



Applicability of rice straw ash incorporation with cement for soft soil improvement in the Mekong Delta, Vietnam

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Abstract

The utilization of agricultural waste materials as soil stabilizers has recently received much attention due to their environmental and economic benefits. This study explores the potential of the incorporation of rice straw ash (RSA) with cement for soil stabilization in the Mekong Delta, Vietnam, where many soft soil types and an abundant source of RSA are present. The objective of the study was to investigate the unconfined compressive strength (UCS) of soil stabilized by cement and RSA. Additionally, scanning electron microscopy (SEM) and X-ray diffraction (XRD) were employed to analyze the microstructure of the stabilized soil. The research findings revealed that RSA can significantly enhance the UCS of soil–cement mixtures. Besides enhancing strength, RSA can be an alternative to replace 10% of the cement in soil improvement. The SEM images and XRD results confirmed the formation of a Calcium Silicate Hydrate (C-S-H) gel and a denser microstructure upon incorporation of RSA into the stabilized soil. The research also reported that incorporating RSA affected both the strength development and elastic modulus of the soil-cement mixture. This study revealed that RSA could be a sustainable and cost-effective approach in soil stabilization while addressing the challenge of agricultural waste management.

Keywords Rice straw ash · Cement · Soft soil stabilization · Unconfined compressive strength · Strength development

Introduction

Soil improvement is a critical activity in geotechnical engineering and is aimed at enhancing the physical and mechanical properties of soil, including compressive, tensile strength, and shear strength, as well as structural durability, and workability. One of the most common and well-established methods of soil improvement is the cement deep

mixing method. It has been used since the 1970s in Japan and has become one of the most widely adopted techniques worldwide. However, the current challenge is that the use of conventional cement in soil ground improvement is often associated with high costs and environmental issues, particularly due to CO₂ emissions generated during cement production. In recent decades, the use of agricultural waste byproducts in combination with cement for soil stabilization has gained considerable attention. Various types of agricultural post-production ashes used in soil stabilization have been reported in the literature [1–12]. The stabilized soil strength parameter increases with the additional formation of calcium silicate hydrate (C-S-H) gel through pozzolanic reactions between SiO₂ and Ca(OH)₂ when these ashes are incorporated into the treated soil [1, 6, 13–15].

Rice is considered one of the most common staple foods worldwide. According to reports, the total global production of rice in the 2024/2025 crop season is estimated to reach nearly 535.8 million metric tons [16]. The Vietnamese market is ranked as the fifth largest unmilled rice producer, with an output of approximately 43.5 million metric tons of unmilled rice in 2024 [17]. The production of 1 kg of paddy

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(unmilled rice) generates approximately 1 to 1.5 kg of straw [18]. After milling, 1 kg of paddy rice produces approximately 0.2 kg of rice husk. Thus, every year, rice production in Vietnam is capable of generating up to 60 million tons of straw and 8 million tons of rice husk. In rice plants, the husk and leaves contain a relatively high silica content, with more than 20% dry mass in the husk and approximately 12% in the leaves [19]. After rice straw is burned, the residual component is rice straw ash (RSA) (accounting for about 15% of rice straw weight) [20], which contains a high silica (SiO_2) content. As one of the most abundant agricultural residues globally, rice straw presents an environmental challenge due to its disposal, often through open-field burning, which contributes to air pollution and greenhouse gas emissions. However, when transformed into ash, rice straw becomes a valuable material with potential applications in civil engineering. Previous studies have demonstrated that RSA can be used as a supplementary material in normal concrete [21–24], lightweight concrete [25], cement replacement materials [26], or the production of clay bricks [27]. In the context of soil stabilization, Anupam et al. [28] investigated the use of various waste materials, including fly ash (FA), rice husk ash (RHA), bagasse ash (BA), and rice straw ash (RSA), for stabilizing A-7-6 soil in road construction. The research results indicated that RSA, along with other waste materials, significantly improved the geotechnical properties of stabilized soil, such as enhancing the shrinkage limit and California Bearing Ratio (CBR). Sabat et al. [29] also reported that increasing the RSA content leads to higher unconfined compressive strength (UCS) and CBR values in expansive soil. Consequently, 20% RSA was identified as the optimal content for achieving the highest UCS and CBR values. However, regarding swelling behavior, they concluded that RSA should not be used to improve the parameters of expansive soil, as the addition of 20% RSA still results in high swelling pressure in stabilized soil [29]. Previous studies showed that while RSA has shown considerable potential as a supplementary material in concrete production, its application in combination with cement for soil stabilization has received limited scholarly attention.

The Mekong Delta is the largest river delta in Vietnam and is characterized by various types of soft soils with significant thicknesses. In many areas, these soft soils are typically found near the ground surface and extend to depths of up to ten meters. Thus, soft soil improvement is a common practice in the region. In this context, the deep cement mixing method has been extensively applied for soft ground improvement in this region [30, 31]. The Mekong Delta is also the largest rice-producing region in Vietnam, with a production of about 24 million tons of rice paddy in 2024 [32]. The amount of rice straw in the Mekong Delta is estimated to be approximately 36 million tons per year. This

shows great potential for producing electricity in this region through controlled active combustion of by-products [33]. As a result, a large amount of rice straw ash can be generated every year (up to about 5.4 million metric tons). However, as mentioned above, research on the application of rice straw ash in soil stabilization remains limited. The present study aims to investigate the applicability of rice straw ash incorporation with cement for the deep mixing technique in the Mekong Delta. In the deep cement mixing method, the UCS is one of the most critical indices for the calculation of the bearing capacity of composite ground. Therefore, the effect of RSA on the UCS of a soil-cement mixture and its development over different curing periods under laboratory conditions will be investigated. Additionally, the effect of cement replacement with RSA on the UCS is examined. The correlation between the UCS and elastic modulus (E_{50}) of the soil-cement-RSA mixtures is also evaluated. The incorporation of rice straw ash in soil stabilization represents a sustainable and cost-effective solution for improving soil properties while addressing agricultural waste management. Its significance lies in enhancing soil strength and durability, making it a valuable alternative to conventional stabilizers. The novelty of using RSA contributes to improving soil bonding and long-term performance through its pozzolanic properties, offering an eco-friendly approach to infrastructure development. This innovation not only minimizes environmental impact but also promotes circular economy principles by repurposing agricultural byproducts.

Materials and methods

Materials

Soil samples

Soil samples were collected from 3 different locations in the coastal area of the Mekong Delta region. The locations were, Tran Van Thoi district-Ca Mau province (Ca Mau clay), Vinh Chau town-Soc Trang province (Soc Trang clay), and Duyen Hai town-Tra Vinh province (Tra Vinh clay) (Fig. 1). As reported in a previous study, the soil profiles at the three locations contain a soft soil layer near the surface with a thickness of more than 10 m [34]. These soft soil layers are young sediments of Q_2^{2-3} age (Middle-Late Holocene), with an alluvial-marine (am) origin as the dominant depositional environment. Consequently, the properties of soft soil within the same layer are relatively uniform with depth [35]. Therefore, the soil sample was manually collected using a shovel by excavating a pit to a depth of 1 m to remove the topsoil layer while still ensuring that the samples were representative of the target soil layer. At each

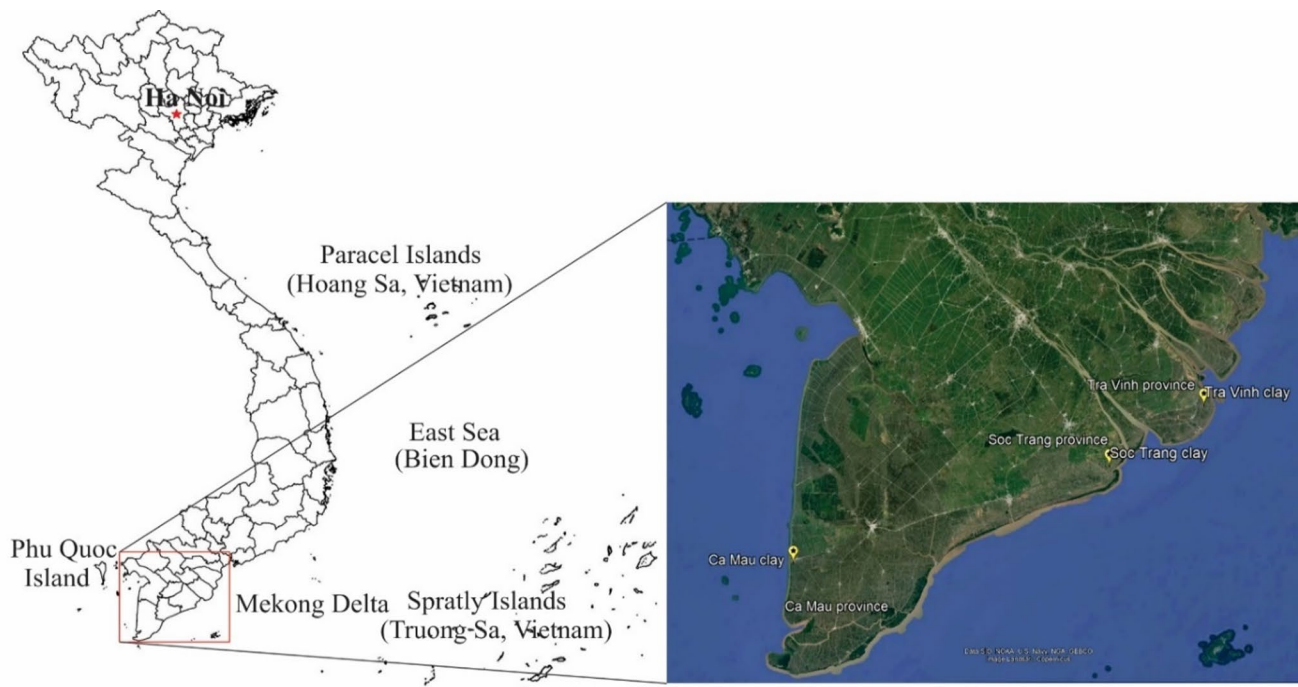


Fig. 1 Sampling locations in the Mekong Delta, Vietnam [36]

Table 1 Selected geotechnical properties of the tested soil samples [36]

Index	Standards	Unit	Ca Mau clay	Soc Trang clay	Tra Vinh clay
Sand (0.075–4.75)	ASTM	%	10.0	11.0	8.1
Silt (0.005–0.075)	D6913;	%	47.0	70.4	60.1
Clay (< 0.005)	ASTM D422	%	43.0	18.6	31.8
Natural water content	ASTM D2216	%	60.5	50.3	63.5
Wet unit weight	ASTM D7263	kN/m ³	16.6	16.5	16.7
Specific density	ASTM D854	kN/m ³	27.1	26.9	27.0
Liquid limit (Cassagrande's method)	ASTM D4318	%	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	ASTM D2974	%	3.20	6.66	8.17
Unconfined compressive strength	ASTM D2166	kPa	30.5	24.3	33.6
pH value	ASTM D4972	-	4.01	6.47	8.30

sampling point, one undisturbed soil sample was collected using a thin-walled sampler (Shelby tube) to determine the wet unit weight and unconfined compressive strength of natural soil.

A list of the determined physical parameters of the studied soil is presented in Table 1. The grain size distribution

curve is plotted in Fig. 2. As shown in Table 1, the soil samples contained clay particles ranging from 18.6% to 43%, plasticity indices ranging from 23.1% to 39.3%, and organic matter contents ranging from 3.2% to 8.17%. The mineralogical compositions of the studied soils are presented in Table 2. The tests revealed that the soil samples consisted of different types of minerals, among which quartz had the highest content, followed by illite, kaolinite, and other minerals. Similar to mineral compositions, the studied soils have different chemical compositions, with SiO₂ accounting for the highest content of approximately 55%, Al₂O₃ accounting for approximately 18–20%, Fe₂O₃ accounting for approximately 8–10%, and other oxides accounting for a small percentage (Fig. 3).

Cement and rice straw Ash (RSA)

Portland cement blended (PCB40) Ha Tien was used in the study. The chemical compositions of the cement samples are shown in Table 3.

Rice straw was burned in open air and cooled under in situ conditions (Fig. 4). It should be noted that the chemical composition of RSA may vary among different batches due to its dependence on the burning temperature [24]. Burning rice straw in controlled temperature conditions (up to 700 °C) will generate high-quality RSA (rich in amorphous

Fig. 2 Particle size distribution curves of the tested soil samples [36]

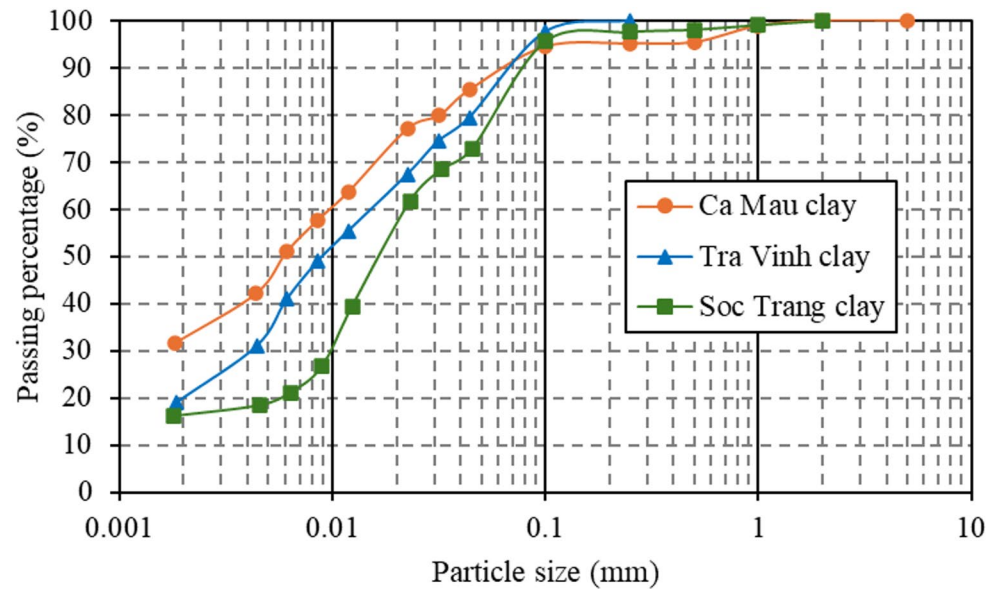


Table 2 Mineralogical compositions of the tested soil samples [36]

Mineralogical compositions (%)	Sample		
	Ca Mau clay	Soc Trang clay	Tra Vinh clay
Illite	17–19	17–19	22–24
Kaolinite	16–18	17–19	14–16
Chlorite	4–6	4–6	5–7
Quartz	38–40	44–46	40–42
Feldspar	4–6	3–5	3–5
Goethite	3–5	4–6	4–6
Others (traces)	Amphibian; Lepidocrocite; Pyrophyllite	-	Amphibian

and reactive silica) [37]. However, the present study aims to utilize the rice straw ash obtained from open-field burning of rice straw, which is a very common practice in rural areas of Vietnam. Therefore, the RSA was collected from a single open-air burning of rice straw to minimize variations in its chemical composition between batches. The rice straw ash was then ground and sieved through sieve No. 200 ($< 75 \mu\text{m}$) (Fig. 5). The fine straw ash was then used to determine the chemical composition, and its oxide component is listed in Table 3. The results show that RSA has the highest content of SiO_2 (65.4%), followed by K_2O (15.5%), CaO (5.11%), and other oxides (a small percentage).

Sample preparation and testing procedure

Sample preparation

In this study, a mixture of rice straw ash was used to investigate the strength improvement, potential of cement replacement by RSA, and strength development of cement-treated soft soil in the Mekong Delta region. According to Farouk

and Shahien [38], for economical and technical reasons, the cement content used in the deep mixing method should be less than 20% of wet soil weight. Bearing that in mind, two cement contents of 15% and 20% were used for laboratory testing. Regarding the RSA, its content used in soil stabilization often ranges from 0 to about 30% of wet or dry soil weight [28, 29]. The high content of RSA will lead to a decrease in the strength of stabilized soil. Thus, in this study, to investigate the strength changes, RSA was added to soil-cement mixtures with contents ranging from 0% to 30% of the wet soil weight (0%, 5%, 10%, 15%, 20%, 25%, and 30%). The treated samples are described as $x\text{-Ca-RSAb}$, where x is the name of the pure soil sample ($x = \text{CM}$ for Ca Mau clay, $x = \text{ST}$ for Soc Trang clay; $x = \text{TV}$ for Tra Vinh clay); a is the content of cement ($a = 15\%$, 20%); and b is the RSA content ($b = 0\%$, 5% , 10% , 20% , 25% , 30%). For example, if Ca Mau clay is treated with 15% cement and 20% RSA, the sample name is CM-C15-RSA20. To investigate the potential of cement replacement by RSA, 15% and 20% of the wet soil weight was partially replaced by RSA. Accordingly, RSA from 10% to 50% of the cement weight was investigated. The soil that was used for testing was Ca Mau clay. The samples are denoted as CM-RCc-RSAd, where RC is the total content of RSA and cement, c is the cement content ($c = 15\%$, 20% wet soil weight), and d is the RSA content replacement of cement ($d = 0\%$, 10% , 20% , 30% , 40% , or 50%). This means that the ratios of RSA to cement are 0:100, 10:90, 20:80, 30:70, 40:60, and 50:50. For example, if the Ca Mau clay is stabilized by 15% cement and RSA, in which the RSA-to-cement ratio is 10:90, the treated sample name will be CM-RC15-RSA10.

To prepare the samples for testing, pure soil was first mixed for even particle distribution [3]. Cement and water with a W/C ratio of 1 were added to the soil and mixed

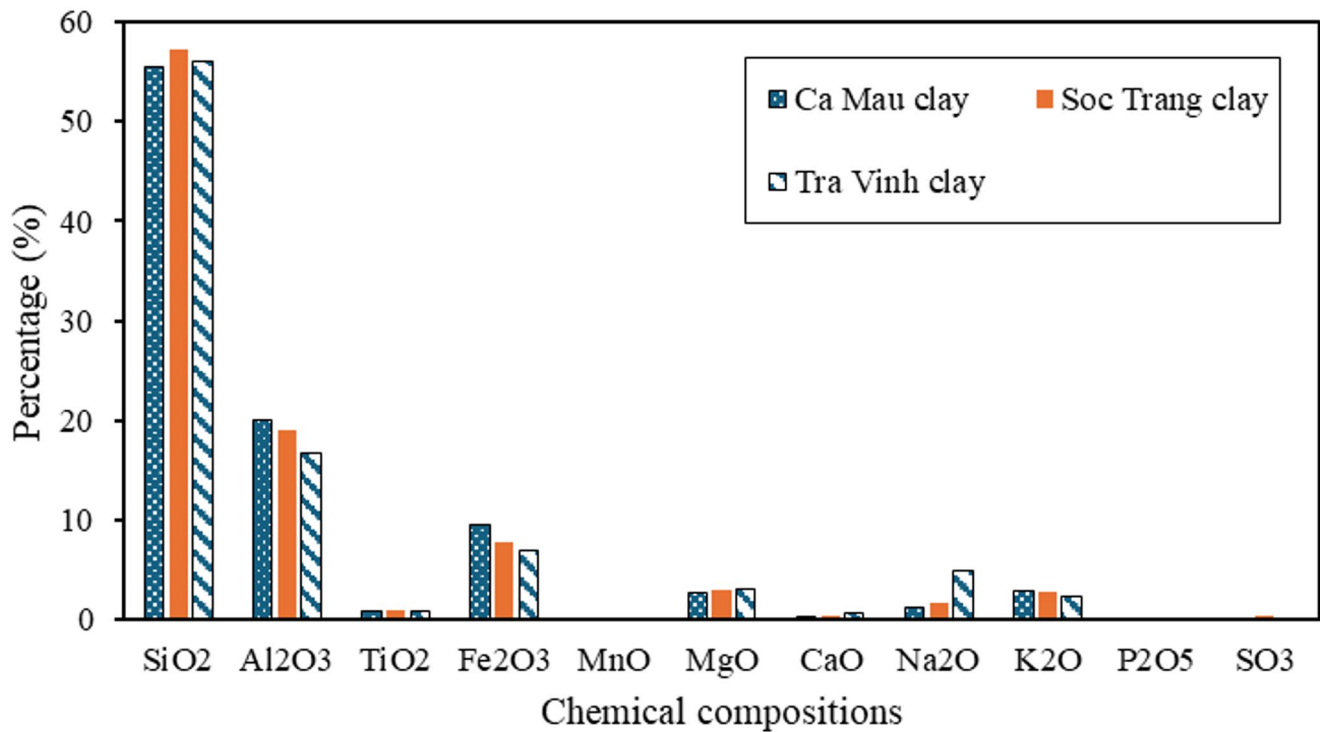


Fig. 3 Chemical compositions of the soil samples

Table 3 Chemical compositions of the cement and RSA

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃
Cement*	24.93	6.94	5.43	0.95	0.14	3.32	43.6	3.22	0.93	0.84	2.68
RSA	65.40	2.30	0.57	0.08	0.26	2.48	5.11	1.72	15.5	1.30	0.91

Note: *The data have been listed in [36]

Fig. 4 Open-air burning of rice straw



again. Finally, the desired RSA content was added to the soil slurry and mixed again. The mixture samples were transferred to the cylinder mold (height of 10 cm, inner diameter of 5 cm) in 4 to 5 layers and compacted via the equipment shown in Fig. 6. The samples and molds were wrapped in plastic bags to avoid excessive evaporation. After two days,

the mold was removed, and the samples were then put into plastic bags and cured under humid conditions until the desired testing time was reached. For the investigation of strength development, the mixture samples of soil-cement-RSA were cured for different periods from 3 to 90 days. The sample preparation and curing procedure are described in



Fig. 5 (a) Sieving rice straw ash; (b) Rice straw ash after sieving



10 cm

5 cm

Fig. 6 Sample preparation via a cylindrical mold

published studies [3, 9, 36]. In this study, three specimens were prepared simultaneously for each mixture, and unconfined compressive strength (UCS) tests were performed on all of them. The UCS value of each mixture was determined as the average of the three individual test results.

Unconfined compressive strength testing procedure

The unconfined compressive test was performed according to ASTM D2166 with a loading rate of 1 mm/min [39]. The vertical displacement and vertical force, F (N), were recorded automatically. The vertical stress was calculated as $\sigma = F/A$, where σ is the vertical stress (kPa), F is the vertical

force (N), and A is the cross-sectional area of the sample (cm^2). The relationship between the vertical stress σ (kPa) and the vertical displacement ϵ (%) is plotted in Fig. 7. On the basis of this relationship, the elastic modulus (E_{50}) is determined as follows:

$$E_{50} = \frac{UCS}{2\epsilon_{50}}$$

where:

E_{50} is the elastic modulus (kPa); UCS is the unconfined compressive strength (kPa); and ϵ_{50} is the vertical displacement at a strength equal to $UCS/2$ (%).

For a better understanding and interpretation of the results, a Quanta450 SEM (Scanning Electron Microscope) and D8 advanced XRD (X-ray Diffraction) instruments were used to analyze the microstructural composition of the stabilized soil [9, 32]. The sample preparation and testing procedure are presented in Fig. 8.

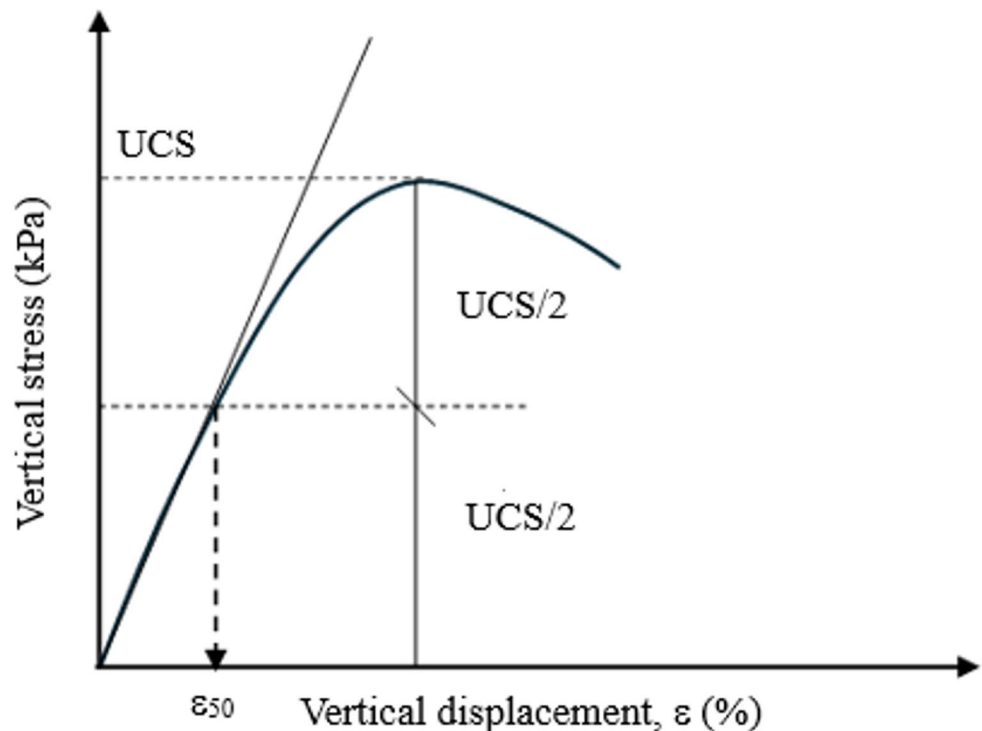
Test results and discussion

Effect of rice straw ash on the strength of the soil-cement mixture

One of the objectives of this study was to investigate the effect of RSA on the unconfined compressive strength of

selected soils. For that purpose, Ca Mau clay, Soc Trang clay, and Tra Vinh clay treated with 15% and 20% cement (C) and different RSA contents were tested to determine the UCS values at 28 days of curing (UCS_{28}). The relationships between the RSA contents and UCS_{28} values of the treated soils with 15% cement and 20% cement are presented in Figs. 9 and 10. The UCS_{28} values of the treated soil increased with increasing RSA content to a threshold value and then decreased as the RSA content increased. This behavior is similar to the effects of rice husk ash (RHA) on the strength of soil-cement mixtures reported in various studies [1, 3, 9, 13, 36, 40]. For Ca Mau and Soc Trang clay, the UCS_{28} values of soil treated with 15% and 20% cement reached the highest value when 15% RSA was added (the optimum content of RSA was 15%), whereas for Tra Vinh clay, for both 15% and 20% cement contents, the optimum RSA inclusion was 20%. In particular, for Ca Mau clay, the UCS_{28} values increased from 306.7 kPa (CM-C15-RSA0) and 468.8 kPa (CM-C20-RHA0) to 629.0 kPa (CM-C15-RSA15) and 1310.7 kPa (CM-C20-RSA15), respectively. This means that when 15% RSA was added to the stabilized soil with 15% and 20% cement contents, the UCS_{28} of the soil-cement mixture increased by 2.05 and 2.80 times, respectively. For Soc Trang clay, the strength of the treated soil increased from 269.2 kPa (ST-C15-RSA0) to 626.5 kPa (ST-C15-RSA15) (a 2.33-fold increase). For a cement content of 20%, the strength of the stabilized soil samples increased from 337.4 kPa (ST-C20-RSA0) to 1032.9 kPa (ST-C20-RSA15) (a 3.06-fold increase). For

Fig. 7 Determination of the elastic modulus, E_{50}



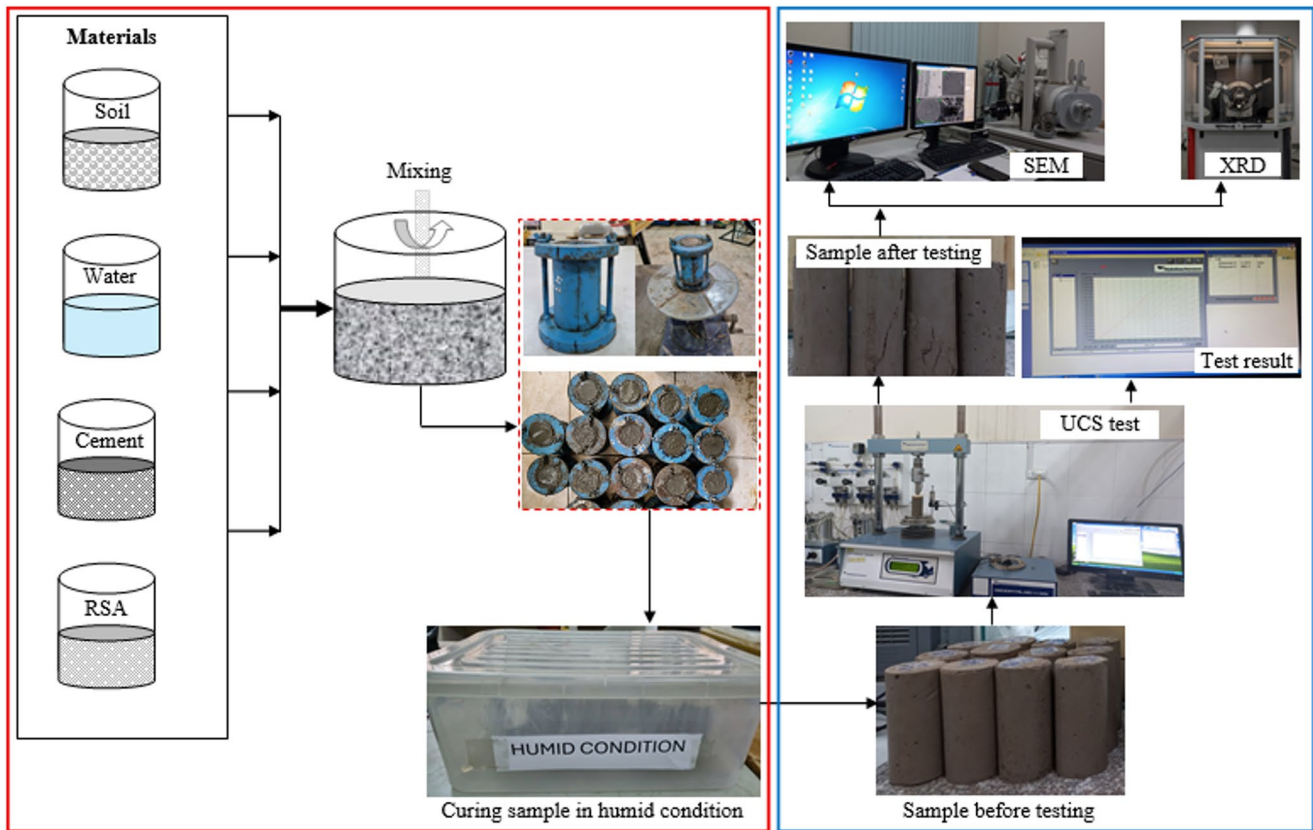


Fig. 8 Summary of sample preparation and testing procedure (After [36])

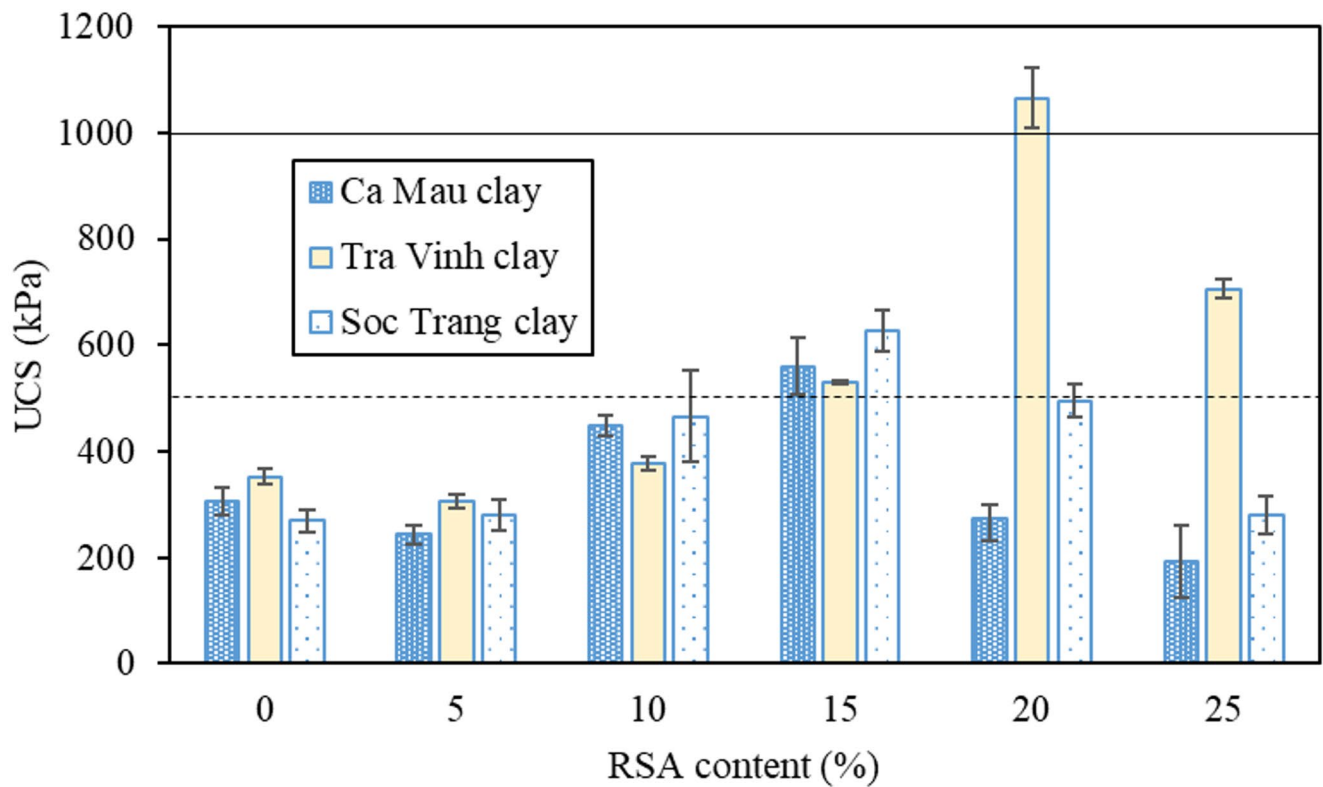


Fig. 9 Relationship between RSA contents and UCS₂₈ values of treated soil with 15% cement content

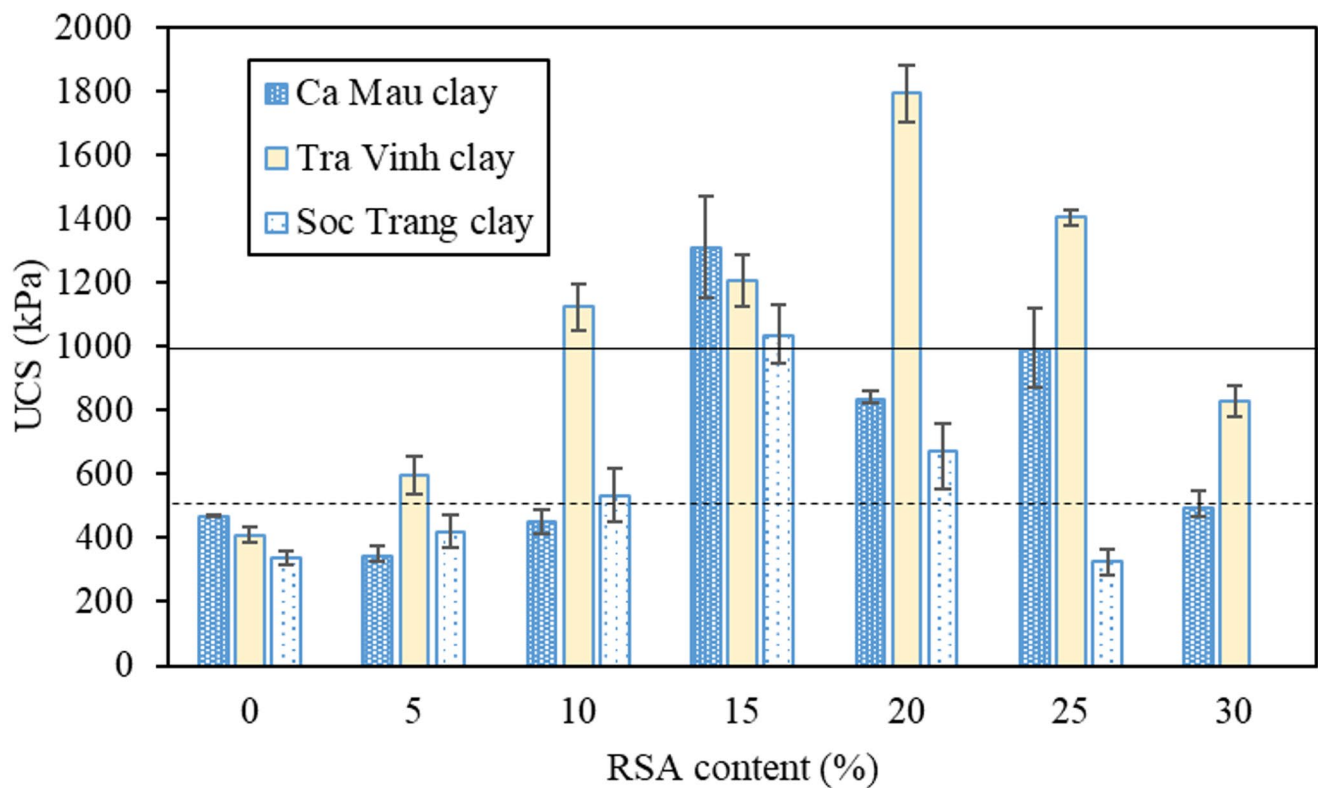


Fig. 10 Relationship between RSA contents and UCS_{28} values of treated soil with 20% cement content

Tra Vinh clay, when the optimum RSA content of 20% was added to the soil-cement mixtures, the UCS values of the treated soil increased from 352.7 kPa (TV-C15-RSA0) to 1065.4 kPa (TV-C15-RSA20) (increased by 3.02 times) and from 408.7 kPa (TV-C20-RSA0) to 1793.0 kPa (TV-C20-RSA20) (increased by 4.39 times). For the soil stabilized with 20% cement, the addition of the optimum RSA content led to higher UCS_{28} values compared with those of the soil stabilized with 15% cement. This finding indicates that the effectiveness of RSA in soil stabilization may increase with increasing cement content. This finding is similar to the research results of Jongpradist et al. [40] and Duong et al. [9], where the use of rice husk ash to increase the strength of the soil-cement mixture was analyzed.

In engineering practice, there is no universal minimum value specified for the unconfined compressive strength (UCS) of soil-cement columns. The target UCS is generally determined based on project requirements, structural loading conditions, soil properties, and the intended application. However, for instance, in Japan, soil-cement columns are typically required to achieve a minimum UCS of 500 kPa at 28 days (dotted line in Figs. 9 and 10) [41]. In Thailand, according to the Department of Highways, soil-cement columns must attain a minimum UCS of 1000 kPa at 28 days (solid line in Figs. 9 and 10) [42]. The results of this study indicate that the UCS values of all soil types stabilized

with 15% and 20% cement without RSA were below 500 kPa, thus failing to meet the minimum UCS requirements. Nevertheless, as shown in Fig. 9, incorporating the RSA into the soil-15% cement mixtures significantly enhanced the strength of the stabilized soil, enabling it to satisfy the minimum UCS criterion of 500 kPa and, in the case of Tra Vinh clay, even exceed 1000 kPa. Similarly, when the soils were treated with 20% cement, the addition of RSA further increased the UCS values, allowing the stabilized soils to meet the minimum UCS requirement of 1000 kPa. In the Mekong Delta region, for the soil-cement column method, the cement content typically ranges from 250 kg/m³ to 350 kg/m³ (corresponding to approximately 15%–20% of the wet soil weight, which is also used in this study), and the required UCS of soil-cement columns commonly varies from 400 kPa to 1000 kPa [43]. Therefore, these findings in this study demonstrate the effectiveness of RSA incorporation in improving the performance of soil-cement columns, confirming its potential applicability in the deep mixing method for engineering practice.

The results of the XRD analysis for the Ca Mau clay (pure clay), CM-C15-RSA0, CM-C15-RSA15, and CM-C15-RSA20 samples are plotted in Fig. 11. As shown, the peak of quartz decreased from 918.7 cps (pure soil sample) down to 542.6 cps (CM-C15-RSA0) and then decreased further to 500.4 cps when RSA was added to the soil-cement

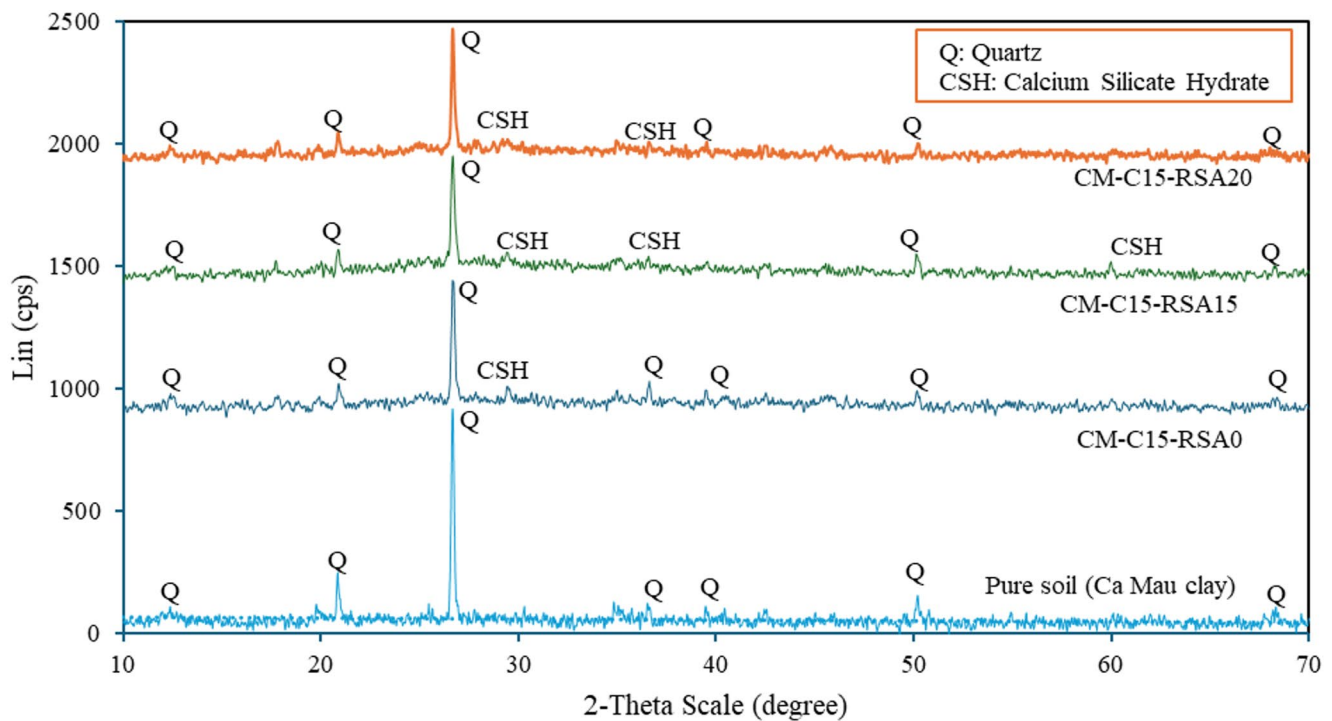


Fig. 11 XRD records for Ca Mau clay + 15% cement mixtures with and without RSA

mixture (CM-C15-RSA15). However, when the RSA content was changed to 20%, the peak of quartz increased from 500.4 cps (CM-C15-RSA15) up to 539.7 cps (CM-C15-RSA20). In contrast, the peak of the C-S-H gel tends to increase when an RSA content is less than or equal to 15% is added to the soil-cement mixture. When the RSA content exceeds 15%, the peak of the C-S-H gel decreases. This proves that adding RSA to the soil-cement mixture leads to an increase in the number of C-S-H gel formations. This phenomenon results in improved strength of the treated soil samples. However, when the content of RSA exceeds the optimum content, the formation of C-S-H decreases, and the residual quartz increases, resulting in a decrease in the strength of stabilized soil samples. This behavior is similar to that of the soil-cement mixture with RHA content [9, 36]. When cement is added to the soil sample, the C_2S ($2CaO \cdot SiO_2$) and C_3S ($3CaO \cdot SiO_2$) in cement will react with free water to form $Ca(OH)_2$ (Eqs. 1, 2) [44]. Since RSA also contains a high content of SiO_2 , when it is added to the soil-cement mixture, the SiO_2 in RSA reacts with $Ca(OH)_2$ via pozzolanic reactions and forms a C-S-H gel (Eq. 3) [45]. The additional formation of C-S-H gel plays an important role in increasing the strength of cement-treated soil.

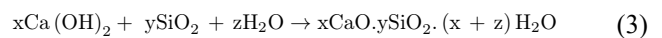
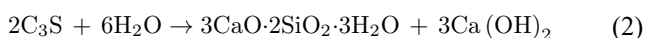
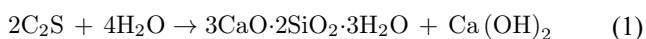


Figure 12 presents SEM images of representative clay samples stabilized with various RSA contents. Adding RSA to the soil-cement mixture enhances the formation of C-S-H gel, which is essential for improving the strength and durability of the treated soil. This process increases the relative density and decreases the void ratio of the soil matrix, thereby enhancing the mechanical performance (Figs. 12a-d). However, when the RSA content exceeds an optimum level, the hydration process becomes imbalanced, resulting in a reduction in cement gel formation. This imbalance weakens the internal structure of the soil, promotes the development of porous area and microcracks (Figs. 12e-f). As a result, the unconfined compressive strength of the treated soil decreases, which negatively affects the load-bearing capacity and overall stability. Regarding other applications of RSA, it also plays an important role in increasing the density of concrete [21, 22, 25]. Agwa et al. [25] reported that adding 10% of RSA significantly enhanced the density of lightweight concrete. Similarly to RSA, Duong et al. [9], Duong et al. [36] also reported that adding RHA to the soil-cement mixture increased the density of the treated soil due to the formation of C-S-H gel. Nevertheless, when the RHA exceeded the optimum value, the treated soil exhibited a weaker structure with numerous porous areas.

Moreover, the treatment of soil with 20% cement and 15% RSA leads to greater formation of C-S-H gel and higher density than that of the sample treated with 15% cement and

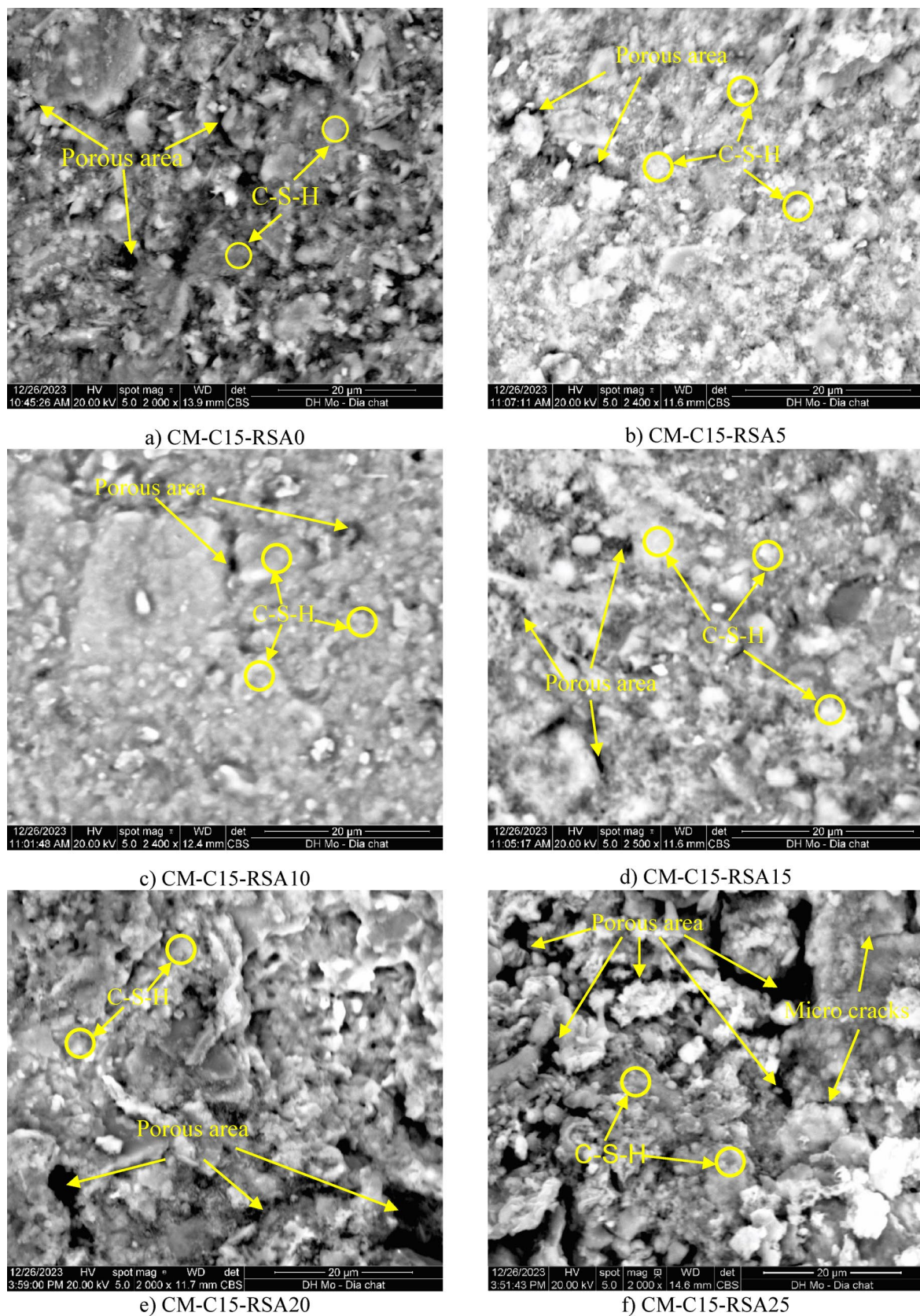


Fig. 12 SEM images of Ca Mau clay with 15% cement and different RSA contents after 28 days of curing

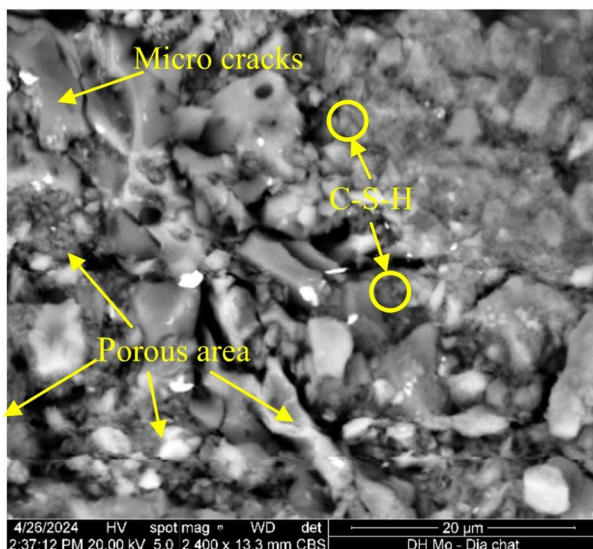
15% RSA, as shown in Fig. 13. This observation aligns with the general conclusion that increasing the cement content enhances the mechanical properties of soil-cement-RSA mixtures. A higher cement content facilitates the hydration process, leading to the generation of additional C-S-H gel, which contributes to a denser and more cohesive soil structure. This improvement in microstructure corresponds directly to an increase in the strength of the soil mixture. For Soc Trang clay, this enhancement is evident in the UCS₂₈ values recorded at 626.5 kPa for samples treated with 15% cement and 15% RSA and 1032.9 kPa for samples with 20% cement and 15% RSA contents.

Strength development of the soil-cement-RSA mixture

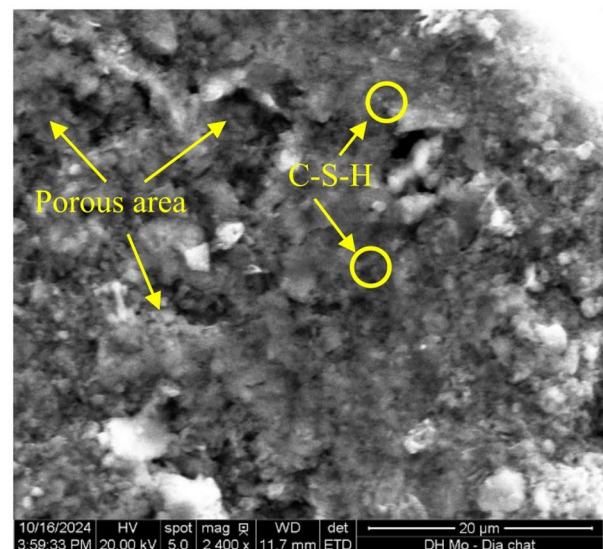
Another objective was to investigate the strength development of Ca Mau clay treated with cement with and without an optimum RSA content. Accordingly, mixture samples of CM-C15-RSA0, CM-C15-RSA15, CM-C20-RSA0, and CM-C20-RSA15 were prepared and cured for 3 to 90 days. The relationship between axial stress and axial strain of these mixture samples curing at different periods is plotted in Fig. 14. The test results of the unconfined compressive strength of the treated soil at different curing times are presented in Figs. 15 and 16. The results show that the strength of the soil treated with cement and cement + RSA increased as the curing time increased. In general, at all curing times, the UCS values of the soils treated with cement + RSA are greater than those of the soils treated with cement. However, the strength development of soil stabilized with cement with and without RSA is different, especially during long-term

curing. In particular, the strength development of the soil-cement mixtures with and without RSA at curing times of less than 28 days does not significantly differ. Nevertheless, at curing times ranging from 28 to 90 days, the UCS values of treated soil with cement and RSA are significantly greater than those of treated soil with cement only. This phenomenon can be attributed to the pozzolanic reactions between SiO₂ in RSA and Ca(OH)₂ in the soil mixture. Pozzolanic reactions can occur over a long period [46], leading to an increase in the strength of the soil-cement-RSA mixture during long-term curing.

Figure 17 presents SEM images of soils stabilized with 15% cement (CM-C15-RSA0) and a combination of 15% cement with 15% RSA contents (CM-C15-RSA15) at various curing times. The images reveal that samples treated with both cement and RSA exhibit a noticeably greater density than those stabilized with only cement. This difference becomes increasingly significant as the curing period extends, indicating that the addition of RSA enhances the relative density and structural integrity of the soil over time. Furthermore, at prolonged curing periods of 56 and 90 days, the CM-C15-RSA15 samples display a reduction in porous areas and a considerable increase in C-S-H gels. These microstructural changes are attributed to pozzolanic reactions, which occur when the reactive silica from RSA interacts with the hydration products of the cement. This reaction promoted the development of additional C-S-H gel, which filled the voids and improved the bonding between the soil particles. As a result, the internal structure of the stabilized soil becomes denser and more cohesive, contributing to enhanced mechanical properties, particularly in terms of strength and durability.



a) ST-C15-RSA15



b) ST-C20-RSA15

Fig. 13 SEM images of Soc Trang clay treated with 15% RSA and different cement contents at 28 days of curing

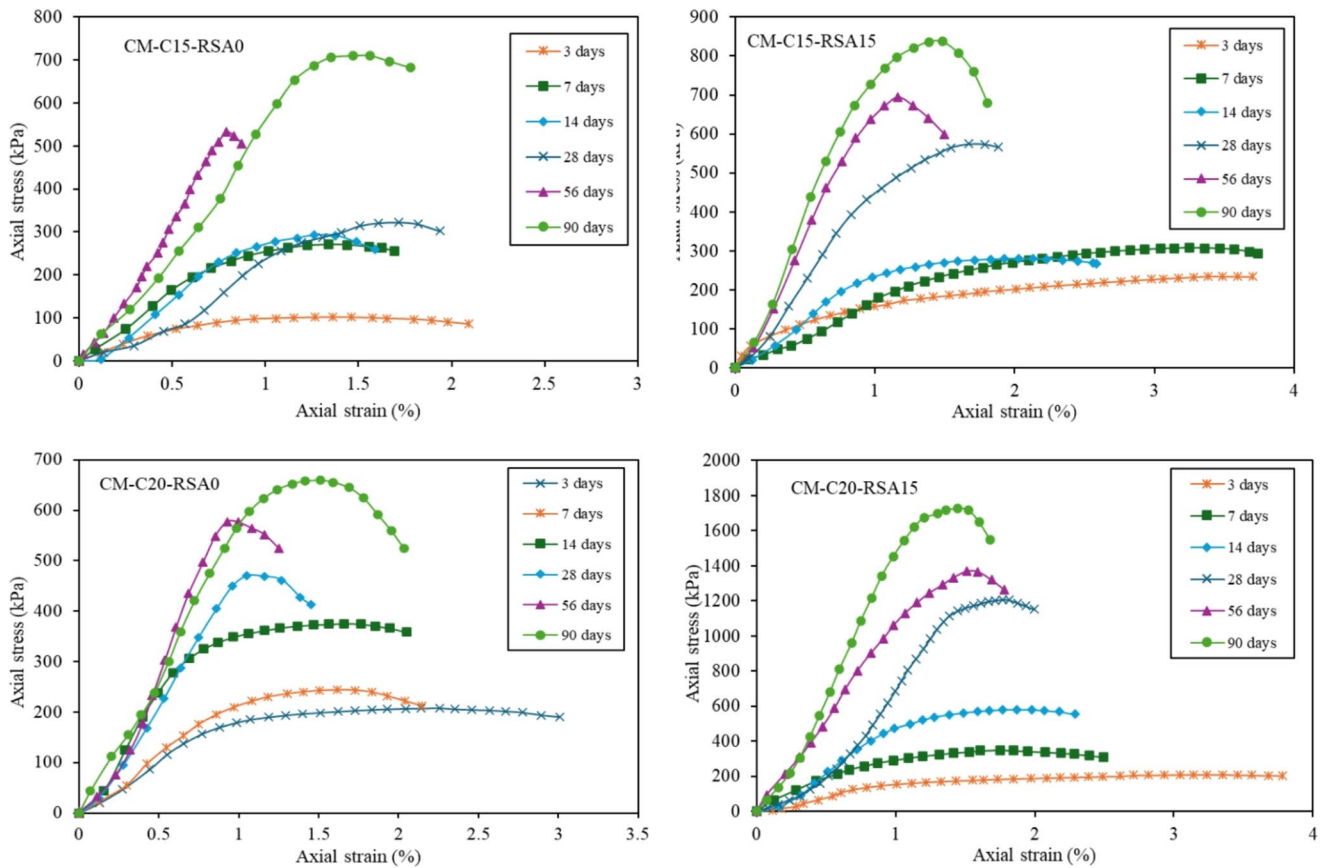
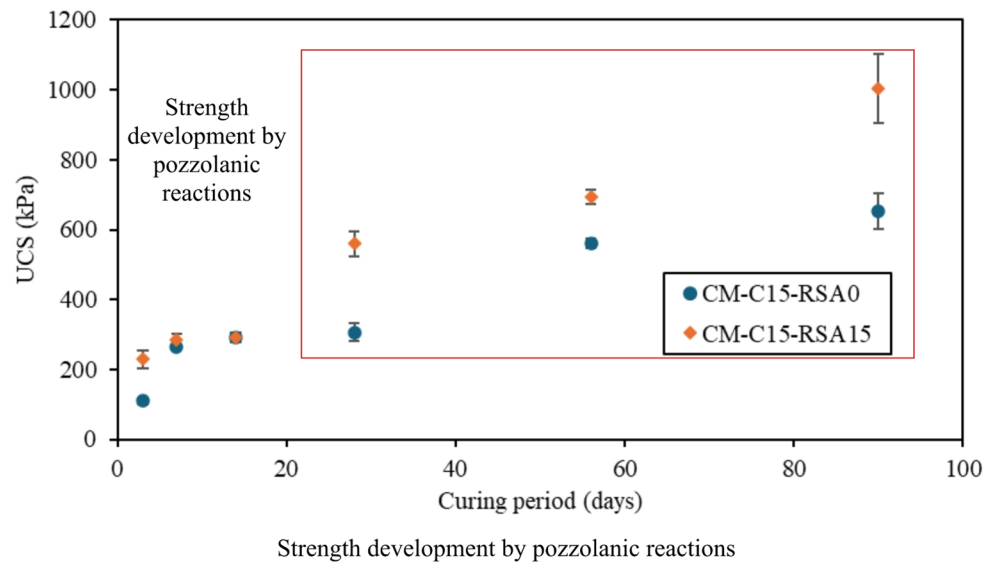


Fig. 14 Stress-strain curve of Ca Mau clay stabilized with cement and optimal RSA contents at different curing days

Fig. 15 Strength development of Ca Mau clay treated with 15% C and 15% C + 15% RSA



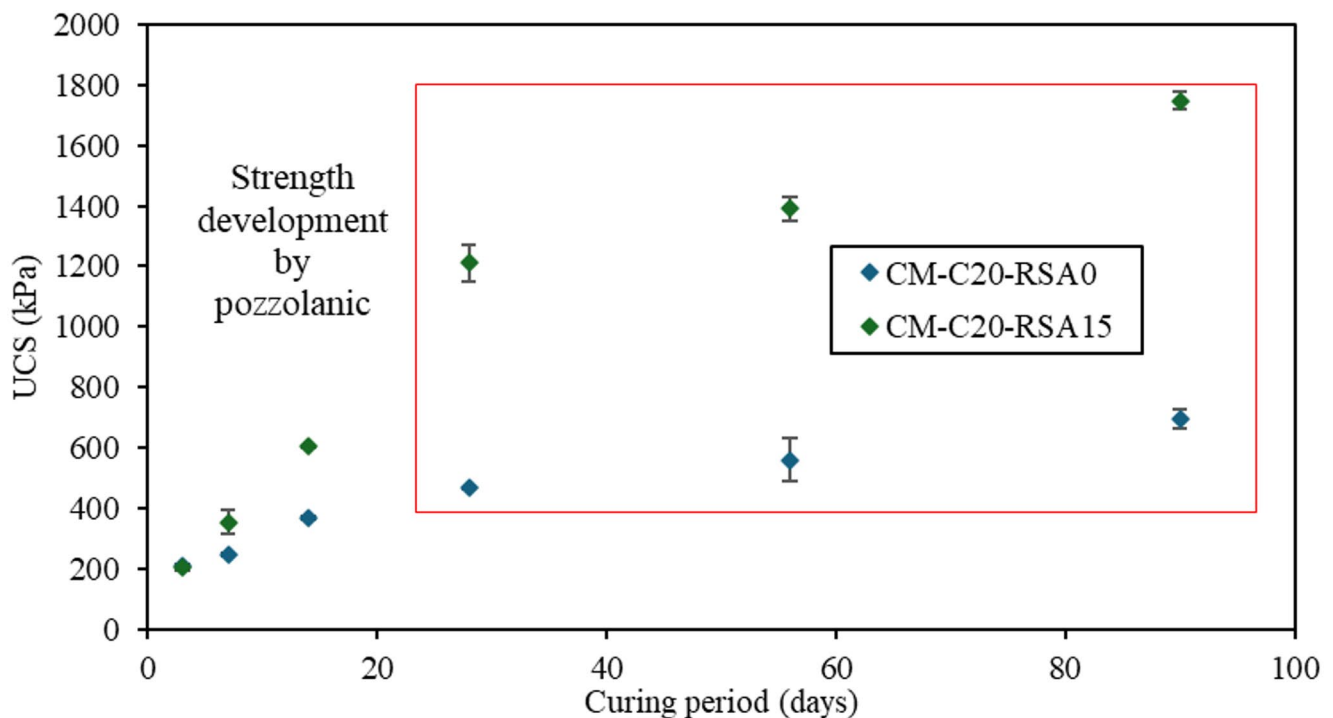


Fig. 16 Strength development of Ca Mau clay treated with 20% C and 20% C + 15% RSA

Potential of cement replacement with RSA

The results indicated that RSA can significantly improve the strength of soil-cement mixtures. Accordingly, the RSA additive can increase the UCS_{28} value of soil-cement mixtures by as much as 4 times in comparison with that of treated soil using cement only. The present study also aimed to explore the potential of cement replacement with RSA for soil stabilization. For that purpose, the weight of the cement (C) used for Ca Mau clay was partially replaced by RSA with the following replacement ratios (%): RSA: C=0:100; 10:90; 20:80; 30:70; 40:60; and 50:50. This means that RSA with a content ranging from 0 to 50% weight of cement was added to the soil mixture, and the unconfined compressive strength at 28 curing days has been analyzed. The total RSA and cement content were 15% and 20%, respectively, of the wet soil weight (RC=15% and 20%, respectively).

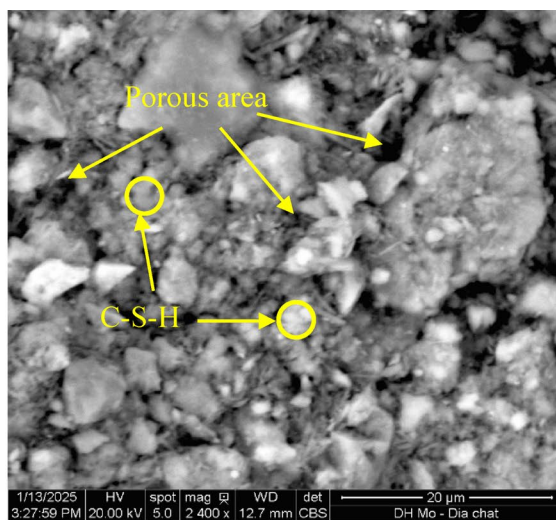
The stress-strain curve of Ca Mau clay stabilized by cement and different cement replacement with RSA at 28 days of curing is depicted in Fig. 18. The results of UCS of the soil-cement mixtures with different ratios of cement replaced with RSA are plotted in Fig. 19. As shown in this figure, when the RSA replacement ratio ranged from 0 to 10%, the UCS_{28} values of the tested samples increased. The highest value of UCS_{28} was obtained in the sample with 10% RSA replacing cement (CM-RC15-RHA10). However, when the RSA replacement ratio increases and exceeds 10%, the UCS_{28} values significantly decrease. This

indicates that the cement content used for the improvement of Ca Mau clay can be partially replaced by 10% RSA. In other words, for the studied soil, the optimum content of RSA for replacing cement is 10%. When the RSA replacement level exceeds the optimum content of 10%, the UCS tends to decrease. This is because, with the total amount of RSA and cement (RSA+C) kept constant, an increase in RSA replacement leads to a corresponding reduction in cement content. Consequently, the higher proportion of RSA and lower cement content may result in an excess of ash, while the amount of $Ca(OH)_2$ released from the hydration of cement compounds becomes insufficient to effectively sustain the pozzolanic reactions. The presence of residual RSA and the incomplete pozzolanic reaction consequently leads to a significant reduction in UCS values.

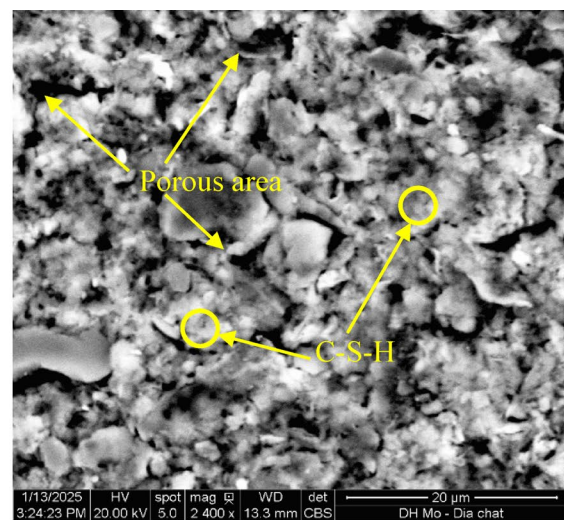
Figure 20 shows the XRD results for the soil-cement mixtures without and with RSA replacement. The results show that with 10% RSA, the peak of quartz decreases from 542.6 cps (CM-RC15-RSA0) to 470.8 cps (CM-RC15-RSA10), and the C-S-H gel is formed instead. This leads to a slight increase in the strength of the soil-cement mixture, as mentioned previously.

Effect of RSA on the elastic modulus of soil-cement mixtures

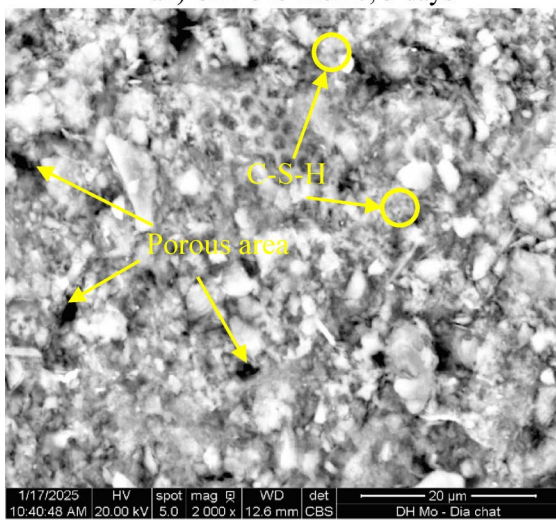
The elastic modulus (E_{50}) is a crucial parameter in the soil-cement deep mixing method. This parameter directly



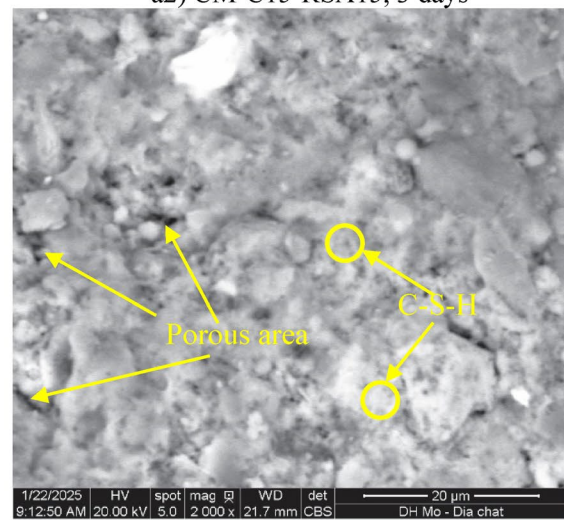
a1) CM-C15-RSA0, 3 days



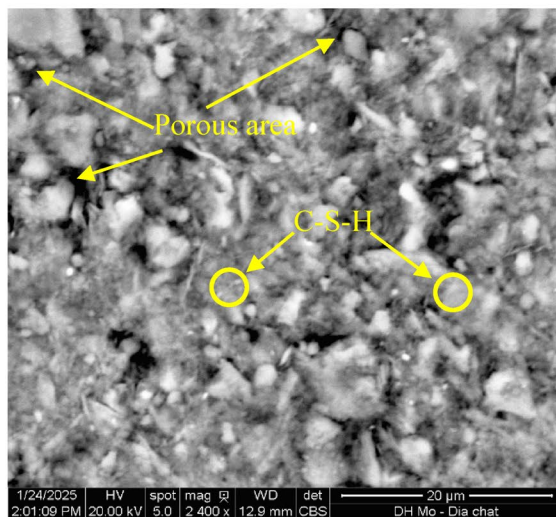
a2) CM-C15-RSA15, 3 days



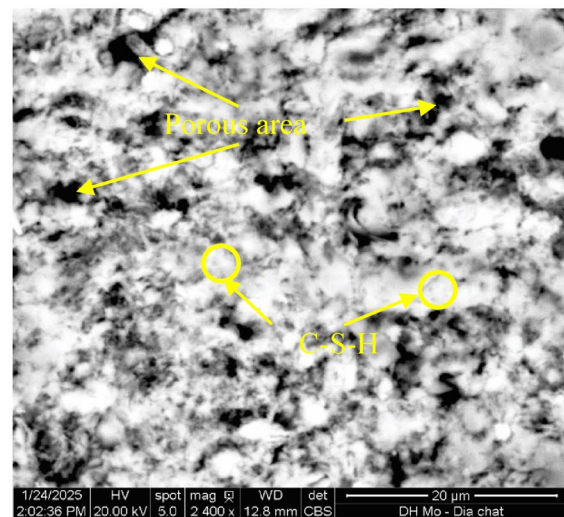
b1) CM-C15-RSA0, 7 days



b2) CM-C15-RSA15, 7 days

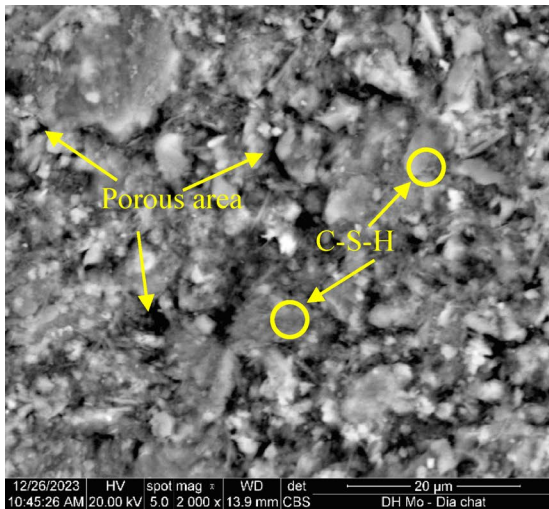


c1) CM-C15-RSA0, 14 days

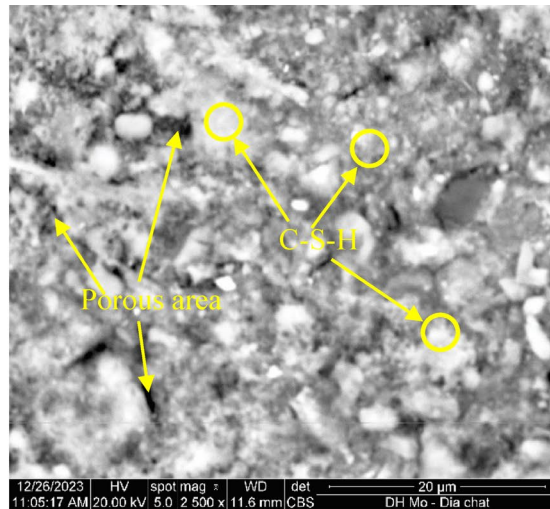


c2) CM-C15-RSA15, 14 days

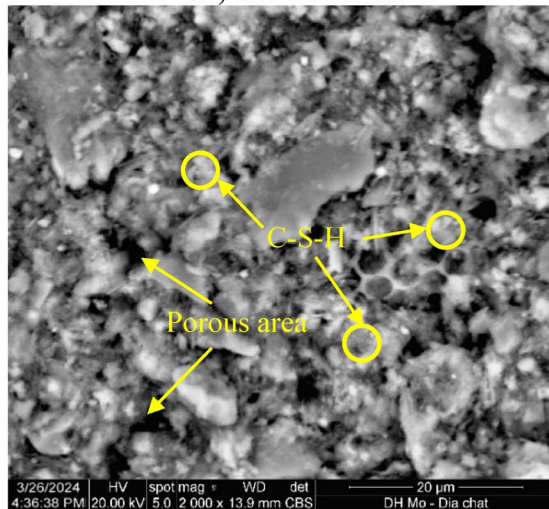
Fig. 17 SEM images of Ca Mau clay treated with 15% C and 15% C+15% RSA for different curing times



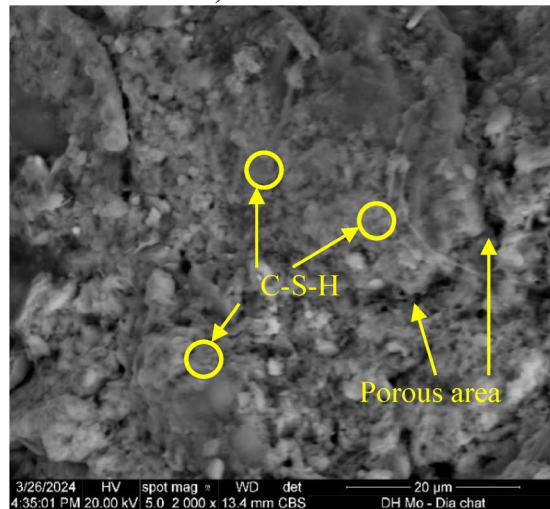
d1) CM-C15-RSA0



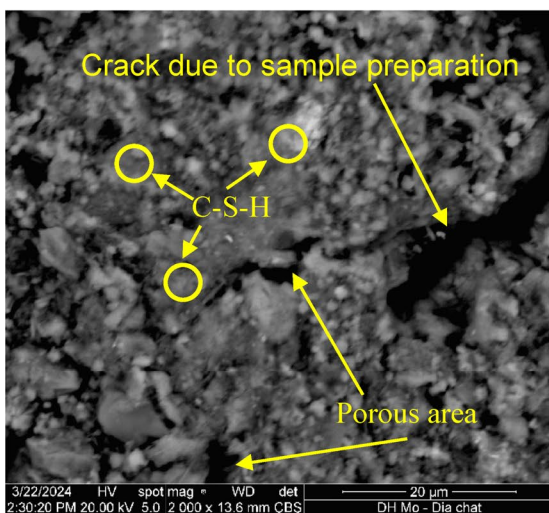
d2) CM-C15-RSA15



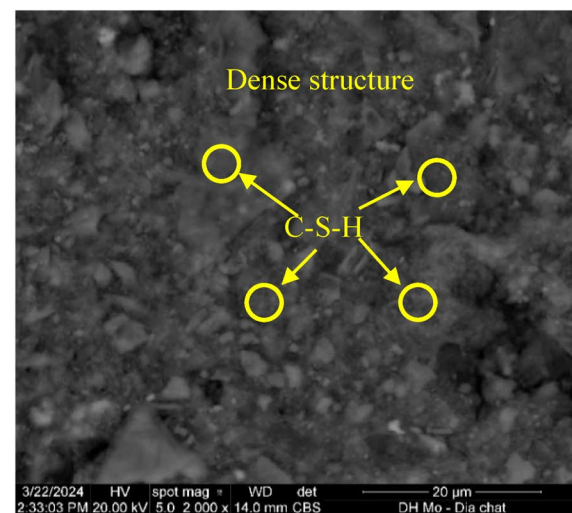
e1) CM-C15-RSA0, 56 days



e2) CM-C15-RSA15, 56 days



f1) CM-C15-RSA0, 90 days



f2) CM-C15-RSA15, 90 days

Fig. 17 (continued)

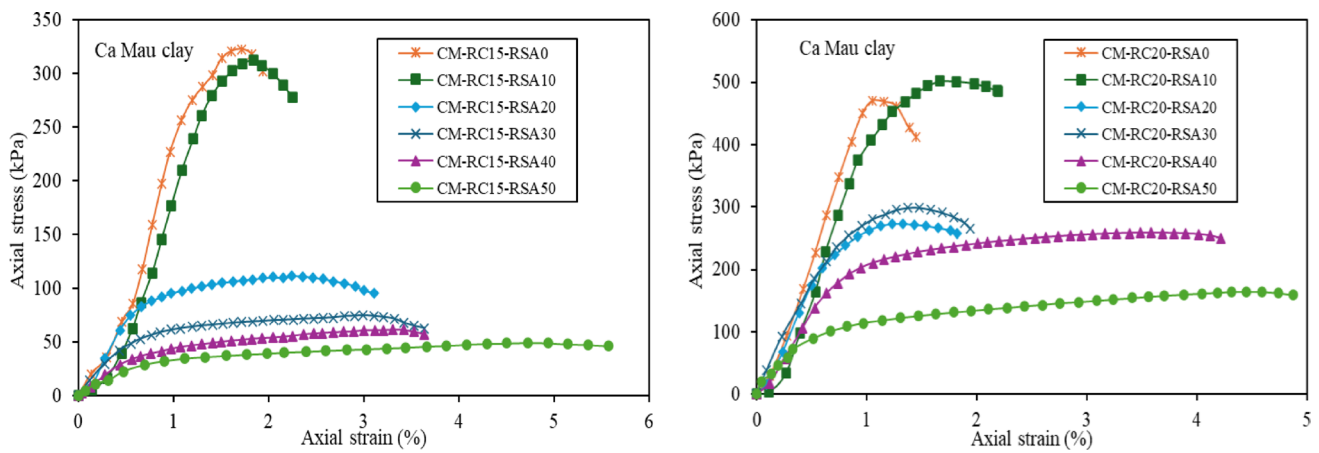


Fig. 18 Stress-strain curve of Ca Mau clay stabilized by cement and different cement replacement with RSA

influences the stiffness, strength, and deformation behavior of improved soil. The present study is the first to explore the incorporation of RSA in the soil-cement deep mixing method. Thus, the effect of RSA on the elastic modulus of soil-cement mixtures will be examined. In this study, the values of E_{50} are determined via unconfined compressive strength tests on the soil-cement-RSA mixtures after 28 days of curing (UCS_{28}). The correlation between the E_{50} and UCS_{28} values of the soil-cement mixtures is presented in Fig. 21. The UCS_{28} values of the cement and RSA-treated soils ranged from 50 to 140, which means that the elastic modulus $E_{50} = (50 \div 140)UCS_{28}$. For soil treated with cement only via the deep mixing method, the results of previous studies revealed that $E_{50} = (30 \div 300)UCS_{28}$ [47], $E_{50} = (350 \div 1000)UCS_{28}$ [48], or $E_{50} = (100 \div 250)UCS_{28}$ [49]. For jet grouting technology, the Japan Jet Grouting Association (1986) reported values of the elastic modulus were $E_{50} = (100 \div 300)UCS_{28}$ [50]. The addition of RSA to the soil-cement mixtures can reduce the E_{50} of stabilized soil. The RSA can considerably affect the stiffness of soil-cement mixtures. For rice husk ash (RHA), the results of previous investigations reported that the correlation between UCS_{28} values and E_{50} falls within the range of values obtained in the present study [40, 51, 52].

Conclusions

This study has investigated the potential application of rice straw ash combined with conventional Portland cement for soft soil stabilization under laboratory conditions. Based on the results of this study, the following conclusions can be drawn:

The laboratory tests indicated that for the examined soil samples, which included Ca Mau clay, Soc Trang clay, and Tra Vinh clay, the addition of RSA to the soil-cement

mixtures significantly enhanced the unconfined compressive strength of the treated soil. The increase in UCS_{28} values of the stabilized soil reached its peak as the RSA content reached the optimal threshold. For cement contents of 15% and 20%, the optimum RSA content, corresponding to the highest UCS values, was 15% for Ca Mau and Soc Trang clay and 20% for Tra Vinh clay. With these optimum RSA contents, the UCS_{28} values of the stabilized soil increased by 2.0 to 4.4 times compared with those of the reference samples containing only cement.

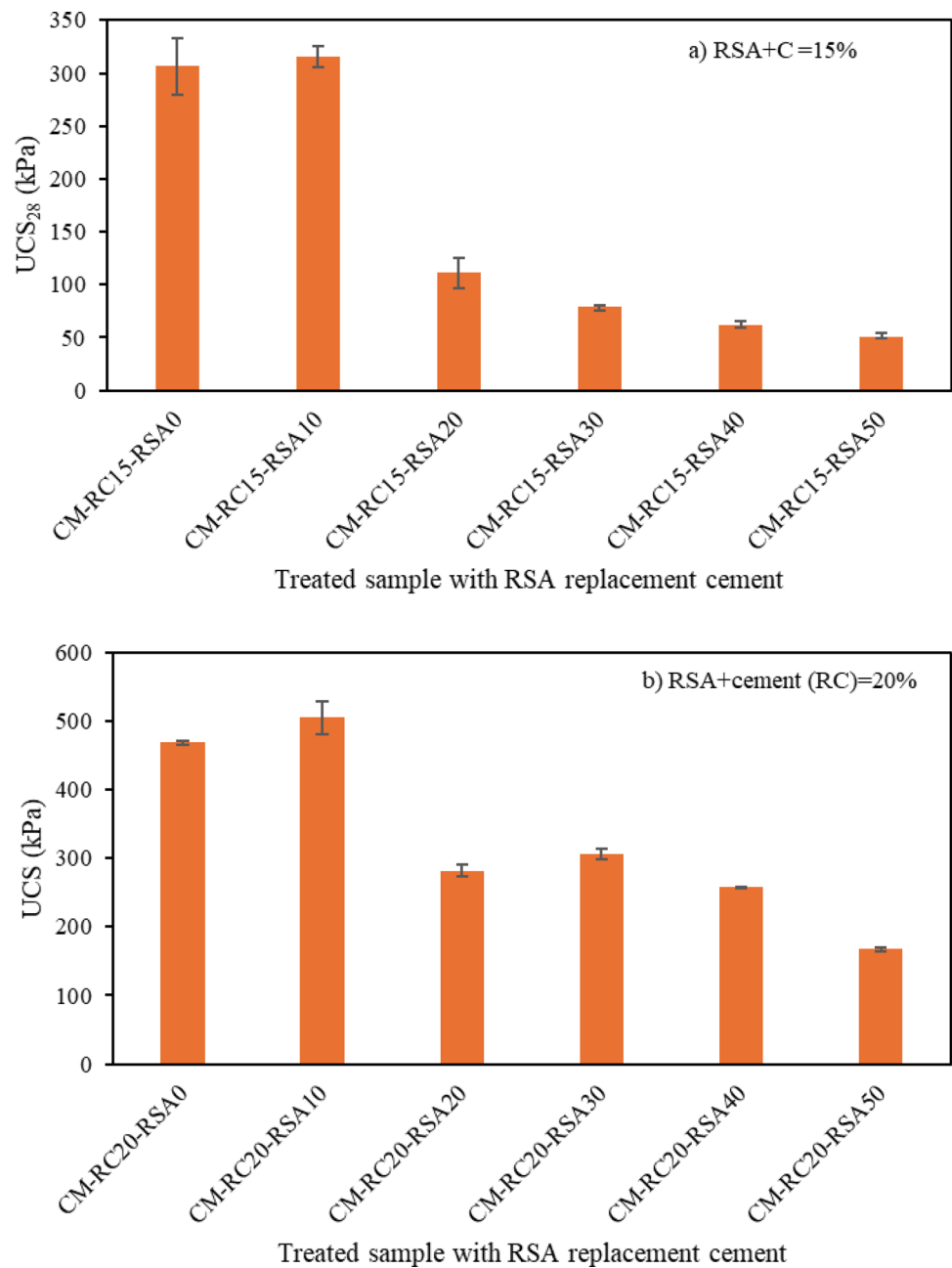
The UCS values of the soil-cement mixtures, with and without RSA, exhibited a noticeable upward trend as the curing time increased. In addition, RSA had a positive effect on the strength development of the soil-cement mixture, particularly during long-term curing. The significant strength gain of the soil-cement-RSA mixtures over extended curing periods was due to the pozzolanic activity of the SiO_2 present in RSA.

In addition to increasing the strength of soil-cement mixtures, RSA can be used to partially replace cement in soil stabilization. The investigation of Ca Mau clay revealed that the cement content can be replaced by 10% RSA.

The inclusion of RSA notably influences the elastic modulus (E_{50}) of soil-cement mixtures, resulting in lower E_{50} values for soils treated with cement and RSA than for those treated with cement alone. In particular, the E_{50} values observed in the tested samples ranged from 50 to 140 times the UCS_{28} .

XRD and SEM image analyses indicate that adding an optimal amount of RSA to soil-cement mixtures enhances C-S-H gel formation, leading to improved soil strength and durability. However, exceeding this optimal level reduces C-S-H formation, increases the residual quartz content, and weakens the soil matrix. XRD analysis confirmed the occurrence of effective pozzolanic reactions, whereas SEM images demonstrated that RSA decreased voids and

Fig. 19 UCS values of the soil-cement mixtures with different RSA contents



increased the relative density. Nevertheless, an excessive amount of RSA disrupts the hydration balance, leading to microcracks and a reduction in UCS. Like RHA, RSA serves as a sustainable soil stabilizer; however, selecting the optimal ratio is crucial for maximizing the performance of the mixture.

The use of rice straw ash in soil stabilization offers a sustainable and cost-effective approach to enhancing soil properties while addressing the challenge of agricultural waste management. Its significance lies in improving soil strength, reducing permeability, and increasing durability, making it a promising alternative to traditional stabilizers. The novelty of RSA application stems from its pozzolanic properties,

which enhance soil bonding and long-term performance, contributing to a more resilient infrastructure. This innovative approach not only reduces the environmental impact but also supports circular economy principles by transforming agricultural waste into valuable construction material.

This research has examined the effect of RSA and the partial replacement of cement with RSA on the compressive strength of soil-cement mixtures and its development over different curing periods under laboratory humid conditions. However, the long-term performance under various environmental conditions, such as freeze-thaw cycles, sulfate attack, and groundwater exposure, has not been evaluated and should therefore be investigated in future studies.

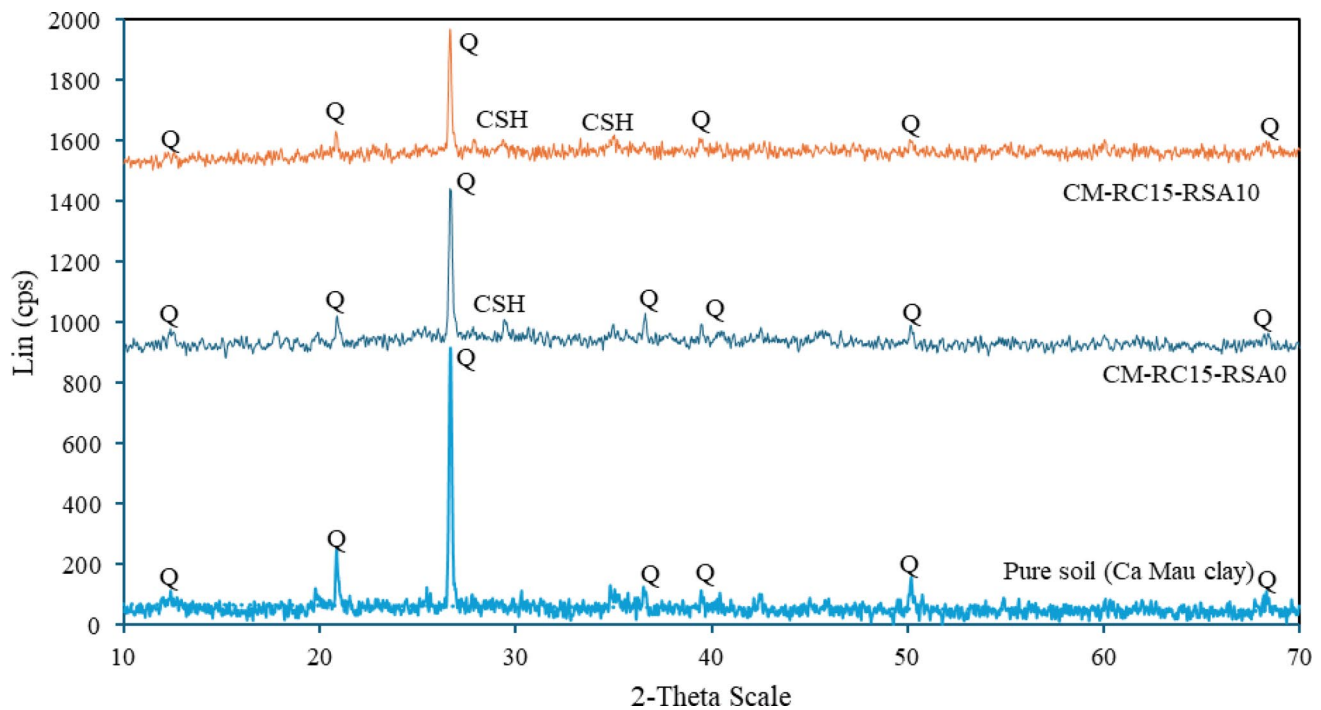
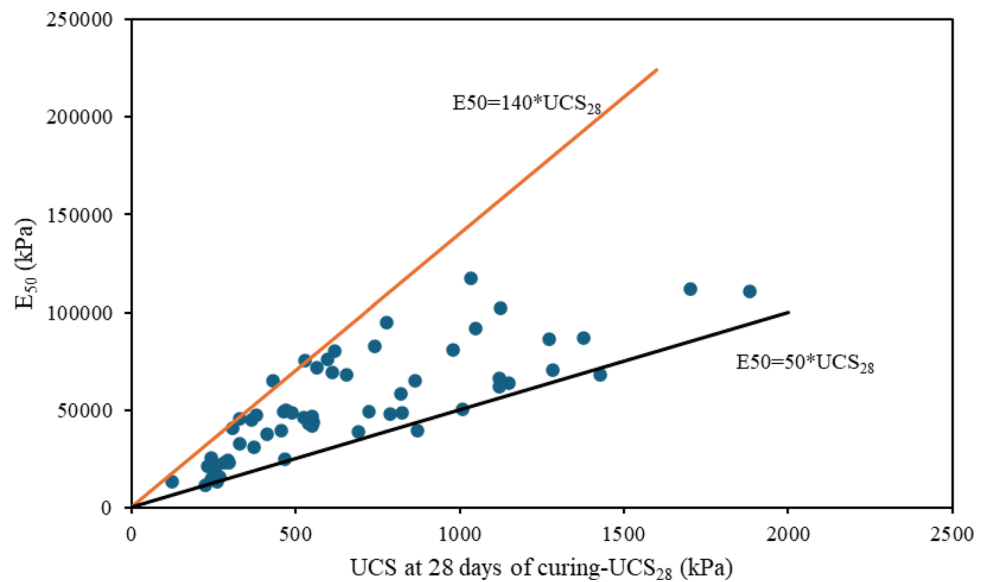


Fig. 20 XRD results for the soil-cement mixtures without and with RSA replacement

Fig. 21 Correlation between the E_{50} and UCS_{28} values of the soil-cement-RSA mixtures



Moreover, further investigations are required to assess the effect of groundwater chemistry and soil mineralogy on the long-term stability and performance of RSA-stabilized soils. Besides, the behavior of the soil–cement–RSA mixture under cyclic and seismic loading should be considered in future research.

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