



Applicability of Rice Husk Ash for Cement-Stabilized Soil in the Mekong Delta, Vietnam

Nguyen Thanh Duong^{1,2,3} · Dang Van Phi^{1,3} ·
Nguyen Van Phong^{1,2}

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Abstract As Vietnam's leading rice-producing region, the Mekong Delta generates vast quantities of rice husk ash (RHA) each year, a by-product which poses significant environmental challenges and demands sustainable management solutions. The soft clayey soil in this region is popular and characterized by low strength and bearing capacity, which adversely affects the development of local infrastructure and necessitates stabilization techniques to improve its performance. This research utilizes RHA, a widely available agricultural by-product in the Mekong Delta, as an additive to enhance the strength of soil–cement mixtures. Soil samples from Ca Mau, Tra Vinh, and Soc Trang provinces were mixed with cement contents of 15% and 20% by wet soil weight and supplemented with RHA at varying proportions of 0%, 5%, 10%, 15%, 20%, and 25% by wet soil weight. The experimental results demonstrate that the unconfined compressive strength (UCS) of the stabilized soil exhibited a marked improvement with the incorporation of rice husk ash (RHA) at an optimal dosage of approximately 10–20%, with the highest enhancement observed when 20% cement is utilized. The samples from Tra Vinh generated higher strength compared to those from Ca Mau and Soc Trang. These findings suggest that the effectiveness of RHA stabilization is governed by both the characteristics of the soft soil and the cement content. Besides, both the strength of the stabilized soil and the optimal RHA content were influenced

by the initial clay–water content of the soil samples. Furthermore, the inclusion of RHA in the soil–cement mixture may reduce the elastic modulus of the stabilized soil, affecting its stiffness. The results of this study indicate that RHA is an effective additive for enhancing the engineering properties of soil–cement mixtures, thereby promoting sustainable infrastructure solutions in the Mekong Delta.

Keywords Marginal soils · Rice husk ash · Cement-stabilized soil · Unconfined compressive strength · Elastic modulus

Introduction

The Mekong Delta, the largest delta in Vietnam, is characterized by Holocene-aged deposits. These deposits primarily consist of various types of soft soils, which are distributed across the surface with thicknesses ranging from a few meters to more than 20 m [1]. Owing to the extensive distribution of soft soil, soil stabilization in the Mekong region is a common engineering practice. Among the different soil improvement methods, the soil–cement deep mixing technique has been widely used in Vietnam, including the Mekong Delta. Recently, there has been an increasing trend of using waste materials for soil stabilization [2–5]. The previous studies have demonstrated that the incorporation of agricultural wastes like rice husk ash (RHA), a by-product from burning rice husk, can significantly enhance the strength of soil–cement mixtures [2, 6]. According to Chen et al. [2], RHA can be used in combination with cement, lime, and other waste materials such as fly ash, slag, carbide slag, and bagasse ash...to stabilize and enhance the strength of various soil types, including lateritic soil, soft clay, expansive soil, marine clay, and black cotton

✉ Nguyen Thanh Duong
nguyenthanhduong@humg.edu.vn

¹ Hanoi University of Mining and Geology (HUMG),
Hanoi 100000, Vietnam

² Research Group of Engineering and Geoenvironment,
HUMG, Hanoi, Vietnam

³ Research Group of Geotechnical Engineering, Construction
Materials and Sustainability, HUMG, Hanoi, Vietnam

soil, etc. In particular, Jongpradist et al. [7] reported that RHA can enhance the strength of cement–clay admixture by more than 100%, depending on the cement content. Furthermore, the previous studies have revealed that RHA not only increases the strength of the soil–cement mixture but also can partially replace cement in soil stabilization applications [8–10]. These findings have confirmed the potential of RHA as a sustainable additive for improving the mechanical performance of cement-stabilized soils. Abhishek et al. [11] reported that waste materials such as RHA offer economical and sustainable solutions for improving the properties of soft soils. In the context of sustainable development, the reuse of waste materials has been recognized as an important objective in geotechnical engineering [12–15]. The Mekong Delta region generates a large quantity of RHA, which poses environmental challenges due to inadequate disposal, while simultaneously facing a high demand for cement-based soil stabilization. Thus, the utilization of RHA as an eco-friendly and cost-effective material not only enhances soil stabilization but also helps address the environmental challenges associated with the disposal of agricultural waste.

The Mekong Delta is home to about 17 million people (17% of the population). This delta is known as the “rice bowl” of Vietnam, producing about 24 million metric tons of paddy rice in 2024 [16]. As estimated, every 100 kg of paddy rice after milling will yield about 20 kg of rice husk [17]. Thus, in the Mekong Delta, a huge amount of approximately 4.8 million metric tons of rice husk can be generated every year. In recent years, the burning of rice husk has been widely used for drying fruit, seafood, power generation, and the production of hot steam for curing concrete piles. After burning, the residual is RHA, which accounts for about 25% of the weight of rice husk [17, 18]. If all rice husk in the Mekong Delta is burnt, about 1.2 million metric tons of RHA will be released. Currently, RHA in the Mekong Delta has not been utilized effectively, which negatively impacts the water and air environment. Therefore, the utilization of RHA in construction in general and in soft soil stabilization in particular is necessary to minimize its negative environmental impacts of RHA, while reducing construction costs and improving construction quality.

This study investigates the applicability of RHA in cement-stabilized soils from the Mekong Delta region under laboratory conditions. The primary objective is to assess the effectiveness of RHA in enhancing the strength of cement-stabilized soils and to examine the influence of initial clay–water content on the strength of the stabilized soil. Additionally, the study explores the correlation between the elastic modulus and unconfined compressive strength of soil stabilized with cement and RHA. These two key mechanical properties are often used to evaluate the performance of soil improved using the deep cement mixing method. In this study, the microstructure characteristics and the formation

of cementitious products of the stabilized soil were analyzed by using scanning electron microscopy (SEM) and X-ray diffraction (XRD).

Study Area

The Mekong Delta, located in the southern part of Vietnam, covers an area of approximately 50,000 km² and is the third-largest delta in the world, following the Amazon and Ganges–Brahmaputra deltas [19]. The Mekong Delta was formed between the late Pleistocene and the Holocene, around 7500 years ago [20, 21]. The sediment deposits include: Late Pleistocene (Q_1^3) (very stiff and stiff clay); Early-Middle Holocene (Q_2^{1-2}) (sand, silt, and medium-coarse sand); and Middle-Late Holocene (Q_2^{2-3}) (soft clayey soil and sandy soil) [22].

The coastal area of the Mekong Delta is characterized by low-lying terrain, with an average elevation of less than 2 m above sea level, making it highly vulnerable to sea level rise and tidal influences [23]. Due to its young geological age, the Holocene-aged sediment in the coastal areas of the Mekong Delta primarily consists of soft soils of alluvial (a), marine (m), or alluvial–marine (am) origin, extending to depths of up to 30–40 m. Additionally, because of the low elevation, rising sea levels, and tidal intrusion, soils in many areas, particularly along the coastline, are affected by soluble salts and acid sulfate contamination [24, 25]. Based on data from boreholes, the ground structure in the coastal area of the Mekong Delta can be divided into two types: Type I-soft soil is distributed right on the ground surface; Type II-soft soil layers are located beneath firm-stiff clayey soil layers. Based on the thickness of the soft soil layer (h), each type was further classified into three sub-types: sub-type a, $h \leq 5$ m; sub-type b, $5 < h < 10$ m, and sub-type c, $h \geq 10$ m [22] (Fig. 1).

Testing Materials

Soil Samples

Soil samples were taken at a depth of approximately 1 m below the ground surface from three different areas in the Mekong Delta region, including Ca Mau, Tra Vinh, and Soc Trang provinces, and were named Ca Mau clay, Tra Vinh clay, and Soc Trang clay (Fig. 2). The physical properties of the soil are provided in Table 1 and Fig. 3. The soil samples had natural water contents ranging from 50% to approximately 60%, organic matter contents ranging from 3.2 to 8.17%, and pH values ranging from 4.01 to 8.30 (Table 1). The XRD results are presented in Fig. 4, while the mineralogical compositions of the examined soils are provided in Table 2. The mineralogical and

Fig. 1 Ground structures in the coastal provinces of the Mekong Delta [22]

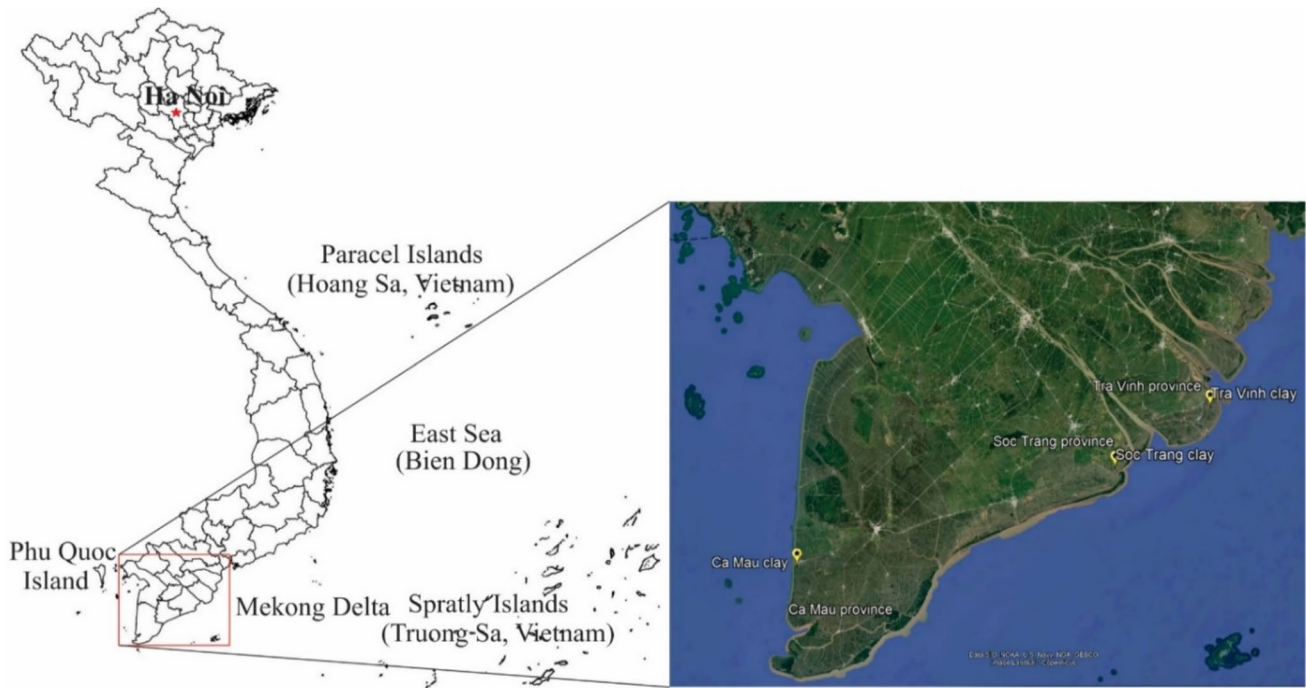
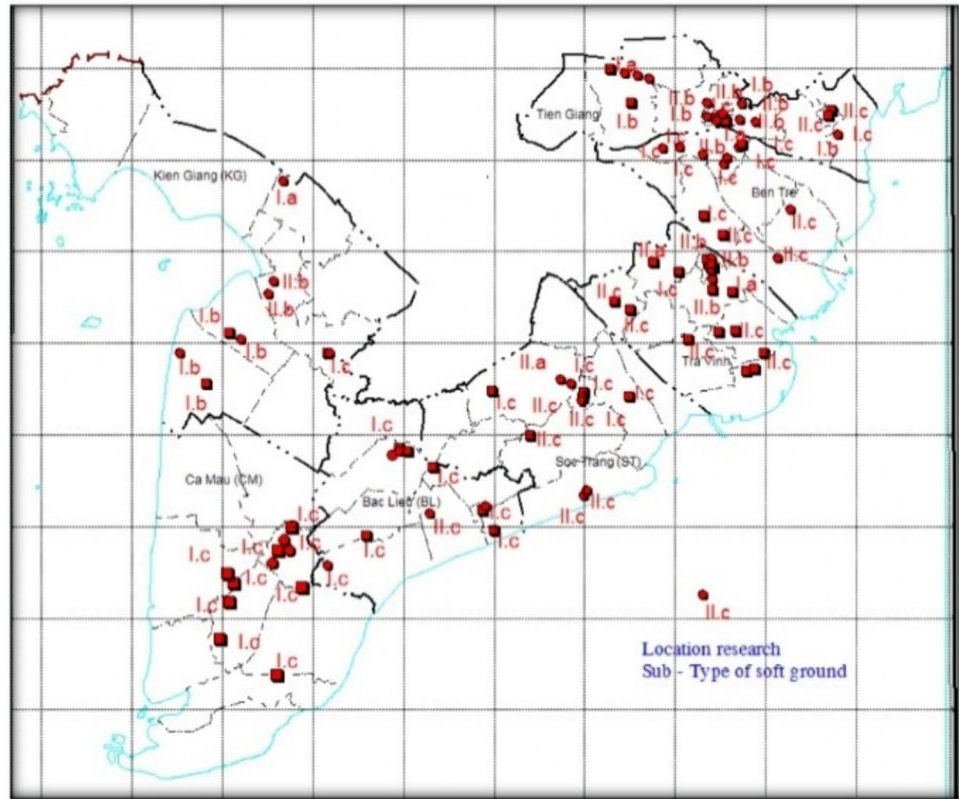


Fig. 2 Study area and sampling location

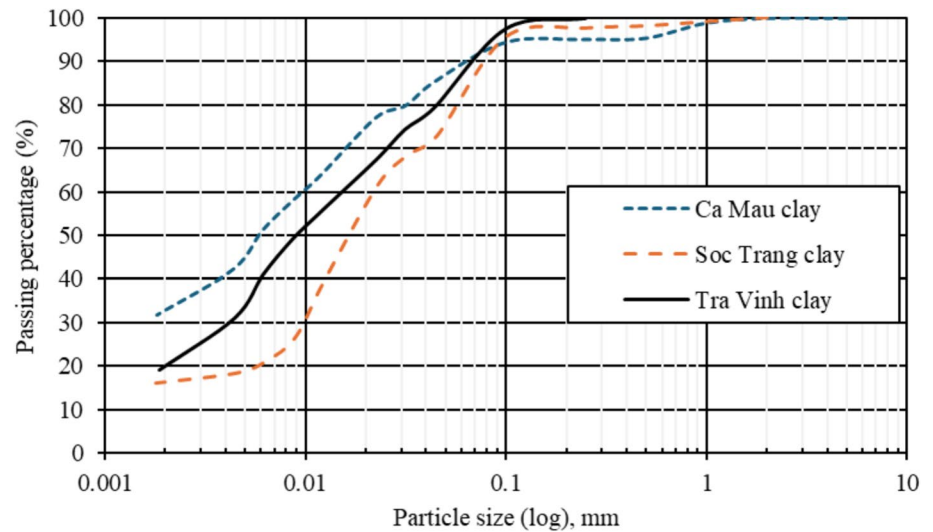
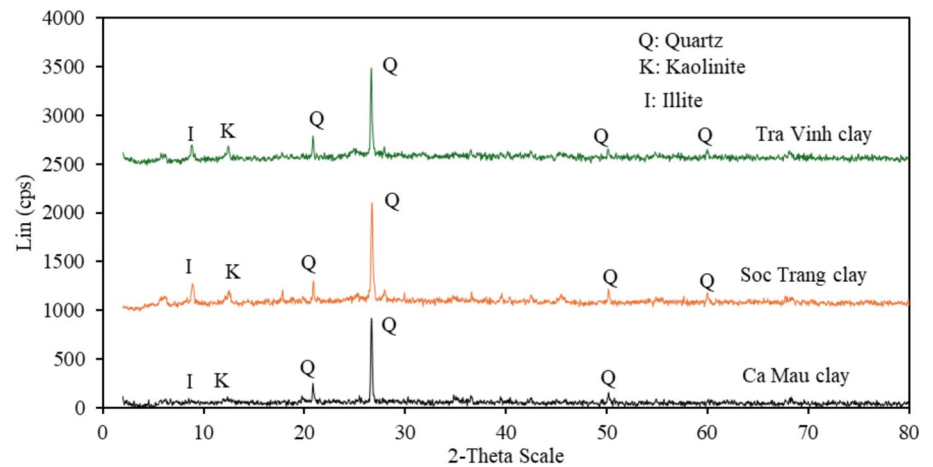
chemical compositions of the studied soils are listed in Tables 2 and 3, respectively. As shown in Table 2, the predominant mineral in the soil samples is quartz, followed

by illite, kaolinite, and other minerals. The data in Table 3 show that the main chemical composition of soil samples is SiO_2 (more than 50%), followed by Al_2O_3 and Fe_2O_3 .

Table 1 Some physical indices of the studied soil samples

Index	Unit	Ca Mau clay*	Soc Trang clay	Tra Vinh clay
Natural water content	%	60.5	50.0	63.5
Wet unit weight	kN/m ³	16.6	16.5	16.7
Specific gravity	—	2.71	2.69	2.70
Liquid limit (Cassagrande's method)	%	71.5	54.2	66.1
Plastic limit	%	44.3	31.1	34.6
Plasticity index	%	27.2	23.1	31.5
Organic matter content	%	3.20	6.66	8.17
pH value	-	4.01	6.47	8.30

*This result has been reported in [10]

Fig. 3 Soil particle distribution curves**Fig. 4** Diagram of X-ray diffraction analysis of the soil samples

Cement and RHA

This study utilized PCB40 (Portland Cement Blended 40), a type of blended Portland cement with a specific gravity of

3.10, as the primary binder. Raw RHA was collected from burning rice husk for heating generation in the Mekong region. Subsequently, the RHA was ground and sieved to obtain particles smaller than 75 μm . Following the sieving

Table 2 Mineralogical composition of the soil samples

Sample	Mineralogical compositions (%)						
	Illite	Kaolinite	Chlorite	Quartz	Feldspar	Goethite	Others
Ca Mau clay	17–19	16–18	4–6	38–40	4–6	3–5	Amp., Lep., Pyr
Soc Trang clay	17–19	17–19	4–6	44–46	3–5	4–6	–
Tra Vinh clay	22–24	14–16	5–7	40–42	3–5	4–6	Amp

Amp: Amphibian; Lep: Lepidocrocite; and Pyr: Pyrophyllite

Table 3 Chemical composition of the soil samples, RHA, and cement

Chemical composition (%)	Samples				
	Ca Mau clay*	Soc Trang clay	Tra Vinh clay	RHA*	Cement*
SiO ₂	55.4	57.2	56.0	91.91	24.93
Al ₂ O ₃	20.1	19.1	16.8	1.44	6.94
TiO ₂	0.87	0.86	0.83	0.01	0.95
Fe ₂ O ₃	9.58	7.79	6.89	0.14	5.43
MnO	0.07	0.13	0.11	0.14	0.14
MgO	2.77	3.01	3.12	1.49	3.32
CaO	0.34	0.44	0.65	0.63	43.6
Na ₂ O	1.26	1.61	4.97	1.21	3.22
K ₂ O	2.86	2.74	2.26	1.62	0.93
P ₂ O ₅	0.09	0.09	0.19	0.40	0.84
SO ₃	–	0.36	–	–	2.68

*This result has been reported in [10]

process, the RHA exhibited a grayish color and a specific gravity of 2.43. The chemical compositions of the cement and RHA are listed in Table 3. The primary chemical constituent of the cement is calcium oxide (CaO), comprising 43.6%, while RHA is predominantly composed of silicon dioxide (SiO₂), accounting for 91.91%.

Sample Preparation and Test Procedure

Sample Preparation

In the deep soil mixing method, the cement content typically constitutes less than 20% of the wet soil weight [26]. In this study, the soil was stabilized using two cement contents (C = 15% and 20%) along with varying RHA contents (RHA = 0%, 5%, 10%, 15%, 20%, and 25%). For all soils, the mixture samples were prepared using the soil at its initial clay–water content, which was equivalent to the natural water content. For Soc Trang clay, in addition to the natural condition, the mixture samples were also prepared at two higher clay–water contents (Wc = 60% and 80%). The specific gravity of each mixture (Gs) was calculated following the method described by Haji and Mir [27], in which the dry weight of soil was obtained from the wet soil weight based on its water content, and then used to determine the soil:C:RHA ratio. For instance,

the mixture sample of Ca Mau clay with 15% cement and 5% RHA (soil + 15%C + 5%RHA) can be expressed as a composition ratio of soil:C:RHA = 75.7:18.2:6.1 (%). The specific gravity of this mixture is calculated as $G_s = 0.757 \times 2.71 + 0.182 \times 3.10 + 0.061 \times 2.43 = 2.76$. The mixture samples used in this investigation, and their corresponding specific gravity values are summarized in Table 4. All mixture samples, with a water-to-cement ratio of 1.0, were prepared and remolded in cylindrical molds with an inner diameter of 5 cm and a height of 10 cm (Fig. 5a). The sample preparation procedure was described in detail in a previous study [10]. After being removed from the molds, all samples were wrapped in plastic bags and cured under humid conditions at room temperature ($20 \pm 2^\circ\text{C}$) for 28 days before testing (Fig. 5b). In each soil mixture, three samples were prepared, and the average UCS was determined from the three samples.

Testing Procedure

The unconfined compressive strength (UCS) test was conducted according to ASTM D2166 with a loading rate of 1.0 mm/min [28]. The elastic modulus (E_{50}) was also determined from the relationship between the UCS and displacement (ϵ , %).

After testing, a sample was taken to determine its water content. Additionally, scanning electron microscopy (SEM)

and X-ray diffraction (XRD) techniques were used to examine the microstructure and the formation of cementitious products of stabilized soil. In which, the SEM technique

has been widely applied to quantitative visualization of the particle arrangement in the microstructure of both untreated and treated soils [29]. SEM QUANTA 450 (Magnification

Table 4 Mixture samples and their specific gravity values (Gs)

Mixture sample	Specific gravity (Gs)				
	Ca Mau clay (W _c = 60.5%)	Tra Vinh clay (W _c = 63.5%)	Soc Trang clay (W _c = 50%)	Soc Trang clay (W _c = 60%)	Soc Trang clay (W _c = 80%)
Soil + 15%C	2.79	2.78	2.77	2.77	2.78
Soil + 15%C + 5%RHA	2.76	2.76	2.75	2.75	2.75
Soil + 15%C + 10%RHA	2.74	2.74	2.73	2.73	2.73
Soil + 15%C + 15%RHA	2.73	2.72	2.71	2.71	2.72
Soil + 15%C + 20%RHA	2.71	2.71	2.70	2.70	2.70
Soil + 15%C + 25%RHA	2.70	2.69	2.69	2.69	2.69
Soil + 20%C	2.80	2.80	2.78	2.79	2.80
Soil + 20%C + 5%RHA	2.78	2.78	2.77	2.77	2.78
Soil + 20%C + 10%RHA	2.76	2.76	2.75	2.75	2.76
Soil + 20%C + 15%RHA	2.75	2.74	2.73	2.73	2.74
Soil + 20%C + 20%RHA	2.73	2.73	2.72	2.72	2.72
Soil + 20%C + 25%RHA	2.72	2.71	2.71	2.71	2.71

Fig. 5 **a** Sample preparation and **b** sample curing

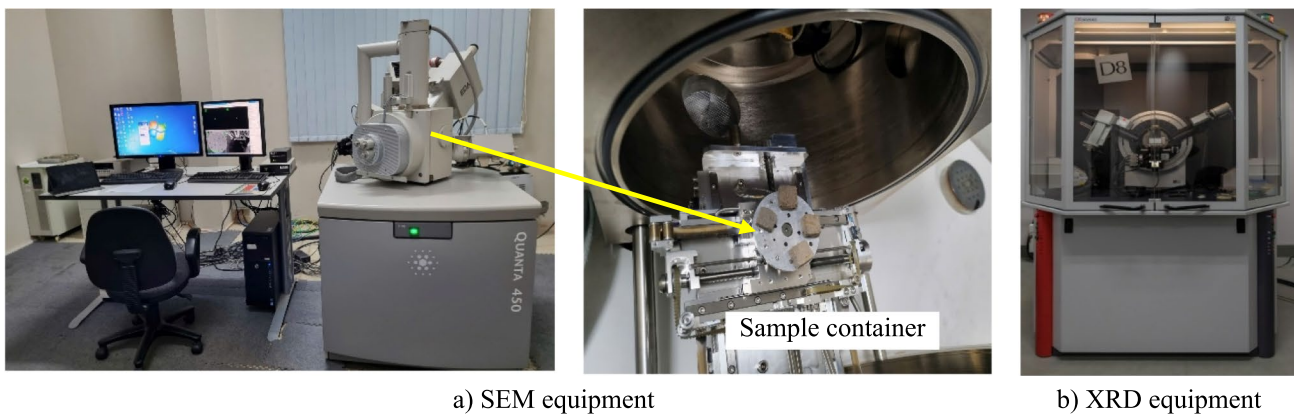


Fig. 6 **a** SEM equipment (QUANTA 450) and **b** XRD equipment (D8 Advance)

of 20 to 50,000x) and XRD D8 Advance (CuK-alpha 40 kV 40 mA) models, as shown in Fig. 6, were employed for this investigation. For SEM analysis, small pieces of the samples after compression testing were dried in an oven and then cut to a size of 1 cm × 1 cm × 0.5 cm (Fig. 6a). The procedures for sample preparation and testing are summarized and depicted in Fig. 7.

Test Results and Discussion

Test Results

The UCS results of stabilized soil at 28 days of curing are calculated and listed in Tables 5 and 6. Table 5 shows the UCS results of soil stabilization by different RHA and

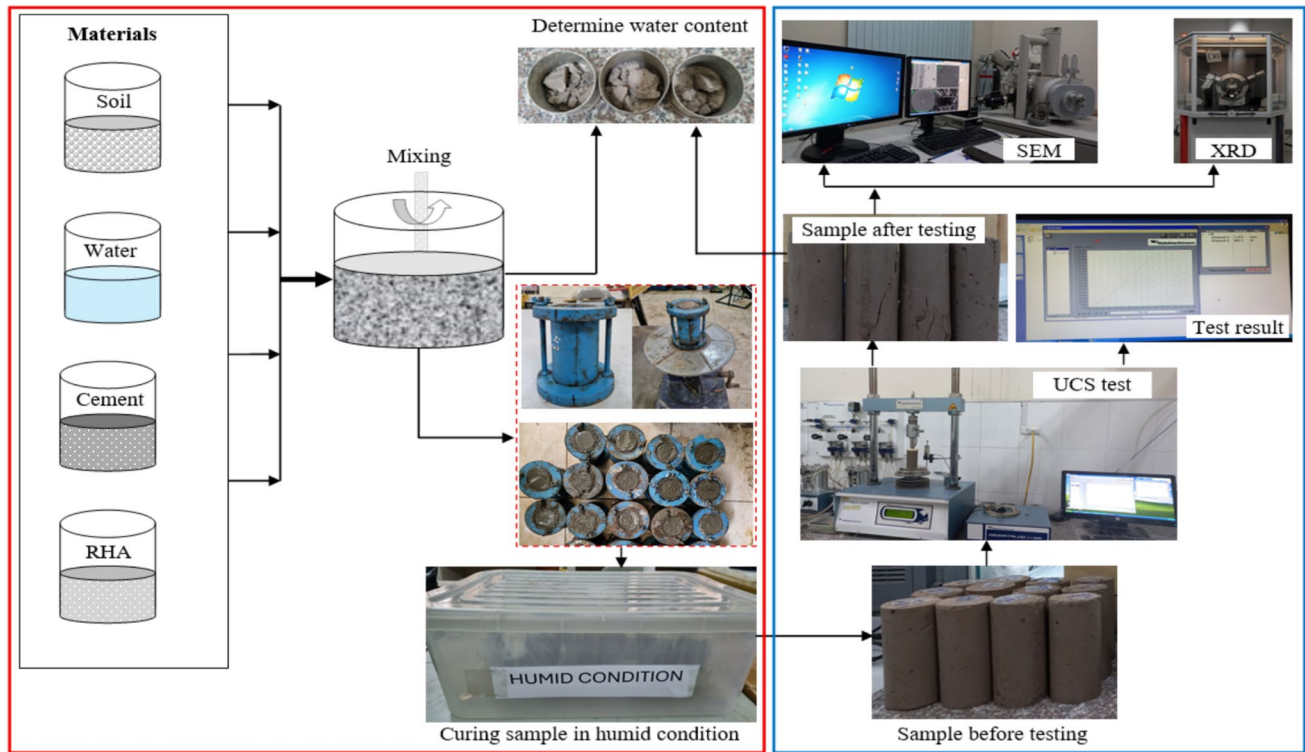


Fig. 7 Schematic of the sample preparation and testing procedures

Table 5 UCS results of mixture samples with different RHA and cement contents

No.	Composite samples	Ca Mau clay*		Soc Trang clay		Tra Vinh clay	
		Natural clay–water content (%)	Average UCS (kPa)	Natural clay–water content (%)	Average UCS (kPa)	Natural clay–water content (%)	Average UCS (kPa)
1	Soil + 15%C	60.5	306.7	50	269.2	63.5	352.7
2	Soil + 15%C + 5%RHA	60.5	250.2	50	277.4	63.5	368.3
3	Soil + 15%C + 10%RHA	60.5	276.3	50	346.6	63.5	425.9
4	Soil + 15%C + 15%RHA	60.5	280.0	50	413.7	63.5	381.2
5	Soil + 15%C + 20%RHA	60.5	336.9	50	255.6	63.5	278.4
6	Soil + 15%C + 25%RHA	60.5	97.7	50	106.5	63.5	220.9
7	Soil + 20%C	60.5	468.8	50	337.4	63.5	408.7
8	Soil + 20%C + 5%RHA	60.5	506.0	50	321.4	63.5	371.9
9	Soil + 20%C + 10%RHA	60.5	436.9	50	373.9	63.5	503.9
10	Soil + 20%C + 15%RHA	60.5	515.0	50	540.6	63.5	668.7
11	Soil + 20%C + 20%RHA	60.5	577.1	50	321.1	63.5	596.8
12	Soil + 20%C + 25%RHA	60.5	421.6	50	161.6	63.5	367.5

*The results have been listed in [10]

Table 6 UCS results of mixture samples for Soc Trang clay at different clay–water contents

No.	Composite sample	Clay–water content (%)	Average UCS (kPa)	Clay–water content (%)	Average UCS (kPa)
1	Soil + 15%C	60	420.7	80	251.3
2	Soil + 15%C + 5%RHA	60	327.0	80	292.8
3	Soil + 15%C + 10%RHA	60	422.5	80	218.2
4	Soil + 15%C + 15%RHA	60	587.7	80	305.7
5	Soil + 15%C + 20%RHA	60	494.3	80	209.7
6	Soil + 15%C + 25%RHA	60	284.3	80	279.5

cement contents. In this table, these mixture samples were prepared with natural clay–water content (natural water content) as shown in Table 1. Table 6 presents the UCS results of Soc Trang clay stabilized by different RHA contents and 15% cement with two clay–water contents of 60% and 80%.

Effect of RHA on the Strength Characteristics of Soil–Cement Mixtures

The axial stress–strain relationships of different soils stabilized with cement and RHA are shown in Fig. 8. This figure reveals that the axial strain at failure in soils stabilized with cement and RHA is higher than that in soils stabilized with cement only. This suggests that the soil–cement–RHA mixture exhibits a more ductile failure behavior compared with the soil–cement mixture. The results of UCS values of the soil–cement–RHA mixtures with different cement and RHA contents are shown in Figs. 9 and 10. It is noted that the UCS results of Ca Mau clay stabilized with cement and RHA were reported in a previous study [10]. The results in Figs. 9 and 10 indicate that the UCS of stabilized soil increases with increasing RHA content up to a threshold; however, the UCS tends to decrease as RHA content continues to increase. This threshold is the optimum content of RHA, which results in the highest value of UCS. Specifically, with 15% cement content, the optimum contents of RHA are 20% for Ca Mau clay and 10% for both Tra Vinh clay and Soc Trang clay. When 20% cement is used, the optimum contents of RHA are 15% for Tra Vinh clay and 20% for both Ca Mau clay and Soc Trang clay. These results indicate that the optimum content of RHA is influenced by both the type of soil and the cement content. The increase in the UCS of stabilized soil with increasing RHA content to the threshold is closely related to the formation of calcium silicate hydrate (C–S–H) gel from pozzolanic reactions, which occur between SiO_2 in RHA and calcium hydroxide $\text{Ca}(\text{OH})_2$ [10]. In addition, the incorporation of RHA into soil–cement mixtures enhances the density of the stabilized soil [10, 30, 31].

SEM and XRD Results of Soil–Cement–RHA Mixtures

The SEM images of untreated soil (original Soc Trang clay) and treated clay with cement and different RHA contents are shown in Fig. 11. This figure shows the formation of C–S–H gel and the development of a denser structure when RHA is added to the soil–cement mixture, which leads to an increase in overall strength. The decrease in the strength of stabilized soil when the RHA content exceeds the optimum level can be attributed to the presence of residual RHA and a lack of sufficient water for the pozzolanic reactions. RHA is a non-cementitious material with a honeycomb structure [32, 33], and as a result, the residual RHA in stabilized soil maintains a porous structure (Fig. 11f). This porosity weakens the cementation between soil particles, leading to a reduction in the strength of the stabilized soil [10]. The increase in RHA content results in a decrease in the water content of the soil–cement mixture, due to the water-absorbing capacity of RHA. The research findings of Duong et al. [10] indicated that the initial water content of soil–cement–RHA mixtures decreased as the RHA content increased, especially when the RHA surpassed its optimum level. The results are presented in Figs. 12 and 13 reveal that the water content of the sample after 28 days of curing decreases as the RHA content increases. Once the RHA content surpasses the optimal value, a marked decrease in water content is observed. The shortage of water limits the occurrence of pozzolanic reactions and reduces the formation of C–S–H gel since this reaction occurs in the presence of water ($x\text{Ca}(\text{OH})_2 + y\text{SiO}_2 + z\text{H}_2\text{O} \rightarrow x\text{CaO} \cdot y\text{SiO} \cdot (x+z)\text{H}_2\text{O}$) [34].

Figure 14 shows the XRD results of stabilized soil with 15% cement and the optimum content of RHA (20% RHA for Ca Mau clay and 10% RHA for Tra Vinh and Soc Trang clay). The stabilized Ca Mau clay exhibits the highest peak intensity of quartz (562.1 cps), whereas the stabilized Soc Trang clay reveals a quartz peak of 488.7 cps, and Tra Vinh clay generates the lowest quartz peak (363.1 cps). The high pH value and clay–water content of Tra Vinh clay provide favorable conditions for pozzolanic reactions. The significant occurrence of pozzolanic reactions in stabilized Tra Vinh clay reduces the intensity of the quartz peak and increases C–S–H gel formation.

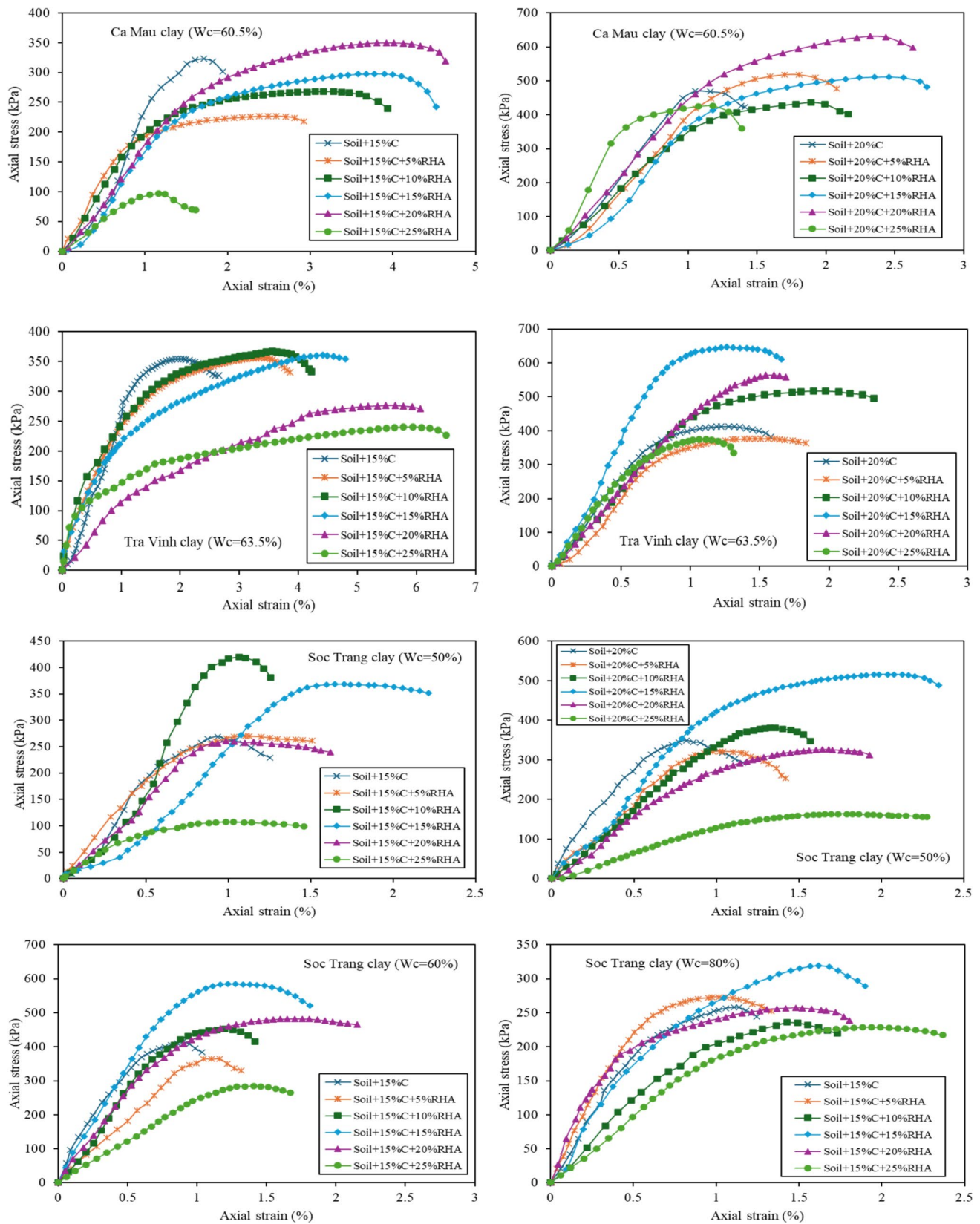


Fig. 8 Relationship between axial stress and axial strain of different soils stabilized by cement and RHA

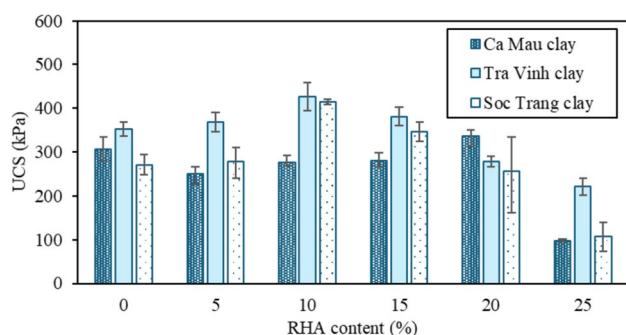


Fig. 9 Effect of UCS of the soil–cement mixtures (cement = 15%)

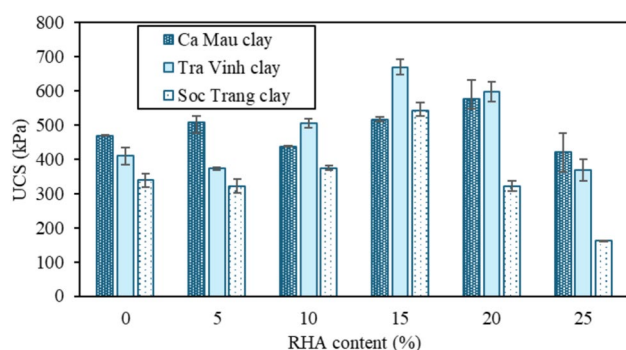


Fig. 10 Effect of RHA on the UCS of the soil–cement mixtures (cement = 20%)

Comparison of the Effectiveness of RHA Incorporation on the Strength of Different Cement-Stabilized Soils

The UCS values of soil stabilized by cement and the optimum content of RHA are compared with those of soil stabilized by cement only (controlled sample). Figure 15 illustrates the percentage enhancement in UCS values achieved through the incorporation of the optimal RHA content. The effectiveness of RHA in enhancing the strength of stabilized soil increases with increasing cement content. This can be attributed to the higher CaO content in cement, which leads to the generation of more $\text{Ca}(\text{OH})_2$ that reacts with the SiO_2 in RHA to form cementitious products. This finding is consistent with the research results of Jongpradist et al. [7]. According to their study, the strength of stabilized soil incorporating 10% cement, with and without RHA, showed no significant variation. Conversely, when the cement content was 20%, the inclusion of RHA resulted in a substantial enhancement in the strength of the stabilized soil compared to soil stabilized without RHA. As presented in Fig. 15, the addition of the optimal RHA content to cement-stabilized Tra Vinh clay produces the highest efficiency, followed by Soc Trang clay and Ca Mau clay. Besides, Tra Vinh clay has the highest pH value of 8.30, whereas Ca

Mau clay has the lowest pH value of 4.01 (Table 1). According to Kinuthia et al. [35] and Ning et al. [36], a high pH environment promotes the hydration process and the formation of cementitious products such as C–S–H, C–A–H, and calcium aluminosilicate hydrates (C–A–S–H).

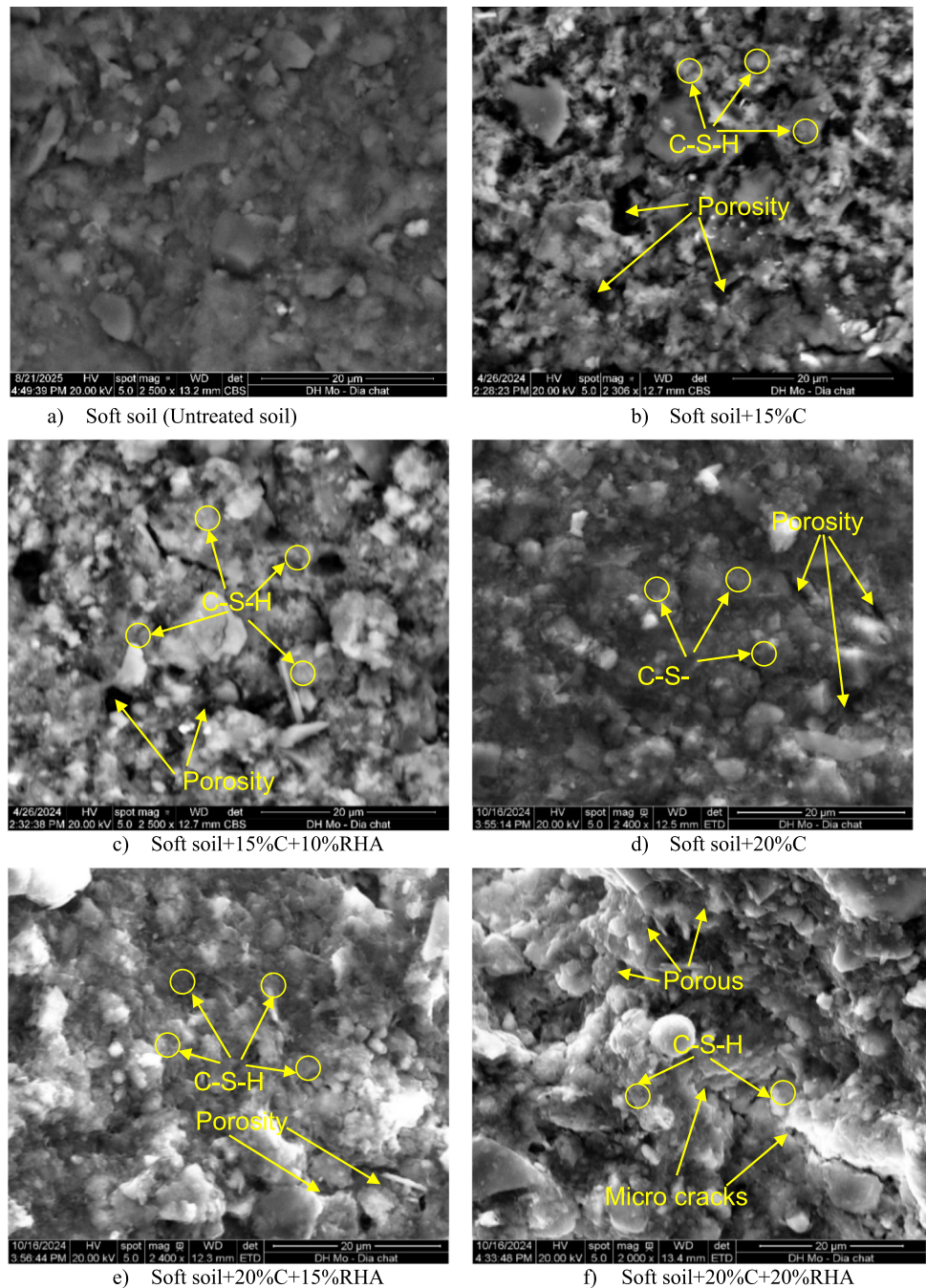
Effect of the Initial Clay–Water Content on the UCS of Stabilized Soil

As mentioned previously, the lack of sufficient water can prevent pozzolanic reactions from occurring, as these reactions require water to enable the interaction between silica and calcium hydroxide to produce the cementitious compounds responsible for strength development. In this study, the effect of the initial clay–water content ($W_c = 50\%$, 60% , and 80%) on the strength of cement + RHA-stabilized Soc Trang clay was investigated. Various proportions of RHA, combined with 15% cement, were incorporated into the soil samples, which were then cured under humid conditions for 28 days. The variation of UCS results of the stabilized soil samples prepared with different initial clay–water contents is plotted in Fig. 16. For all initial clay–water contents, the UCS tends to increase with increasing RHA content up to an optimum level (threshold) and then decreases as the RHA content exceeds the threshold. Specifically, at a clay–water content (W_c) of 50% , the optimum RHA content is 10% , while at W_c values of 60% and 80% , the optimum RHA content is 15% . This indicates that the optimum RHA content is influenced not only by the type of soil and cement content but also by the initial clay–water content. Furthermore, the UCS of stabilized soil increases as the W_c rises from 50 to 60% , but decreases when W_c reaches 80% . The peak UCS value of 587.7 kPa is observed at a W_c of 60% , highlighting the optimal moisture content for strength development (Fig. 16). This demonstrates that the water content significantly affects the effectiveness of RHA in increasing the strength of cement-stabilized soil. This finding contributes to the development of appropriate laboratory testing procedures when investigating the effect of RHA on the strength of stabilized soil. In other words, different clay–water contents or water–cement ratios should be investigated to evaluate and determine the optimum content of RHA for soil stabilization using cement.

Elastic Modulus of the Soil Stabilized with Cement and RHA

The elastic modulus (E_{50}) of stabilized soil is a crucial parameter for calculating the settlement and bearing capacity of composite ground improved using the deep mixing method. Understanding the elastic modulus helps determine settlement behavior, load distribution, and overall

Fig. 11 SEM images of Soc Trang clay stabilized by cement and RHA



performance of stabilized ground under various loading conditions. Figure 17 shows the relationship between the E_{50} and UCS at 28 days of curing. The values of E_{50} range from 50 to 160 times the UCS values. A comparison of the correlations between E_{50} and UCS at 28 days of curing based on the previous studies is presented in Table 7. The comparison results revealed that the E_{50} of soil stabilized by cement and RHA is lower than that of soil stabilized by cement only. Incorporating RHA into the soil–cement mixture leads to a reduction in the E_{50} values of the stabilized

soil. Nevertheless, the findings from the previous studies suggest that the correlation between E_{50} and UCS remains within the range identified in the present study [7, 9, 37].

Conclusions

This study evaluated the effectiveness of rice husk ash (RHA) combined with cement for stabilizing soft soils in the Mekong Delta through a series of laboratory tests. Based

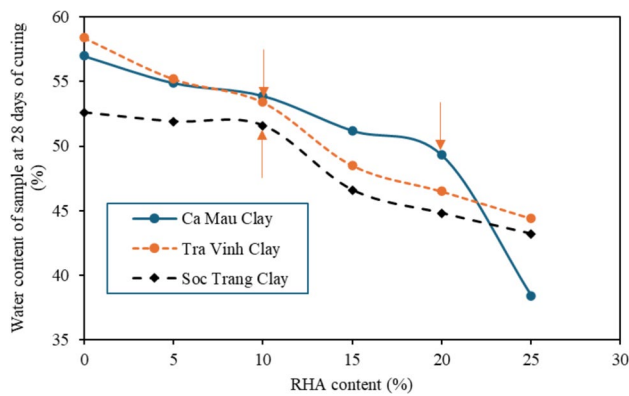


Fig. 12 Water content of the stabilized samples after 28 days of curing (cement, C = 15%)

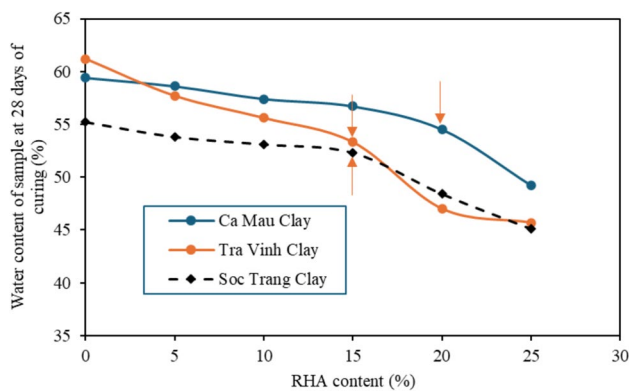
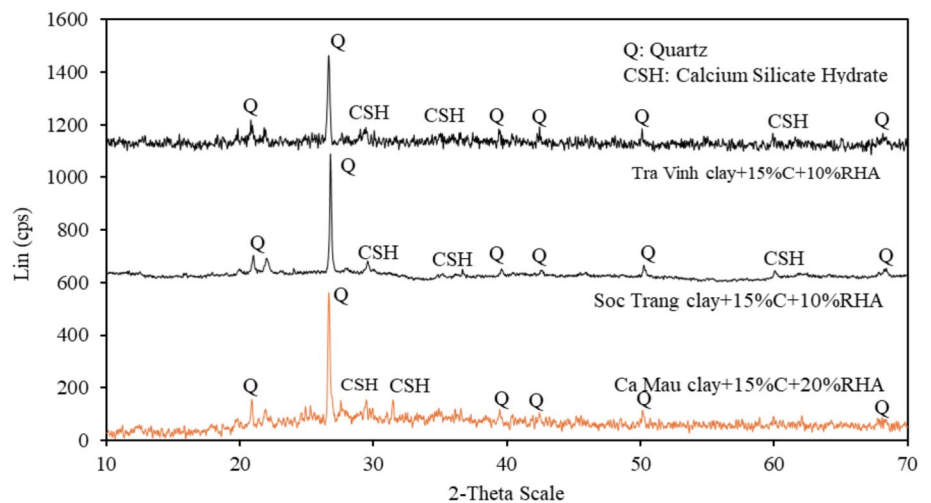


Fig. 13 Water content of the stabilized samples after 28 days of curing (cement, C = 20%)

on the analysis of the experimental results, the following conclusions can be drawn:

1. RHA can serve as an effective additive for enhancing the strength of soil–cement mixtures. At an optimal RHA content of 10–20%, the strength of stabilized soil increases by approximately 10% to over 60% compared to cement-only stabilized soil, depending on the soil type and cement content. The strength enhancement becomes more significant with higher cement contents, highlighting the synergistic effect between RHA and cement.
2. An optimal RHA content and its effectiveness are influenced not only by the type of soil and cement content but also by the initial clay–water content (Wc). The optimal RHA content increases from 10 to 15% as the initial clay–water content (Wc) increased from 50 to 80% in Soc Trang clay stabilized with 15% cement. Furthermore, at these optimal RHA contents, the strength of the stabilized soil increases as Wc increases from 50 to 60%, but tends to decline when Wc reaches 80%.
3. In terms of the stiffness of stabilized soil, the incorporation of RHA decreases the modulus of elasticity (E_{50}) of the soil–cement mixtures, with E_{50} values ranging from 50 to 160 times the UCS, indicating a reduction in stiffness relative to cement-only mixtures.
4. This study is based on laboratory experiments with the primary objective of evaluating the applicability of RHA for cement-stabilized soil in the Mekong Delta, Vietnam. Specifically, the focus is on investigating the unconfined compressive strength of soil–cement–RHA mixtures which is considered one of the most critical parameters for the design of the deep cement mixing method. Consequently, other tests such as triaxial test, compaction and density tests were not included in this research. These tests will be incorporated in the future studies to provide a more comprehensive evaluation. In addition, a field-based investigation concerning the use

Fig. 14 X-ray diffraction patterns of stabilized soil with 15% C and optimum RHA contents



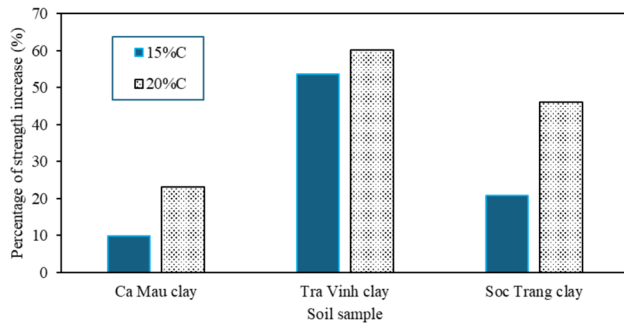


Fig. 15 Strength enhancement percentage of soil stabilized with cement and optimum RHA content

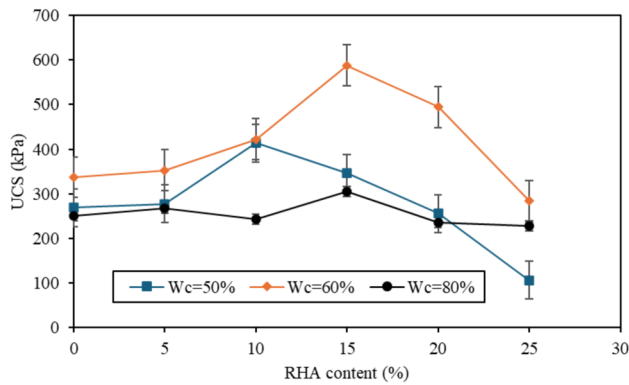


Fig. 16 Effect of the initial clay–water content on the UCS of Soc Trang clay stabilized with cement and RHA

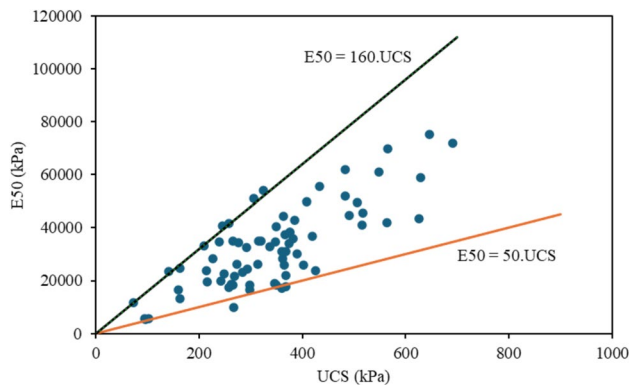


Fig. 17 Relationship between E_{50} and UCS of stabilized soil using cement and RHA

of RHA in combination with cement for soil stabilization is planned for future work.

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Table 7 Correlation between E_{50} and UCS at 28 days of curing

Materials	Correlations	References
Cement	$E_{50} = (30 \div 300) \text{UCS}$	[38]
Cement	$E_{50} = (350 \div 1000) \text{UCS}$	[39]
Cement	$E_{50} = (100 \div 250) \text{UCS}$	[40]
Cement	$E_{50} = (100 \div 300) \text{UCS}$	[41]
Cement + RHA	$E_{50} = 63.8 \text{UCS}$	[37]
Cement + RHA	$E_{50} = 61.7 \text{UCS}$	[9]
Cement + RHA	$E_{50} = 84.3 \text{UCS}$	[7]
Cement + RHA	$E_{50} = (50 \div 160) \text{UCS}$	This study

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

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