International Journal of GEOMATE, Dec., 2024 Vol.27, Issue 124, pp.143-150
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.124.g14324
Geotechnique, Construction Materials and Environment

CEMENT STABILIZATION OF DREDGED SEDIMENTS FROM DRAINAGE CANALS: EFFECT ON PHYSICO-CHEMICAL PROPERTIES

*Supakij Nontananandh[1], Nattapas Khumsuprom[2], Thanet Thongdetsri[3], Sukit Youdee[4], Apiniti Jotisankasa[5], Susit Chaiprakaikeow[6] and Shinya Inazumi[7]

[1,2,5,6]Department of Civil Engineering, Kasetsart University, Bangkok, Thailand;
[3]School of Engineering, University of Phayao, Phayao, Thailand;
[4]Royal Irrigation Department, Ministry of Agriculture and Cooperatives, Bangkok, Thailand;
[7]College of Engineering, Shibaura Institute of Technology, Tokyo, Japan

*Corresponding Author, Received: 19 Nov. 2024, Revised: 12 Dec. 2024, Accepted: 18 Dec. 2024

ABSTRACT: Dredged sediments from drainage canals (canal dredged sediment; CDS) encountered significant challenges, particularly in Phetchaburi Province. This research focuses on the properties of CDS when stabilized with ordinary Portland cement (OPC). The sediments, characterized as silty sand with high water content and low compressive strength, were typically unsuitable for construction. In this study, air-dried CDS samples were treated with OPC at varying proportions of 150, 200, and 250 kg/m³, and initial water content of 14.32% and 17.00%, with curing times of 3, 7, 14, and 28 days. The investigation primarily centered on assessing the strength development using the unconfined compression test and evaluating the physico-chemical properties of cement-stabilized CDS through shear wave velocity (V_s) and suction tests. The findings revealed that the unconfined compressive strength (UCS) of the successful mixtures at 7 days of curing exceeded 689 kPa, indicating suitability for application as a subbase material. Moreover, the UCS consistently increased with the appropriate water-to-cement ratio and prolonged curing time, aligning with the trends observed in V_s measurements. A correlation between UCS and V_s tests is proposed based on the observed relationship. Furthermore, the suction tests revealed that the water content of cement-stabilized sediments was lower compared to natural soil, resulting in reduced volume strain changes upon mixing with cement. This underscores the potential of cement stabilization in enhancing the engineering utility of CDS, thereby supporting a sustainable waste management approach based on geo-environmental engineering practices.

Keywords: Sediments, Cement, Unconfined compressive strength, Shear wave velocity, Suction

1. INTRODUCTION

Due to economic expansion and population growth in Thailand, the Royal Irrigation Department has undertaken the construction of hydraulic structures to support the country’s development. These structures include dams, reservoirs, and irrigation and drainage canals, which store and distribute water for public consumption, agriculture, and flood mitigation during the rainy season. However, various factors, such as environmental conditions and terrain characteristics, have led to the accumulation of significant amounts of sediment. These sediments cause multiple problems such as water quality, water management, agricultural activities, the efficiency of hydraulic structures, and storage capacity [1].

Phetchaburi province, located 176 kilometers from Bangkok, faces significant sediment management challenges in its reservoirs and canals. The province receives an average annual rainfall of 1,100 millimeters and relies on three main reservoirs: Kaeng Krachan reservoir (710 million cubic meters), Huai Mae Prachan Reservoir (42.20 million cubic meters), and Huai Phak Reservoir (27.50 million cubic meters). These reservoirs supply water to 4 main irrigation canals (total length 98,446 kilometers) and 41 minor irrigation canals (total length 313 kilometers) and drain water into 28 drainage canals (total length 426 kilometers) [2], which eventually release water into the sea. Sediment particles carried by the water accumulate in the drainage canals, obstructing water flow as illustrated in Fig. 1. Consequently, dredging plans for these canals are necessary to enhance water discharge efficiency. The quantity of sediment and dredging costs from 2018 to 2022 are presented in Table 1. This requires substantial annual budget allocations for dredging, and currently, there is no strategy for managing the dredged sediment, which is often left along canal banks. This causes road narrowing and deterioration, with rainfall washing sediment back into canals [3-4].

Therefore, there is a proposal to improve the quality of the dredged sediment for use as construction material, following the concept of geo-environmental engineering [5-6]. The NICE criteria were used in selecting the materials (where N = non-hazardous, I = improvability, C = consistency, and E

= economic) [7]. Additionally, dredged sediment can potentially be used as subbase or base material for road pavement [8-11].

Fig. 1 Sediments in drainage canal

Table 1 The quantity of sediments and the budget

Years	Quantity of sediments (m^3)	Dredging budget (USD)
2018	640,000	402,695
2019	900,000	584,512
2020	555,700	348,028
2021	117,000	120,946
2022	478,000	367,126

Stabilization of soft soils and dredged sediments by chemical methods involves improving their physical and engineering properties by mixing cementitious substances with an appropriate water-to-cement ratio [12-13]. The increased shear strength of soil resulted from chemical reactions among soil particles, cementitious substances, and water. This is confirmed by the quantities of reactants and products formed, as determined through X-ray diffraction analysis. Ordinary Portland cement (OPC) and quicklime or hydrate lime are commonly used stabilizers. Additionally, a wider variety of binders is now used, including synthetic cement produced from waste, geopolymer from fly ash, and cementing agents from industrial by-products [14-17].

In a previous study, the free-free resonance (FFR) test was employed to investigate the properties of stabilized sediment. This non-destructive geophysical testing method has gained widespread popularity due to its rapid execution, applicability to various dimensions of samples [18-20]. Additionally, the relationship between compressive strength and shear wave velocity (V_s) can be used to develop predictive equations for the material’s strength.

In addition, the rate of decrease in water content is relatively large during the early hydration and tends to decrease with increasing of curing time. Our previous studies revealed that the relative humidity in various incubation conditions was inversely proportional to the rate of water reduction. The analysis of suction indicated that the soil water retention curves (SWRCs) could predict the behavior of the cement-stabilized soils which were more resistant to changes in the environment than natural soil. [21-23].

The objective of this study is to stabilize the sediments dredged from the drainage canals in Phetchaburi Province using OPC and examine factors affecting UCS development of cement-stabilized soils and the quantity analysis of reaction products resulting from the cement hydration using XRD. The physico-chemical properties of the cement-stabilized soils were investigated through soil suction test to determine SWRCs for study their properties and using FFR test to determine the correlations between UCS and shear wave velocity which can use V_s for predict their strength.

2. RESEARCH SIGNIFICANCE

The use of dredged sediments, which is natural waste is an efficient method to solve the problems of sediments management. This study introduces the properties of CDS stabilized with OPC including UCS, V_s, G_0 and suction. The finding is significant as it demonstrated that the cement-stabilized CDS could be used as construction materials due to their strength that meeting the criteria and can use V_s to predict their strength from the correlation.

3. MATERIALS

The research examines the use of natural waste, known as dredged sediments from drainage canals (canal dredged sediment; CDS). The sediments were collected from the area along the drainage canal from kilometer 2+500 to 3+000. Based on the basic properties test as illustrated in Table 2, it reveals that the specific gravity is 2.67. The natural water content is 117%, which is the water content of natural sediments within the canal. After dredging, the sediments are stored in the dumping areas along the side of the canal and being left air-dried for approximately 3 - 6 months.

In this study, the water content at the time of sampling is 5 - 10%. CDS were classified as silty sand (SM) with non-plastic, according to the unified soil classification system (USCS) and were categorized as A-4 (0) under the AASHTO classification system, which is suitable for use as construction material at low to medium levels. Additionally, the soil exhibits maximum dry density from the standard compaction test at 17.26 kN/m^3, and optimum water content of 14.32%. When using this water content for compaction and conducting soil compression tests, the soil demonstrated a compressive strength of 49.03 kPa (Control value).

Table 2 Basic properties of CDS

Properties	CDS [2]
Specific gravity	2.67
Natural water content (%)	117
Liquid limit (%)	N.P.
Plastic limit (%)	N.P.
Plastic index (%)	N.P.
Gravel (%)	0.71
Sand (%)	51.94
Silt (%)	28.46
Clay (%)	18.90
Soil classification (USCS*)	SM
Soil classification (AASHTO**)	A-4 (0)
Maximum dry density (kN/m^3)	17.60
Optimum water content (%)	14.32

**Unified Soil Classification System*
***American Association of State Highway and Transportation*

The chemical compositions of the dredging sediment from the drainage canal were tested by using X-ray fluorescence (XRF) analysis. The result shown in Table 3, reveals that the main components of the CDS are 79.61% of Silicon Dioxide (SiO_2), 10.33% of Aluminium Oxide (Al_2O_3) and 3.80% of Iron (III) oxide (Fe_2O_3) [2]. In addition, a small amount of chloride salt (Cl) is found, which is consistent with the influence of sea water entering the drainage canal.

The heavy metal testing for material toxicity analysis, using Atomic Absorption (AA) method, on the CDS as illustrated in Table 4. It was found that this sediment has low heavy metal content, which meets the standard criteria set by the Department of Pollution Control [25]. Therefore, it can be concluded that the material is non-toxic to the environment and humans, which aligns with the guidelines for material selection for waste utilization (NICE Criteria) in this research.

Table 3 Chemical compositions

Oxide Component	CDS [2]
SiO_2	79.61
Al_2O_3	10.33
Fe_2O_3	3.80
K_2O	2.20
CaO	0.84
MgO	1.30
P_2O_5	0.18
TiO_2	0.56
SO_3	0.91
MnO	0.24
Na_2O	-
LOI	-
Cl	0.004

Table 4 Heavy metal test by AA method

Elemental metals	Standard [25] (mg/kg)	CDS [4] (mg/kg)
Cr (VI)	500	ND
Cr (III)	2500	ND
Sb	500	ND
As	500	6.99
Ba	10,000	ND
Be	75	ND
Cd	100	ND
Cr	2,500	31.7
Co	8,000	ND
Cu	2,500	7.33
Pb	1,000	N/A
Hg	20	0.017
Mo	3,500	ND

4. METHODOLOGY

4.1 Specimen Preparation for UCS Test

Based on the previous research [24], the initial water content was identified as a significant factor affecting the UCS of soil cement. In addition, the samples mixed with the optimum water content exhibited higher UCS than those mixed with a water content exceeding 100% and even when a smaller amount of cement was used. The air-dried CDS were adjusted the initial water content before mixing to 14.32%, which was the optimum water content. The moist soils were thoroughly mixed with OPC in a Hobart mixer with the proportions of 150, 200, and 250 kg/m³ by dry weight. From each mixture specimens with a diameter of 50 mm and a height of 100 mm were made for UCS test, producing six samples per batch. After molding, the specimens were sealed tightly in plastic sheets and cured at room temperature for 3, 7, 14, and 28 days as illustrated in Fig. 2 (a).

To enhance the workability and ensure uniformity of the mixture, another similar set of specimens was prepared using the initial water content of 17.00%. All mixing proportions and symbols are shown in Table 5

Table 5 Mix proportions and symbols

Symbol	Initial water content (%)	Cement content (kg/m^3)	w/c ratio
CSC1	14.32	150	1.68
CSC2	14.32	200	1.26
CSC3	14.32	250	1.01
CSC4	17.00	150	1.99
CSC5	17.00	200	1.50
CSC6	17.00	250	1.20

After the completion of curing, unconfined compression tests were conducted on three samples per curing age according to [25] as illustrated in Fig. 2 (b). The samples were tested using an automatic universal testing machine (UTM) until failure, under a strain rate of 0.01 min^{-1}. The UCS was recorded as either the compressive stress at peak or the at 15% axial strain whichever is smaller.

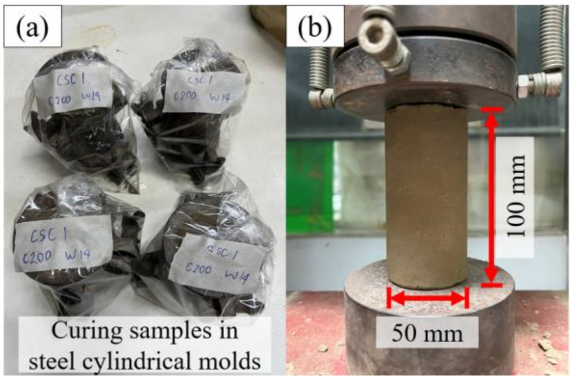

Fig. 2 (a) Specimen preparation (b) Unconfined compression test

4.2 Free-Free resonance (FFR) Test

FFR test, a simple non-destructive laboratory test has been employed for many years to determine the small-strain stiffness and V_s of soil cement. In this study, after the completion of curing, three samples (the same samples used for UCS testing) were tested in transverse motion as illustrated in Fig. 3. Waves were generated by a small hammer at one end and recorded by an accelerometer attached to the other end. The measured peak amplitude was considered as the resonant frequency of the sample. Hence, V_s and G_0 can be calculated with the following equation.

$$V_s = f\lambda = 2fL \quad (1)$$

$$G_0 = \rho (V_s)^2 \quad (2)$$

where f is resonant frequency, λ is wavelength, L is length of sample and ρ is density of sample.

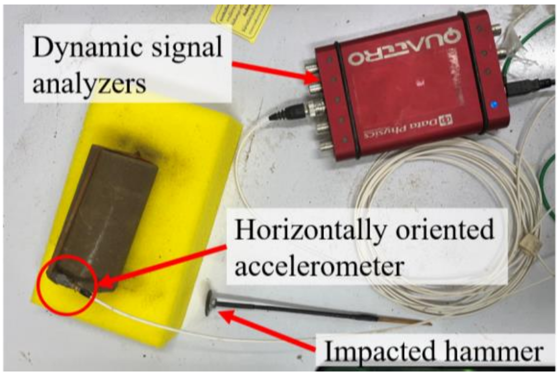

Fig. 3 Free-Free resonance test

4.3 Soil-Water Retention Curves (SWRCs) Test

To establish the soil water retention curves (SWRCs) for a comprehensive understanding of the properties of the CDS, a suction test was conducted using a KU-tensiometer within the suction range of 0 to 90 kPa. Additionally, other specimens were prepared under the same conditions as the UCS test samples and trimmed to a thickness of 1 cm, with two specimens prepared for each of CDS, CSC1, and CSC4. These specimens will be tested using the isotropic humidity control technique, which can measure suction in the range of 4,000 to 400,000 kPa.

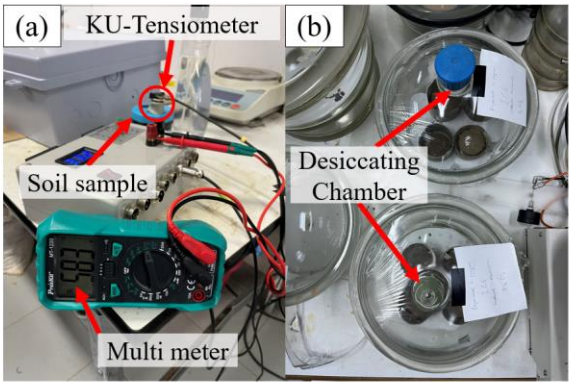

Fig. 4 (a) KU-Tensiometer (b) Isopiestic technique

5. RESULTS AND DISCUSSIONS

5.1 Unconfined Compressive Strength (UCS)

After mixing CDS with cement, it was found that the UCS of the sediment significantly increased with curing time as illustrated in Fig. 5 and Fig. 6. CSC6 is the mix proportion with the highest strength. At early curing time (7 days), average UCS was 3,403.7% higher than CDS, and up to 5,788.8% at intermediate curing time (28 days). Additionally, the increase in cement content and the optimal initial water content were also key factors influencing the reaction in cement-stabilized sediments and strength development, as illustrated in Fig. 7 and Fig. 8.

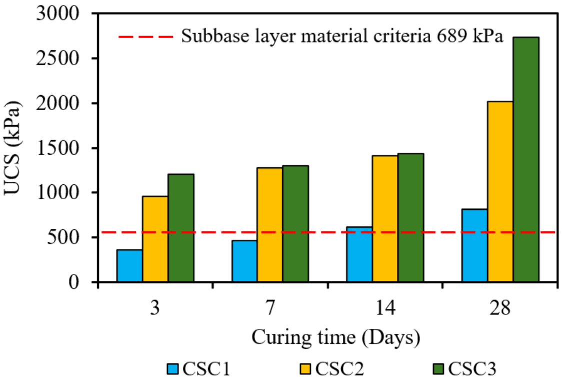

Fig. 5 UCS versus curing time (w_i = 14.32%)

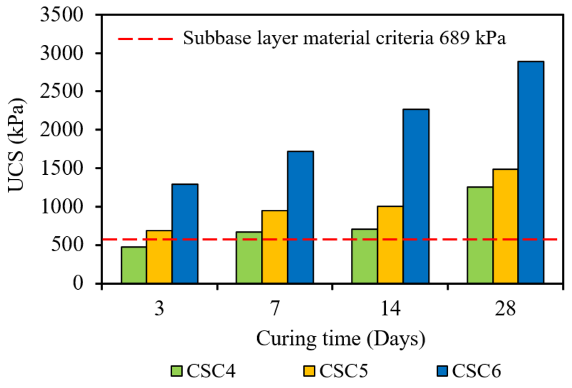

Fig. 6 UCS versus curing time (w_i = 17.00%)

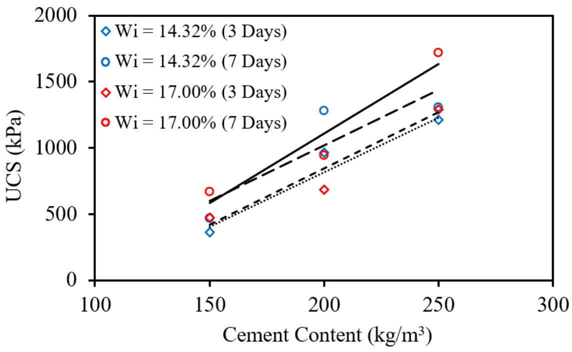

Fig. 7 UCS versus cement content (3-7 Days)

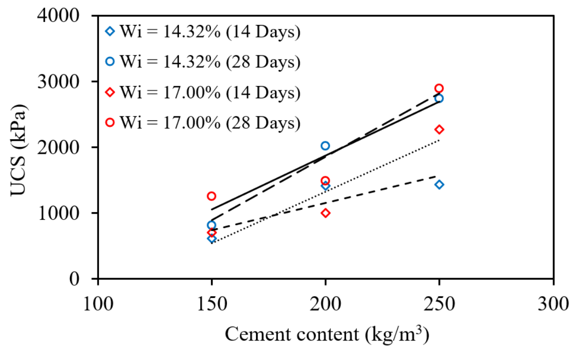

Fig. 8 UCS versus cement content (14-28 Days)

When comparing CSC2 and CSC3 with an initial water content of 14.32% (optimal from the standard compaction test), their strengths were similar at 7 days, with values of 1,282 kPa and 1,306 kPa, respectively. However, at 28 days, UCS of CSC3 was significantly higher (2,020 kPa vs. 2,739 kPa). Additionally, CSC3 and CSC6, which both had a cement content of 250 kg/m^3 but different water contents (14.32% and 17.00%, respectively), showed that CSC6 had higher strength throughout the curing time. For example, UCS of CSC3 and CSC6 at curing time of 7 and 28 days were 1,306 and 2,739 kPa and 1,718 and 2,887 kPa, respectively. This can be attributed to the higher initial water content of CSC6, which was suitable and sufficient for the reaction. However, a higher initial water content does not always indicate greater strength. When comparing CSC2 and CSC5, which both had a cement content of 200 kg/m^3 and water contents of 14.32% and 17.00%, CSC2 exhibited higher strength at all curing times.

When cement is mixed with CDS, the hydration reaction significantly affects the stress-strain characteristics by increasing stiffness and reducing ductility. Notably, the strain at failure (ε_f) of the cement-stabilized CDS decreases considerably. For example, compared to the control, which had an average ε_f of 4.5%, CSC3 at 28 days of curing exhibited a peak strain of only 1.45%, representing a reduction of approximately 68%. This indicates a notable stiffening effect due to cement stabilization.

Fig. 9 shows the water content over 0-28 days, with a rapid decrease in the first 0-3 days and a slower decrease from 7-28 days. This indicates that the rate of water reduction is initially high and decreases over time, corresponding to reaction rate. When analyzing the relationship between the UCS and the water-to-cement (w/c) ratio, it was found that for all mixing proportions and curing periods, UCS increases as the w/c ratio decreases, as illustrated in Fig. 10. Similarly, when comparing CSC2 and CSC6, which have similar w/c ratios (1.26 and 1.20 respectively), it was found that the UCS of CSC6 was significantly higher than that of CSC2 at all curing times.

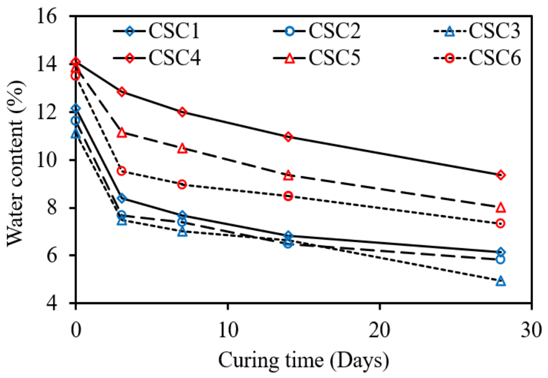

Fig. 9 Water content versus curing time

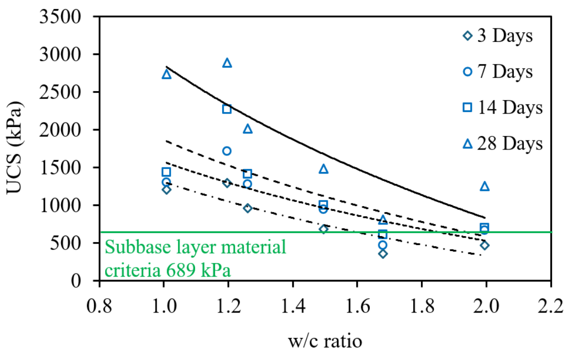

Fig. 10 UCS versus w/c ratio

The Department of Highways has set a standard for soil-cement subbase layers in roads construction, requiring a minimum UCS of 689 kPa at curing time of 7 days. This study used this criterion to determine suitable mixing proportions and found that an appropriate mix ratio should have a w/c ratio ranging from 1.00 to 1.50. In addition, not only cement content, but initial water content was also identified as a critical factor affecting strength development. For cement-stabilized sediment, a w/c ratio in the range of 1.20-1.26 ensures homogeneity of the mixture and significantly enhances the efficiency of chemical reactions, leading to strength development.

5.2 Shear Wave Velocity and Shear Modulus

The results of the FFR test on cement-stabilized CDS indicate a significant increase in shear wave velocity (V_s) and shear modulus (G_0) with an increase in unconfined compressive strength, as illustrated in Fig. 11 and Fig. 12. These figures demonstrate the increased stiffness of the improved soil. Equations for predicting UCS from the FFR test, which is a non-destructive testing method, can be derived as illustrated in Eq. (3) and Eq. (4). The R-squared values for these equations are 0.8424 and 0.8441, respectively.

$$UCS = 0.0011(V_s)^{2.2648} \quad (3)$$

$$UCS = 1.2556(G_0)^{1.1518} \quad (4)$$

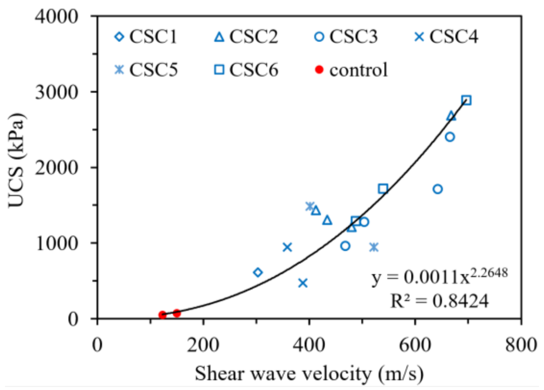

Fig. 11 UCS versus shear wave velocity

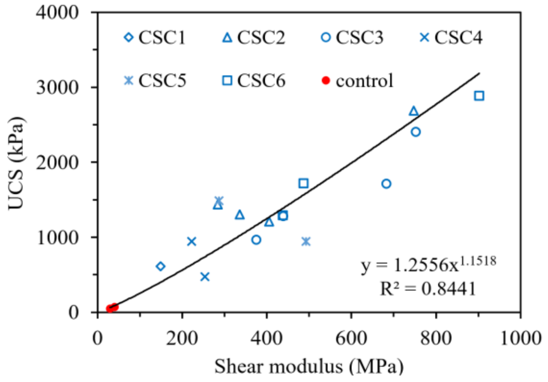

Fig. 12 UCS versus shear modulus

5.3 X-ray diffraction analysis

The physico-chemical properties of CDS and CSC6 were tested using an X-ray diffractometer. The results revealed that the main mineral component of CDS is Quartz (PDF 05-0490) and various types of clay minerals identified as secondary components, including Montmorillonite (PDF 03-0010), Illite (PDF 43-0686) and Kaolinite (PDF 05-0143) as illustrated in Fig. 13. The mineral components contribute to the differing behaviors of the soil, particularly the quantity of clay minerals. However, it was found that the amount of clay mineral is relatively low, consistent with the soil classification results.

Additionally, Fig. 13 also shows the chemical components of CSC6, which has the highest UCS. A substantial amount of C_3S (PDF 42-0551) is observed during the early stages of curing (3-7 days). As the curing period extends to 14 and 28 days, the quantity of C_3S decreases, which is attributed to its transformation into primary chemical reaction products, namely CSH (PDF 00-012-0739) and Ettringite (PDF 04-013-3691).

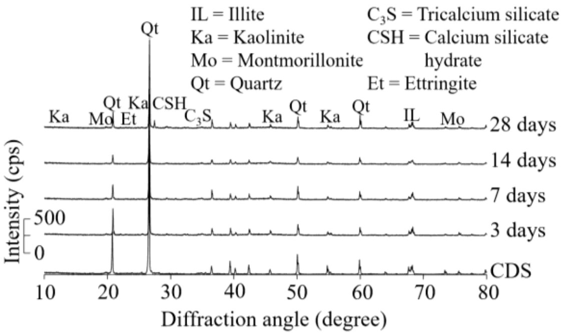

Fig. 13 XRD pattern of CDS and CSC6

5.4 Suction Characteristics

The suction characteristics of CDS were compared with CSC1 and CSC4 at a curing time of 14 days, as illustrated in Fig. 14. CDS within a suction range of 0-14,012 kPa has the gravimetric water content ranged from 7.51% to 19.48%. In contrast, CSC1 and CSC4 exhibited gravimetric water content values of 4.66% - 19.00% and 6.50% - 20.27% at the same suction range. The lower water content indicates a change in the cement-stabilized CDS, which is attributed to water consumption during the reaction and the formation of CSH that adhere to soil particles. This observation is consistent with the UCS results and water content at various curing times.

Additionally, this relationship can be used to analyze the correlation between volumetric strain and suction, as illustrated in Fig. 15. The figure demonstrates that, under varying moisture conditions, the volumetric strain of CDS changes by -7.43%. In contrast, the volumetric strain changes of cement-stabilized sediments by -6.23% and -6.94% for CSC1 and CSC4, respectively. This indicates that mixing sediments with OPC reduces the change in volumetric strain.

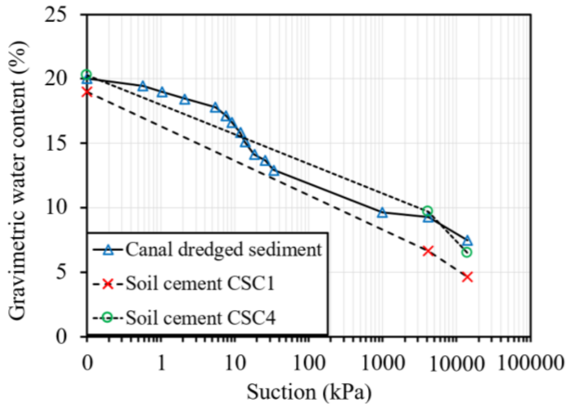

Fig. 14 Soil-water retention curves of untreated and cement-stabilized sediments

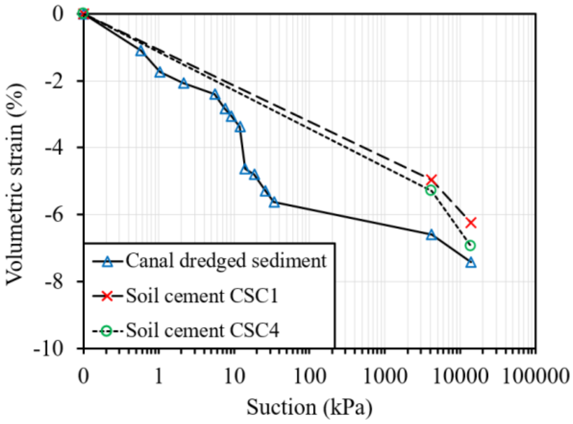

Fig. 15 Volumetric strain versus suction

It is true that the physical properties of CDS will change from time to time. It may not be possible to eliminate this problem, however, the quality of cement-stabilized material can be controlled by strictly checking the chemical compositions, particularly those of the main oxides of CDS collected from different periods, in order to evaluate eventual behavior. This study explores the feasibility of utilizing CDS in a laboratory setting. In addition, future research should focus on additional aspects, such as the durability of the material and the performance of cement-stabilized CDS, to ensure its practical application in engineering projects.

6. CONCLUSIONS

This study explores the potential of utilizing CDS for construction purposes. Based on the experimental results, conclusions can be drawn.

1. Cement stabilization significantly enhances the strength of CDS, achieving a UCS of 1,718 kPa after 7 days, meeting the criteria for use as a subbase layer material. However, the gradation falls short of standards, requiring future research on mix adjustments.
2. Strength development depends on initial water content, cement content, and the w/c ratio. Optimal conditions are 14.32 and 17.00% water content and a w/c ratio of 1.0 - 1.5.
3. The development of UCS correlates with increases in V_s and G_0, indicating that cement stabilization enhances the stiffness of sediment. Furthermore, this relationship can be used to predict the strength of cement-stabilized sediment from V_s.
4. Cement-stabilized CDS exhibits reduced water content, consistent with moisture measurements from UCS tests. The suction-volumetric strain relationship indicates that OPC reduced volumetric changes.

7. ACKNOWLEDGMENTS

The authors would like to acknowledge the Faculty of Engineering, Kasetsart University, for partially funding this research and express their gratitude to the Royal Irrigation Department, Ministry of Agriculture, and Cooperatives, for using dredged sediments from drainage canals. Moreover, the authors would like to thank the Department of Civil Engineering, Faculty of Engineering, Kasetsart University, for providing access to the Dynamic signal analyzers and KU-Tensiometer. Their contributions have helped to achieve the objectives of this research.

8. REFERENCES

[1] Royal Irrigation Department, Project of sediment accumulation impacting the capacity of reservoirs: A case study of Huai Mae Prachan Reservoir at Nong Ya Plong District Phetchaburi Province. Phetchaburi, Thailand, 2014.

[2] Youdee S., Nontananandh S., Khumsuprom N., and Thongdetsri T., Improvement of Sediment Dredged from Drainage Canal Using Cement. The 11th Nontri E-san National Academy Conference, Sakonnakhon, Thailand, 2023, pp. 472-482.

[3] Royal Irrigation Department, Project Budget Report Year 2018 - 2022. Phetchaburi Operation and Maintenance Project, 2023, Bangkok.

[4] Thongdetsri T., Nontananandh S., Khumsuprom N., Youdee S., Jotisankasa A., and Inazumi S., Influence of Initial Water Content and Water-to-Cement-Ratio on the Strength and Suction Characteristics of Cement-Stabilized Sediments from Drainage Canal. Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol. 55, Issue 2, 2024, pp. 1-9.

[5] Julphunthong P., Thongdetsri T., and Chompoorat

T., Stabilization of Soft Bangkok Clay Using Portland Cement and Calcium Sulfoaluminate-Belite Cement. Key Engineering Materials, Vol. 775, 2018, pp. 582-588.

[6] Sani Y. H., and Eisazadeh A., Influence of Coir Fiber on the Strength and Permeability Characteristics of Bottom Ash-and Lime-stabilized Laterite Soil. International Journal of Geosynthetics and Ground Engineering, Vol. 9, Issue 5, 2023, pp. 63.

[7] Kamon M., Nontananandh S., and Tomohisa S., Environmental Geotechnology for Potential Waste Utilization. Proceedings of the 9th Asian Regional Conference on Soil Mechanics and Foundation Engineering, 1991, pp. 397-400.

[8] Bhurtel A., and Eisazadeh A., Strength and Durability of Bottom Ash and Lime Stabilized Bangkok Clay. KSCE Journal of Civil Engineering, Vol. 24, Issue 2, 2020, pp. 404-411.

[9] Phai H., and Eisazadeh A., Geotechnical Properties of Rice Husk Ash-lime-stabilised Bangkok Clay. Journal of Engineering Science and Technology, Vol. 15, Issue 1, 2020, pp. 198-215.

[10] Yoobanpot N., Jamsawang P., Simarat P., Jongpradist P., and Likitlersuang S., Sustainable Reuse of Dredged Sediments as Pavement Materials by Cement and Fly Ash Stabilization. Journal of Soils and Sediments, Vol. 20, 2020, pp. 3807-3823.

[11] Chompoorat T., Thepumong T., Taesinlapachai S., and Likitlersuang S., Repurposing of Stabilised Dredged Lakebed Sediment in Road Base Construction. Journal of Soils and Sediments, Vol. 21, Issue 7, 2021, pp. 2719-2730.

[12] Horpibulsuk S., Miura N., and Nagaraj T., Assessment of Strength Development in Cement-admixed High Water Content Clays with Abrams' Law as a Basis. Geotechnique, Vol. 53, Issue 4, 2003, pp. 439-444.

[13] Thongdetsri T., Nontananandh S., Noipasee S., Ruangchai S., and Jotisankasa A., Stabilization of Water Treatment Sludge with Cement for Use in Road Materials. Technical Education Journal KMUTNB, Vol. 12, Issue 2, 2021, pp. 12-23.

[14] Kamon M., and Nontananandh S., Combining Industrial Wastes with Lime for Soil Stabilization. Journal of Geotechnical Engineering, Vol. 117, Issue 1, 1991, pp. 1-17.

[15] Khomcom K., Nontananandh S., Vardhanabhuti B., Kamhangrittirong P., and Tengya P., Stabilization of Soft Bangkok Clay with Geopolymer Produced from Alkaline Activated Fly Ash. Proceedings of the 49th Kasetsart University Annual Conference: Architecture and Engineering, The Thailand Research Fund, Bangkok, Thailand, 2011, pp. 148-155.

[16] Nontananandh S., Yoobanpot N., Chaysuwan D., and Thongdaeng K., Influence of Fineness of Cement Produced from Industrial Wastes on Strength of Mortar. Agriculture and Natural Resources, Vol. 45, Issue 4, 2011, pp. 762-772.

[17] Inazumi S., Hashimoto R., Shinsaka T., Nontananandh S., and Chaiprakaikeow S., Applicability of Additives for Ground Improvement Utilizing Fine Powder of Waste Glass. Materials, Vol. 14, Issue 18, 2021, pp. 5169.

[18] Åhnberg H., and Holmén M., Assessment of Stabilised Soil Strength with Geophysical Methods. Proceedings of the Institution of Civil Engineers-Ground Improvement, Vol. 164, Issue 3, 2011, pp. 109-116.

[19] Yoobanpot N., Jamsawang P., Poorahong H., Jongpradist P., and Likitlersuang S., Multiscale Laboratory Investigation of the Mechanical and Microstructural Properties of Dredged Sediments Stabilized with Cement and Fly Ash. Engineering Geology, Vol. 267, 2020, pp. 105491.

[20] Kowsura S., Chaiprakaikeow S., Jotisankasa A., Malaikrisanachalee S., Nontananandh S., Nusit K., and Inazumi S., Properties and Performances of Soil Cement Modified with Concentrated Para-Rubber. GEOMATE Journal, Vol. 24, Issue 102, 2023, pp. 42-49.

[21] Nuntasarn R., and Wannakul V., The Relationship Between Soil Suction and the Maximum Unsaturated Undrained Shear Strengths of Compacted Khon Kaen Soil. GEOMATE Journal, Vol. 2, Issue 3, 2012, pp. 166-170.

[22] Abeykoon T., and Trofimovs J., Shear Strength of Unsaturated Expansive Soils from Queensland Natural Slopes. GEOMATE Journal, Vol. 20, Issue 82, 2021, pp. 53-60.

[23] Barus R. M. N., Jotisankasa A., Chaiprakaikeow S., Nontananandh S., Inazumi S., and Sawangsuriya A., Effects of Relative Humidity During Curing on Small-Strain Modulus of Cement-Treated Silty Sand. Geotechnical and Geological Engineering, Vol. 39, Issue 3, 2021, pp. 2131-2146.

[24] Thongdetsri T., Nontananandh S., Noipasee S., Ruangchai S., and Jotisankasa A., Stabilization of Water Treatment Sludge with Cement for Use in Road Materials. Technical Education Journal KMUTNB, Vol. 12, Issue 2, 2021, pp. 12-23.

[25] Department of Pollution Control, Criteria for the Quality of Seabed Sediments, 2015.

[26] American Society for Testing and Materials. ASTM D2166/D2166M-24, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, 2024.