where other products fail. <https://www.powercem.co.uk/our-products/RoadCem>. Accessed 10 March 2024
52. Vietnamese, Standard, TCVN 9403 (2012) Stabilization of soft soil - the soil cement column method
53. ASTM, D2166 (2000) Standard test method for unconfined compressive strength of cohesive soil. *ASTM Philadelphia, USA*
54. Kitazume M, Terashi M (2013) *The deep mixing method*. CRC, p 405
55. Koslanant S, Onitsuka K, Negami T (2006) Influence of salt additive in lime stabilization on organic clay. *Geotech Eng* 37(2):95
56. Kinuthia JM, Wild S, Jones GI (1999) Effects of monovalent and divalent metal sulphates on consistency and compaction of lime-stabilised kaolinite. *Appl Clay Sci* 14(1–3):27–45
57. Locat J, Trembaly H, Leroueil S (1996) Mechanical and hydraulic behaviour of a soft inorganic clay treated with lime. *Can Geotech J* 33(4):654–669
58. Sumra Y, Payam S, Zainah I (2020) The pH of Cement-based materials: a review. *J Wuhan Univ Technol Mat Sci Edit* 35(5):908–924
59. Eades JL, Grim RE (1966) A quick test to determine lime requirements for lime stabilization. *Highway Res Rec* 139
60. Modmoltin C, Voottipruex P (2009) Influence of salts on strength of cement-treated clays. *Proc Inst Civ Eng - Ground Improv* 162(1):15–26
61. Ebailila M, Kinuthia J, Oti J (2022) Role of gypsum content on the long-term performance of lime-stabilised soil. *Materials* 15(15):5099
62. Suganya K, Sivapullaiah PV (2016) Role of sodium silicate additive in Cement-Treated Kuttanad soil. *J Mater Civ Eng* 28(6):06016006
63. Marjanovic P, Egyed CEG, de La Roij P, de La Roij R (2009) *RoadCem, the road to the Future - Manual working with road-Cem*. PowerCem Technologies B.V
64. Vakili MV, Chegenizadeh A, Nikraz H, Keramatikerman M (2016) Investigation on shear strength of stabilised clay using cement, sodium silicate and slag. *Appl Clay Sci* 124:243–251

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.