Influence of Initial Water Content and Water-to-Cement-Ratio on the Strength and Suction Characteristics of Cement-Stabilized Sediments from Drainage Canal

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ABSTRACT: This research aimed at investigating the basic properties of the canal sediments, which constitute waste materials dredged from drainage canal in Phetchaburi province. They were originally classified as silty sand with low shear strength due to their high water content and being unsuitable for construction use in their original conditions. An attempt was made to stabilize the canal dredged sediments with the Ordinary Portland Cement (OPC) in order to solve the environmental problems caused by the large amount of sedimentation to determine the potential use of construction materials based on the geo-environmental engineering framework. In this experimental study, air-dried canal dredged sediments were mixed with OPC by applying cement mix proportions of 150, 200, and 250 kg/m^3 and initial water contents of 14.32% and 17.0% with early curing times of 3, 7, 14, and 28 days in order to investigate the gain in strengths with different water-to-cement ratio (w/c ratio) using unconfined compression tests. The underlying mechanisms which contributed to the hardening effects were evaluated using moisture properties, suction test, X-ray diffraction analysis (XRD), and scanning electron microscopic observation (SEM). The results indicated that a desirable unconfined compressive strength of the cement-stabilized canal sediments of more than 689 kPa could be achieved after being cured for 7 days. Utilizing this criterion, the appropriate w/c ratio within the range of 1.00 - 1.50 ensured that the material had been suitable as a subbase layer for all mixing proportions. In addition, higher initial water content with similar w/c ratio played significant role in the strength development. These findings were confirmed by the formation of reaction products such as calcium silicate hydrate (CSH) and Ettringite which improved internal microstructures. In addition, Soil-Water Retention Curve (SWRC) revealed that an increase in suction significantly reduced water content which conformed to an increase in strength. The utilization of cement-stabilized canal sediments had the potential to be used as construction materials, representing a sustainable approach to waste management.

KEYWORDS: Sediments, Cement, Unconfined Compressive Strength, SWRCs, XRD, and SEM.

1. INTRODUCTION

Many provinces in Thailand have currently encountered a huge amount of natural sediments due to the flow of water runoff into sea, river, lake, and reservoir. These sediments are considered as waste materials that may cause multiple problems such as water quality, water management, agricultural activities, the efficiency of hydraulic structures, and the storage problems. Therefore, it is necessary to dredge the sediments in order to increase the efficiency of water management in the area. Phetchaburi Province, an important strategic area located around 176 kilometers southwest from Bangkok, is also significantly impacted by considerable amount of sediments accumulated in dam reservoirs, water supply canals, and drainage systems across various areas (Youdee et al., 2023).

The average annual rainfall of Phetchaburi Province is approximately 1,100 milliliters which should then deal with disasters from water every year. There are three main reservoirs of water storage and conveyance, with their respective capacities: 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). Their main duties include diverting water into the water supply canal for agricultural and the consumption purposes, as well as draining into the drainage canal and disposing water into the sea. Consequently, sediment particles carried by the water settle and accumulate in the drainage canals obstructing the flow, as shown in Figure 1. To address these challenges and to provide improvement for water conveyance and drainage efficiency, regular sediment dredging operations are carried out annually. The amount of sediments and operation costs of dredging from year 2018 to 2022 are given in Figure 2 (Royal Irrigation Department, 2023). The dredging plan reveals that a significant budget has to be allocated for canal dredging each year, however, there is no strategy for utilizing the dredged sediment. Therefore, the concept of waste utilization as construction materials which is based on the geo-environmental engineering framework in accordance with NICE criteria has been recommended as an alternative approach to seek compromise in technical, environmental, and economical concerns (Kamon et al., 1991).

Figure 1 Drainage canal in Phetchaburi province, Thailand

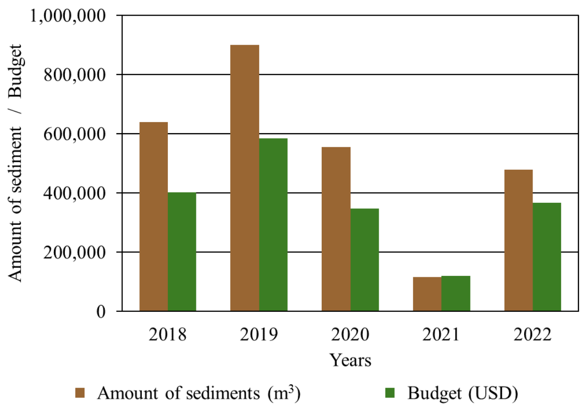

Figure 2 Amount of sediment and the budget from 2018-2022

Stabilization of soil materials such as dredged sediments and soft soils by chemical methods involves improving physical and engineering properties by mixing cementitious substances and the appropriate ratio of water to cementitious substances (w/c ratio) (Horpibulsuk et al., 2003; Thongdetsri et al., 2023). The increased shear strength of soil is resulted from chemical reactions among soil particles, cementitious substances, and water. Ordinary Portland Cement (OPC), quicklime, or pozzolanic materials are just some of the commonly used stabilizers. Besides, there is also a wider variety of binders being used nowadays, such as the production of synthetic cement from wastes, geopolymer from fly ash, and cementing agents from industrial wastes. (Kamon and Nontananandh, 1991; Khomcom et al., 2011; Nontananandh et al., 2011; Inazumi et al., 2021). According to the previous studies using XRD analysis and SEM observation, the strength of the cement-stabilized soils were contributed to the formation of reaction products such as calcium silicate hydrate (CSH) and Ettringite which combined with the soil particles, resulting in the formation of hardened structures (Kamon and Nontananandh, 1990; Horpibulsuk et al., 2010; Yoobanpot et al., 2020a; Chompoorat et al., 2021b; Thongdetsri et al., 2023).

The rate of decrease in water content is relatively large during the early hydration and tends to decrease with increasing age. Our previous studies revealed that the relative humidity in various incubation conditions was inversely proportional to the rate of water reduction. The analysis of the suction pressure indicated that the soil water retention curve could predict the behavior of the cement-treated soils which were more resistant to changes in the environment than in the natural compacted soil. The relationship between the changing water content was related to the suction pressure and the relative humidity (Barus et al., 2021; Thongdetsri et al., 2023). In recent years, many studies have focused on using stabilized natural dredged sludges and water treatment sludges as alternative materials for construction (Julphunthong et al., 2018; Thongdetsri et al., 2021; Sani and Eisazadeh, 2023). Additionally, utilization of excavated soil sediment can be applied as subbase and base course materials for road pavement. (Bhurtel and Eisazadeh, 2020; Phai and Eisazadeh, 2020; Yoobanpot et al., 2020b; Chompoorat et al., 2021c).

The objective of the current study is to stabilize the sediments which were dredged from the drainage canals in Phetchaburi Province by using Ordinary Portland Cement, and then to study factors affecting the development of unconfined compressive strength (UCS) of cement-stabilized soils. These factors include initial water content, the amount of cement, water-to-cement ratio (w/c ratio), and the curing time. The physico-chemical properties of the unsaturated and cement-treated canal sediments were investigated using soil suction test, XRD analysis, and SEM observations in order to determine the soil water retention curves (SWRCs) which can be used to elucidate qualitative correlations between the increase in strength and the reduction in water contents, and also the formation of reaction products and the changes in microstructures.

2. MATERIALS AND TESTING METHOD

2.1 Materials

The soil used in this research is sediment dredged from the drainage canals in Phetchaburi Province, collected from the area along the drainage canal from kilometer 2+500 to 3+000, which was closed to the Regional Irrigation Office No.14, as shown in Figure 3. The soil particles exhibit the characteristics of suspended sediment, mixed with sediment in the water. In its natural state, the soil has a reddish-brown color, but when dried along the canal, it appears grayish-brown, which clumps together, has low water content, and emits a faint odor.

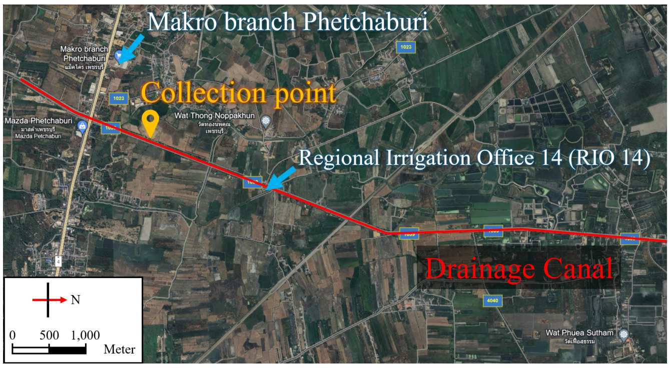

Figure 3 Location of sediments sampling

The physical properties test, as presented in Table 1 reveals that the canal dredged sediments has a water content of 5% at the time of sampling, which is the water content after dredging and drying along the canal (the average water content of the natural sediment within the canal is 117%). The specific gravity is 2.67. The grain size analysis by wet sieving and hydrometer of the canal dredged sediments, as shown in Figure 3, has indicated the soil composition includes 0.71% gravel, 51.94% sand, 18.90% silt, and 28.46% clay. Regarding the Atterberg's Limits, the liquid limit (LL), plastic limit (PL), and plasticity index (PI) cannot be determined due to the minor presence of clay, thus considering the soil as non-plastic.

Using the Unified Soil Classification System (USCS), the canal dredged sediments is classified as non-plastic silty sand (SM), while using the AASHTO classification system, it is classified as A-4-(0), which is suitable for the use of construction material from low ranges to medium levels. Additionally, the soil exhibits maximum dry density from the standard compaction test at 17.26 kN/m^3, and it has an optimal water content of 14.32%. When using this water content for compacting and conducting soil compressive strength tests, the soil will exhibits a strength of 49.03 kPa. It could be observed that the canal dredged sediments (CS) in this study had different properties with water treatment sludge (WS) from our previous study. Therefore, in this study, relative increasing in initial water contents were required for suitable soil stabilization. (Youdee et al., 2023; Thongdetsri et al., 2023)

Table 1 Physical properties of the canal dredged sediments and water treatment sludge

Properties	CS[1]	WS[2]
Specific gravity	2.67	2.58
Natural water content (%)	117	120 - 150
Liquid limit (%)	N.P.	58.7
Plastic limit (%)	N.P.	53.8
Plastic index (%)	N.P.	4.9
Soil classification (AASHTO)	A-4 (0)	A-7-5 (20)
Soil classification (USCS)	SM	MH

Notes: [1] Youdee et al. (2023)
[2] Thongdetsri et al. (2023)

The chemical compositions of the canal dredged sediment (CS) compared with water treatment sludge (WS) are shown in Table 2. It reveals that the main components of the canal dredged sediment are Silicon Dioxide (SiO_2) and Aluminum Oxide (Al_2O_3). Meanwhile, a small amount of chloride salt discovered has been found to be consistent with the influence of sea water entering the drainage canal. In addition, Calcium oxide (CaO) and SiO_2 were found to be main components in OPC, as shown in Table 2.

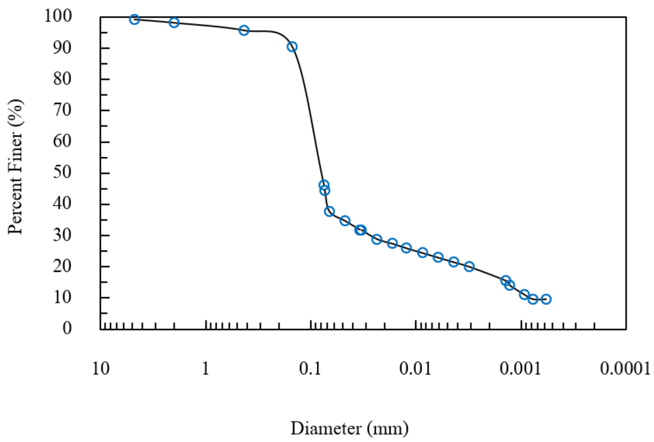

Figure 4 Grain size distribution curve

Table 2 Chemical compositions of CS, WS and OPC

Oxide Component	CS (%)	WS[1] (%)	OPC (%)
SiO_2	79.61	56.30	12.42
Al_2O_3	10.33	28.60	2.49
Fe_2O_3	3.80	7.78	2.15
K_2O	2.20	2.15	-
CaO	0.84	1.18	79.01
MgO	1.30	1.24	0.48
P_2O_5	0.18	0.91	-
TiO_2	0.56	0.89	0.14
SO_3	0.91	0.22	3.26
MnO	0.24	0.19	-
Na_2O	-	0.36	-
LOI	-	0.17	-
Cl	0.004	-	-

Note: [1] Karawek et al. (2019)

The results of the heavy metal testing for material toxicity analysis, using Atomic Absorption (AA) method, on the canal dredged sediments in Phetchaburi Province are summarized in Table 3. It was found that this sediment has low heavy metal content, which meets the standard criteria set by the Department of Pollution Control. Therefore, it can be concluded that the material is non-toxic to the environment, which aligns with the guidelines for material selection for waste utilization (NICE Criteria) proposed by Kamon et al. (1991) and Katsumi et al. (2019). These criteria encompass non-hazardous composition, suitability for application, compatibility, consistent behavior over time, and cost-effectiveness.

2.2 Method

2.2.1 Specimen Preparation for UCS Test

In the previous studies, the initial water content before mixing was identified as a significant factor affecting the development of UCS of soil cement (Youdee et al., 2023). The appropriate amount of water from standard compaction test tended to result in higher compressive strength than mixing with natural water content, which often has higher values.

Therefore, after the canal dredged sediments had been proven to be non-hazardous material, the next step was to add water into the air-dried canal dredged sediments by spraying and mixing to adjust the initial water content before mixing to be equal to 14.32%, which was the optimum water content. Then, the moist soils were thoroughly mixed with OPC in a Hobart mixer using the proportions of 150, 200, and 250 kg/m³ by dry weight. The water contents after mixing were also measured. From each mixtures, cylindrical specimens of 50 mm diameter by 100 mm long were made for UCS test, producing six samples per batch. After molding, the specimens were sealed tightly in plastic sheets to prevent the loss of moisture created from the surface evaporation and cured at room temperature for periods of 3, 7, 14, and 28 days, as shown in Figure 5.

In order to enhance the workability and ensure the uniformity of the mixture, another similar set of specimens was prepared using a water content of 17.00%. All mixing proportions and symbols are shown in Table 4.

Table 3 Heavy metal test by Atomic Absorption (AA) method

Elemental metals	Standard[1] (mg/kg)	CS (mg/kg)	WS[2] (mg/kg)
Cr(VI)	500	ND	ND
Cr(III)	2500	ND	32.2
Sb	500	ND	ND
As	500	6.99	3.46
Ba	10,000	ND	76.0
Be	75	ND	ND
Cd	100	ND	ND
Cr	2,500	31.7	32.2
Co	8,000	ND	7.77
Cu	2,500	7.33	21.4
Pb	1,000	N/A	ND
Hg	20	0.017	ND
Mo	3,500	ND	ND
Ni	2,000	11.2	23.2
Se	100	0.774	ND
Ag	500	ND	0.020
Tl	700	ND	0.023
V	2,400	ND	32.0
Zn	5,000	27.3	88.8

Notes: [1] Department of Pollution Control (2015)
[2] Metropolitan Waterworks Authority (2019)

Table 4 Mix propotions and symbols

Symbol	Initial water content (%)	Cement content (kg/m³)	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

To investigate the effects of initial water content and w/c ratio on the strength of the cement-stabilized sediments, UCS tests were performed in accordance with ASTM D2166 (2016) standards. Samples then were tested using an automatic universal testing machine (UTM) following the prescribed curing time, until failure sets, employing a strain rate of 0.02 min^{-1}. The recorded UCS represents the smaller value between the compressive stress at peak and 15% axial strain. After each UCS test, a small amount of specimen along the failure surfaces was collected to measure the water content after being cured at a specified day in order to clarify the gain in strength and the formation of major reaction products. In addition, a variety of mixtures were experimented with using cement proportions of 150, 200, and 250 kg/m³ as a target to attain the requisite strength for subbase layers in highway structures, following the recommendations of the Department of Highways of Thailand (2007).

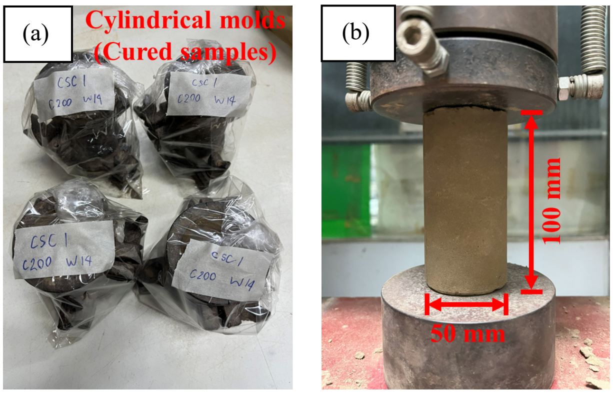

Figure 5 (a) specimen preparation (b) UCS test

2.2.2 Soil-Water Retention Curve (SWRC) Test

The SWRC test illustrated the water contents at different suction levels. For untreated samples, suction was managed through measurement using specific techniques: tensiometer for suctions between 0 and 100 kPa, pressure plate for suctions ranging from 100 kPa to 15,000 kPa, and the isopiestic technique for suctions exceeding 1,000 kPa, as shown in Figure 6. The wetting path and drying path were performed using the tensiometer to show the characteristics of this sediment at various suctions.

For treated sample, suction of CSC1 and CSC4 at 14 days curing time was measured by using isopiestic technique. The continuous loss of pore-water during the cement-hydration reaction of treated samples rendered the attainment of suction equilibrium challenged when using tensiometers. This will lead to cavitation problems, particularly when suction levels often exceeded 100 kPa. As a result, the SWRCs of cement-treated samples were exclusively determined within the high total suction range utilizing the isopiestic technique (Barus et al., 2021).

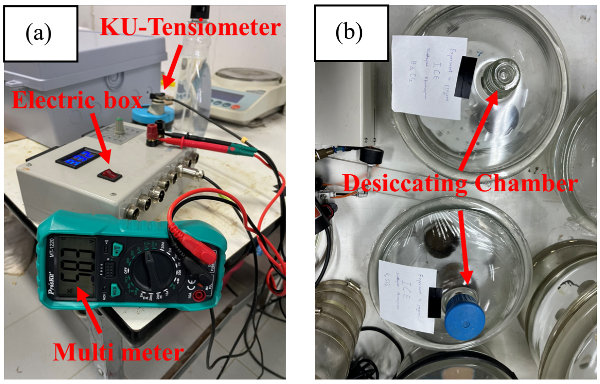

Figure 6 (a) KU-Tensiometer (b) Isopiestic technique

2.2.3 X-Ray Diffraction (XRD) Test

XRD analysis that was conducted on soil samples was subjected to UCS test. The samples were taken from the failure plane and prepared by finely scraping and grinding them into small particles. XRD, a widely-used analytical technique was employed to characterize the chemical composition of the tested samples through X-ray irradiation. C_3S, CSH, and Ettringite compounds, were investigated with a Philips X'Pert PRO MPD X-ray diffractometer using a Cu-target with a Ni-filter and input energy of 30 kV and 30 mA. In this study, the positions corresponding to 2θ angles of 34.22 degrees were utilized for identifying the initial compounds (C_3S). Subsequently, the principal resultant compounds were identified at 2θ angles of 29.35 and 45.77 degrees for CSH, and 15.81 and 22.97 degrees for Ettringite, respectively. These specific angles were selected to ensure the minimum interference from the components or minerals inherent in the natural clayey soil matrix presented within the samples.

2.2.4 Scanning Electron Microscope (SEM) Observation

SEM was employed to analyze soil specimens after UCS test. Small fragments were collected from critical sections, particularly the failure surfaces, which were meticulously examined under the microscope to scrutinize alterations in the microstructure of the soil matrix. In this study, the microstructure of the natural sediments and the reaction products of the improved sediments as well were observed by a Hitachi SU3500 scanning electron microscope using input energy of 20 kV and 20 mA.

3. RESULTS AND DISCUSSIONS

3.1 Suction of the Canal Dredged Sediments

Utilizing KU-Tensiometer instrumentation, SWRC of the canal dredged sediments was investigated across the range of 0 - 90 kPa, encompassing both drying and wetting path. Figure 7 to Figure 10 illustrate the soil behavior of untreated samples in regard to various suction values, depicting its relationship with gravimetric water content, volumetric water content, degree of saturation, and void ratio.

The wetting path demonstrates changes in water retention as soil water content increases, while the drying path indicates alterations as water content decreases. Notably, at equivalent suction values, the drying path exhibits higher water content compared to the wetting path, attributable to the initial saturated testing phase, promoting uniform water infiltration and dispersion within the soil particles.

Suction values from drying path between 0 - 90 kPa correspond to gravimetric water content from 12.93 - 19.48%, volumetric water content from 23.70 - 34.08%, degree of saturation from 0.76 - 0.99 and void ratio from 0.46 - 0.53. When comparing the result with water treatment sludge by Thongdetsri et al. (2023), it revealed that the water content prior to the improvement of the canal dredged sediments was relatively lower, and also exhibited a slower rate of moisture loss compared to water treatment sludge in suction value between 0 - 90 kPa.

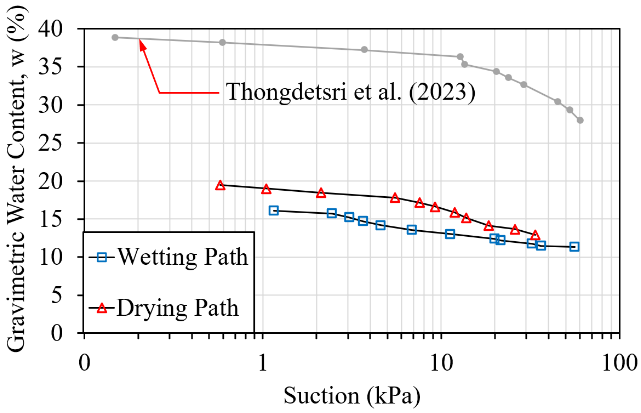

Figure 7 Gravimetric water content versus suction

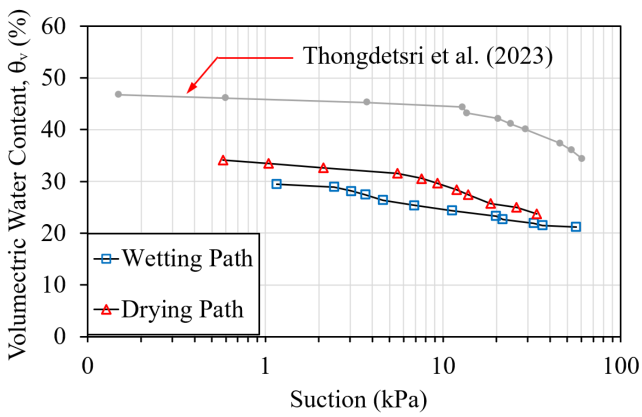

Figure 8 Volumetric water content versus suction

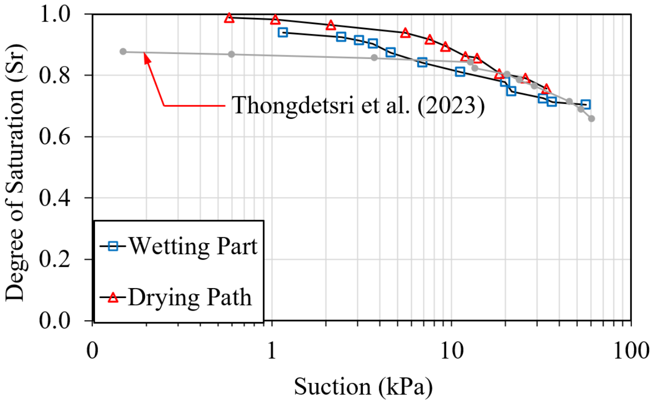

Figure 9 Degree of saturation versus suction

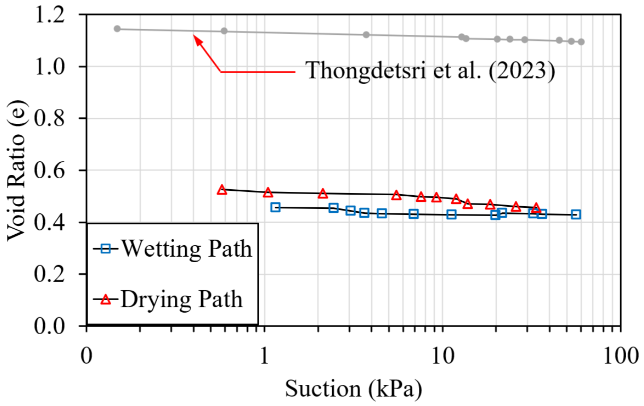

Figure 10 Void ratio versus suction

3.2 Strength Characteristics

Subsequent to soil improvement, the UCS of treated soils demonstrated higher strength than previous research (Thongdetsri et al., 2023). When compared to untreated soil, the UCS of cement-stabilized soil will significantly be improved. For all mixtures, the UCS of treated soil exhibited progressive rises with curing time, as shown in Figures 11 and 12. Additionally, there has been a corresponding enhancement with the increase in cement content, as shown in Figures 13 and 14. However, with the use of appropriate initial water content and cement content, rapid increased in the UCS during the early curing time (3-7 days), which were attributed to the early hydration, could be observed. Gain in strength also continued steadily during the intermediate curing time (7-28 days).

For example, in mixtures CSC2 and CSC3, despite the cement content of CSC3 was higher than CSC2 and although CSC3 exhibited higher UCS during the early curing time (3-7 days), the UCS of both mixtures were seemingly similar at intermediate curing time. For example, the UCS of CSC2 and CSC3 at 7 and 14 days curing time were 1,282 and 1,418 kPa, and 1,306 and 1,437 kPa, respectively. This is likely due to inadequate water content for the reaction for CSC3. However, at 28 days curing time, the UCS of CSC3 was higher than CSC2 again, suggesting that the mechanism of the chemical reaction and the hardened structures of these mixtures should be further studied. On the other hand, when compared CSC3 with CSC6, it was found that CSC6 exhibited higher UCS at all curing times. For example, during the early curing time (3-7 days), CSC3 and CSC6 showed the UCS ranging from 1,210-1,306 kPa and 1,293-1,718 kPa, respectively. In addition, during the later curing time (14-28 days), the UCS of CSC3 and CSC6 were within the ranges of 1,437-2,739 kPa and 2,270-2,887 kPa, respectively. Similarly, when comparing CSC2 and CSC6, which had similar w/c ratios (1.26 and 1.20, respectively), it was found that the UCS of CSC6 were obviously greater than those of CSC2 at all curing time.

As illustrated in Figure 15, during the initial curing time of 0-3 days, there was a rapid decrease in water content. Comparatively, during the subsequent curing time of 3-7 days, 7-14 days, and 14-28 days, the rate of moisture reduction decreased gradually. This decrease was observed to be slightly slower when comparing CSC6, CSC5, and CSC4, which had initial water content of 17%, with a corresponding decrease in cement content. Similarly, CSC1, CSC2, and CSC3 starting with 14% water content, exhibited a comparable rate of moisture reduction. Thus, it was assumed that the rate of moisture reduction was correlated with the increasing rate of reactions during the early curing time (0-3 days) and decreased gradually during subsequent curing time. Additionally, the trend of moisture reduction corresponded with the decrease in C_3S content. Further discussion was held to substantiate this assumption. Upon analyzing the relationship between UCS and w/c ratio, it was found that for all mixing proportions and curing time, the compressive strength increased as the w/c ratio decreased, as shown in Figure 16.

The Department of Highways of Thailand has set standards for materials that can be used as subbase layers for roads, requiring a 7-day UCS of 689 kPa. Utilizing this criterion for determining suitable mixing proportions in this study, it was found that the appropriate w/c ratio ensuring material compliance as a subbase layer falls within the range of 1.00-1.50 for all mixing proportions. In addition, when the w/c ratio exceeds 1.5, it was observed that some particular mixing proportions failed to meet the criteria for subbase layer materials due to increased cement content and water volume.

Although the w/c ratio in the range of 1.0-1.5 may meet the standard criteria for cement-stabilized canal dredged sediment for highway materials, the initial water content remained a crucial factor in strength development to achieve the appropriate w/c ratio. Consequently, the suitable w/c ratio for the best reaction of cement-stabilized canal dredged sediment in this study was found to be between 1.20-1.26. Therefore, in order to ensure homogeneity of the mixture and substantially enhance the efficiency of chemical reactions, it is essential to consider not only the cement content but also the initial water content in order to provide suitable w/c ratio.

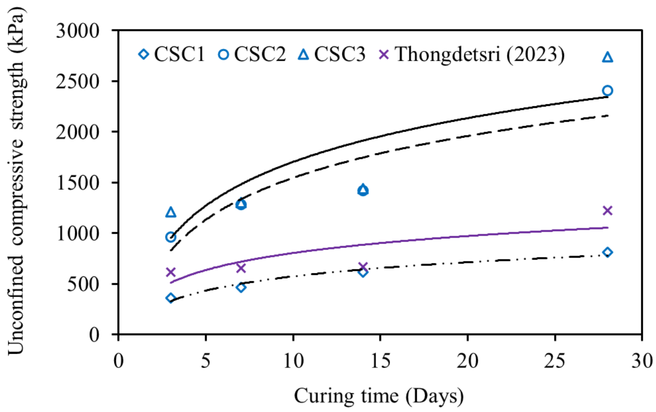

Figure 11 UCS versus curing time (w = 14.32%)

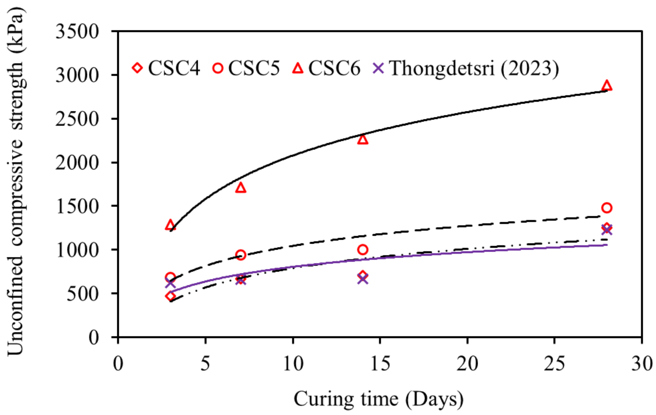

Figure 12 UCS versus curing time (w = 17.00%)

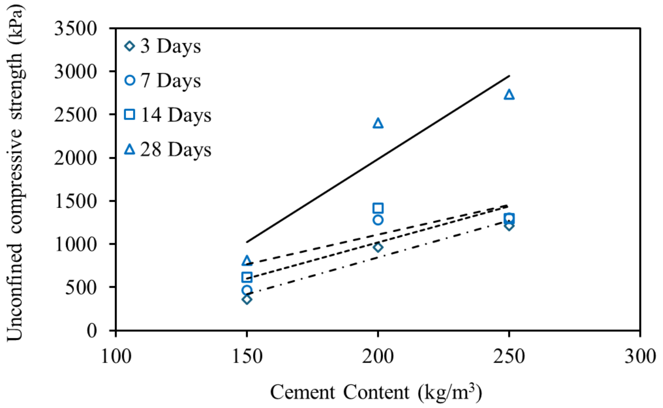

Figure 13 UCS versus cement content (w = 14.32%)

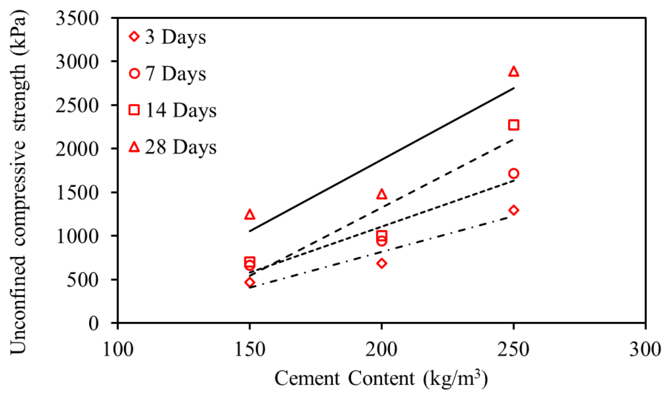

Figure 14 UCS versus cement content (w = 17.00%)

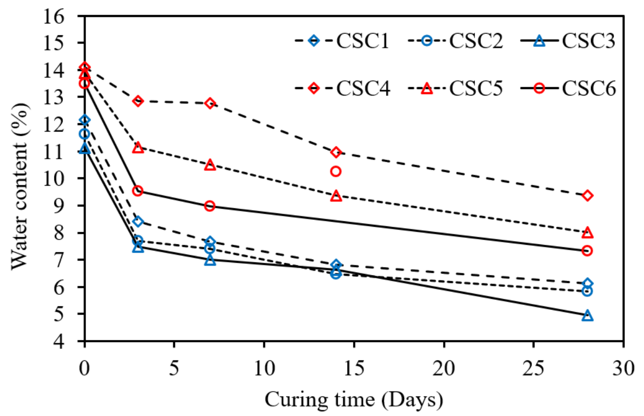

Figure 15 Water content versus curing time

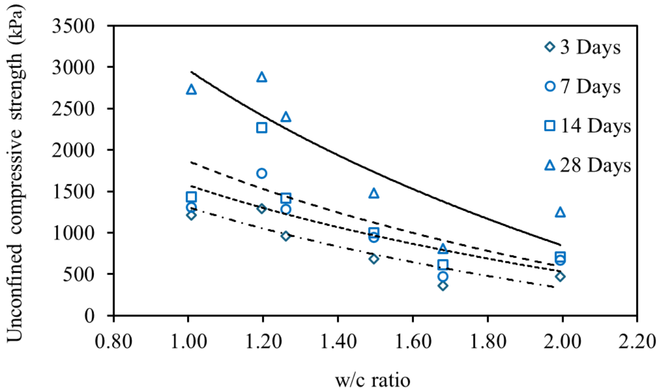

Figure 16 UCS versus w/c ratio

3.3 Compounds of Chemical Reaction

Table 5 indicated the XRD intensity of CSH, Ettringite, and C_3S of the representative mixtures such as CSC2, CSC3, and CSC6 and relevant UCS at various curing times. The results showed significant attenuation of C_3S intensity and the increase in CSH intensity which, it is believed, contribute to strength development of the cement-stabilized sediment. In this study, the role of Ettringite on increase in strength, which was due to relatively low water contents of the mixtures, was less pronounced when compared with the early study by Kamon and Nontananandh (1991).

The XRD pattern of the representative mixture (CSC3) as shown in Figure 17 revealed that the mineral components of the soil were Quartz (PDF 05-0490) and clay minerals including Illite (PDF 43-0686), Kaolinite (PDF 05-0143), and Montmorillonite (PDF 03-0010). Upon mixing with cement, a significant quantity of C_3S (PDF 42-0551) was detected during the initial curing phase (3-7 days), which decreases as the curing time progresses (14-28 days). Consequently, it transformed into the main chemical reaction products including CSH (PDF 00-012-0739) and Ettringite (PDF 04-013-3691).

Table 5 XRD intensity of CSH, Ettringite, C_3S and UCS

Mixture	Curing Time (days)	CSH Intensity (cps)	Ettringite Intensity (cps)	C_3S Intensity (cps)	UCS (kPa)
CSC2	3	123	34	31	964
	7	111	31	29	1282
	14	153	34	32	1418
	28	149	46	33	2406
CSC3	3	132	29	55	1210
	7	159	33	40	1306
	14	79	39	25	1437
	28	129	37	19	2739
CSC6	3	149	32	35	1293
	7	121	52	34	1718
	14	88	34	38	2270
	28	134	32	38	2887

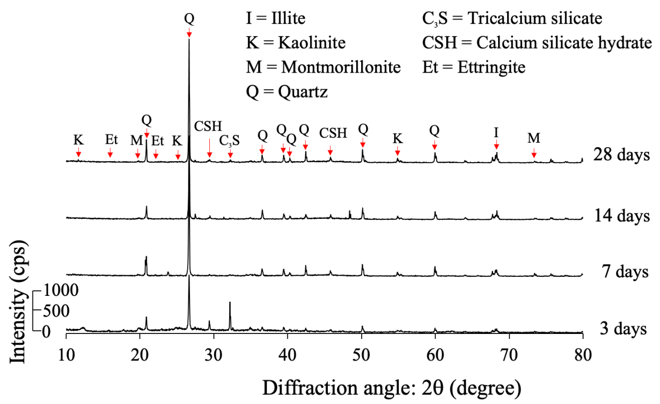

Figure 17 XRD pattern of CSC3 with curing time

From Figure 18, it was found that the diffraction intensities of C_3S significantly decreased during the first week of curing, then became almost steady. The rate of reduction of CSC2, CSC3, and CSC6 were identical, however, CSC6 exhibited an exponentially declining curve a little greater than CSC2 and CSC3, respectively which conformed to the results of UCS and the rate of changes in water contents.

The relationship between CSH and Ettringite formation and UCS are illustrated in Figures 19 and 20. Consequently, as obviously shown from Figure 19, the attained strength increase in correspondence with the X-ray intensity of CSH. Notably, CSH would have been produced in higher magnitude in the mixtures with lower w/c ratio. However, slight scattering of data was probably due to the variation of water combined in the crystals of reaction products which fabricated the hardened structures during the course of hydration as has been indicated by Kamon and Nontananandh (1990). Additionally, similar trend can be observed on Ettringite formation. However, it is likely that Ettringite exhibit less contribution to strength when stabilizing soils are having low water content.

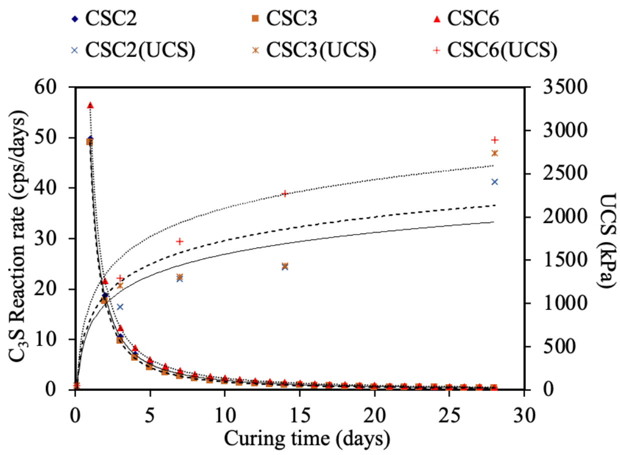

Figure 18 Relative between rate of reaction and UCS

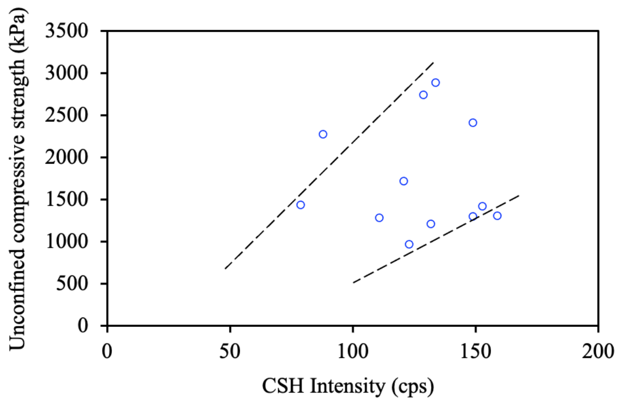

Figure 19 UCS versus CSH intensity

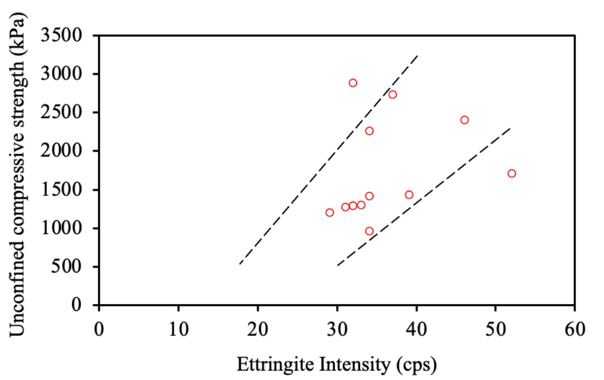

Figure 20 UCS versus Ettringite intensity

3.4 Internal Microstructure of Natural Canal Sediments and Improved Sediments

The examination of the microstructure of the excavated soil from the drainage canal, magnified 5,000 times, reveals the presence of many small pores and minor residues of small plant tissue incorporated within the soil structure, as depicted in Figure 21.

Furthermore, in agreement with the results from XRD, Figures 22 and 23 exhibit the microstructures of CSC2 at 28 days which confirmed the occurrence of CSH and Ettringite in the structures of the cement-stabilized soil. It could be observed that the CSH appeared in plate-like shapes, covering the surface of the soil uniformly. Similarly, Ettringite, characterized by its stick-like shape, also covering the surface. Similar results could also be observed in the other mixtures. This illustrates the production of chemical reaction products, contributing to the formation of solid substances and structures, as well as decreasing the soil porosity, which conformed to a study by Latifi et al. (2016); (2017); Chompoorat et al. (2021a); (2022).

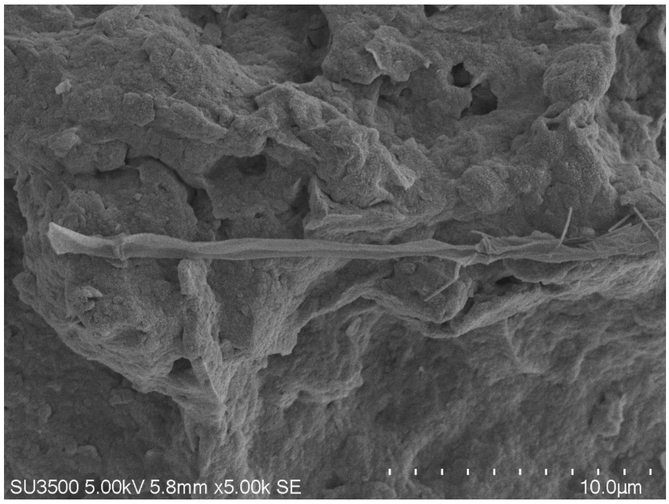

Figure 21 Microstructure of canal dredged sediment (x5000)

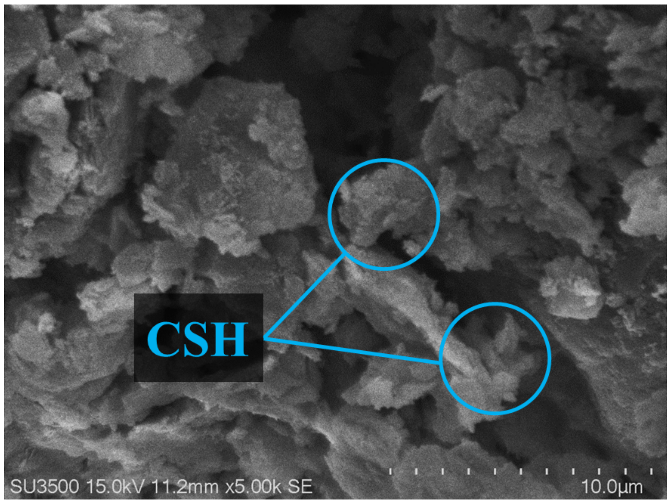

Figure 22 Microstructure of CSC2 at 14 curing time (x5000)

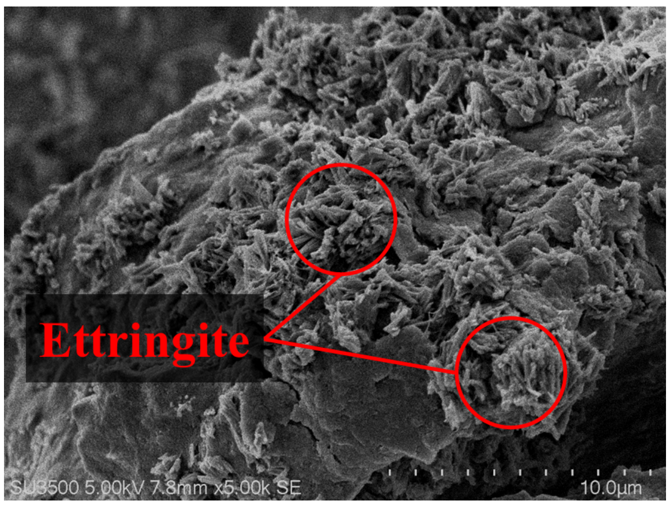

Figure 23 Microstructure of CSC2 at 28 curing time (x5000)

3.5 Suction Characteristics

The gravimetric water content (water content by weight) of the natural canal sediments were ranges from 7.51% to 19.48% at suction between 0 - 14,012 kPa, with a graph resembling bi-modal curve, as shown in Figure 24. This phenomenon occurs when the soil sediments have two levels of porosity which includes small voids within the microstructure. The result was consistent with SEM micrograph as had been previously explained and shown in Figure 21.

Furthermore, the relationship between suction and gravimetric water content of the cement-stabilized sediments under pressures of 4,183 and 14,012 kPa revealed that water contents at 14 days reduced from 6.84% to 4.78% and 10.02% to 6.60% for soil-cement mixtures of CSC1 and CSC4, respectively. These values were lower than the natural water content (by weight) of the canal dredged sediments at the same suction value, indicating changes in the physico-chemical properties of soil mixed with cement. These results confirm that increasing the suction will significantly reduce the water content of the cement-stabilized sediments over the curing time. In addition, the reduction in water content reflected cement hydration which contributed to strength development.

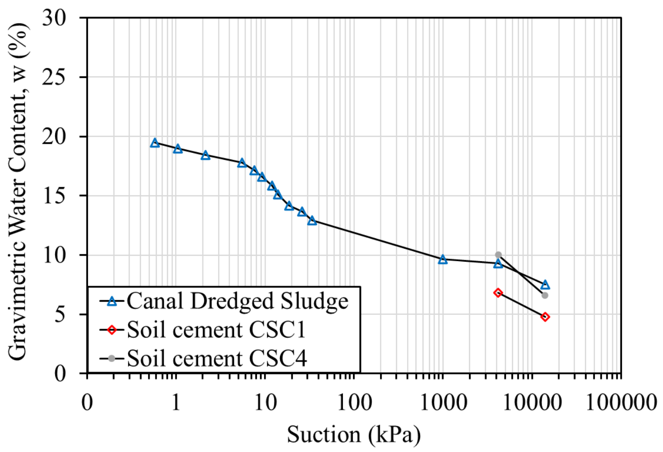

Figure 24 Soil-water retention curves of untreated and cement-stabilized sediments

4. CONCLUSIONS

Study was being carried out about the influence of initial water content and water-to-cement ratio on the unconfined compressive strength and physico-chemical properties of the sediments dredged from a drainage canal. Initially, the basic properties of these sediments were conformed to NICE criteria. Based on the experimental results, the following conclusions can be drawn.

1. The initial water content, cement content and subsequent water-to-cement (w/c) ratio significantly influenced the strength of the cement-stabilized canal dredged sediment. For silty sand sediment (SM), suitable initial water content falled within approximately optimum water content +2% incorporated with w/c ratio within a range of 1.0 - 1.5. This condition can effectively promote the desirable development of strength for subbase materials, however, future studies are needed to provide practical applications and to evaluate the potential use in the field.

2. Results from X-ray Diffraction (XRD) analysis revealed that strength developing mechanism of the cement-stabilized sediment was substantially influenced by the reaction rate of C_3S, which reflected the rate of reduction of water contents as indicated by the conventional standard water content test and suction test. The suitable initial water content and w/c ratio provided a better rate of reaction of C_3S. The attained strength was increased in correspondence with the X-ray intensity of CSH. In addition, Ettringite exhibit less contribution to strength when stabilizing soils which had low water content.

3. Scanning Electron Micrograph (SEM) supports the findings from XRD and showing changes in the microstructures. The formation of CSH and Ettringite covered the surface of soil cement, resulting in denser soil cement structure as the curing time increased.

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