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Phản biện 1:
Phản biện 2:
Phản biện 3:

LIST OF PUBLICATIONS

The publications related to this dissertation are:

International Journal

1. T. Nguyen Thanh, D. Nguyen Minh, T. Nguyen, and C. Phan Thanh, “Interface Shear Strength Behavior of Cement-Treated Soil under,” *Buildings*, vol. 13, no. 7, 2023, doi: https://doi.org/10.3390/buildings13071626.

International Conference

2. T. Nguyen Thanh, D. Nguyen Minh, and T. Le Huu, “The Effects of Soaking Process on the Bearing Capacity of Soft Clay Reinforced by Nonwoven Geotextile,” Lecture Notes in Civil Engineering, vol. 62, pp. 669–676, 2020, doi: 10.1007/978-981-15-2184-3_87.
3. T. Nguyen Thanh and D. Nguyen Minh, “Effects of Soaking Process on CBR Behavior of Geotextile Reinforced Clay with Sand Cushion,” Proceedings of 2020 5th International Conference on Green Technology and Sustainable Development, GTSD 2020, pp. 162–167, 2020, doi: 10.1109/GTSD50082.2020.9303053

National Journal

4. T. Nguyễn Thanh, Đ. Nguyễn Minh, T. Trần Văn, and B. Lê Phương, “Ứng xử cố kết của đất sét lòng sông khi gia cường đệm cát và vải địa kỹ thuật dưới điều kiện nén 3 trục,” Tạp chí Vật liệu và Xây dựng, vol. 4, pp. 90–97, 2021. Available: http://ojs.jomc.vn/index.php/vn/article/view/159
5. T. Nguyễn Thanh, Đ. Nguyễn Minh, N. Mai Trần, T. Trần Văn, and P. Lê, “Ảnh hưởng của bão hoà đến sức kháng cắt không thoát nước của đất bùn sét lòng sông gia cường vải địa kỹ thuật trong điều kiện nén 3 trục,” Tạp chí Xây dựng, vol. 5. pp. 68–71, 2022. Available: https://tapchixaydung.vn/anh-huong-cua-bao-hoa-den-suc-khang-cat-khong-thoat-nuoc-cua-dat-bun-set-long-song-gia-cuong-vai-dia-ky-thuat-trong-dieu-kien-nen-3-truc-20201224000011282.html.

CHAPTER 1: LITERATURE REVIEW – MAIN OBJECTS

1.1. An overview on research direction:

Sand plays a vital role in construction and is the primary component of cement, asphalt, backfill, and other building materials. Nowadays, the demand for building sand in Vietnam is extremely high. Actually, many road construction projects are facing the situation of needing more sand for backfill material [3]. The construction costs of rural roads will be drastically lowered if riverbed soil is substituted for sand. However, the muddy soil from the riverbed has a high void ratio and poor shear strength, creating instability and excess settlement for the works. When using riverbed soil to replace sand as a backfill, reinforced methods should be taken to strengthen the soil's capacity.

1.2. Reinforced methods

There are three noteworthy methods to improve its strength, including geotextile, sand cushion, and cement reinforcement, since they are cheap and popular.

1.2.1. Geotextile reinforcement

Geotextiles can perform a drainage role to preserve and even improve the shear strength of the subsoil, enhancing long-term structural stability. Soil holding capacity and permeability coefficient are two evaluation criteria for the features of geotextiles.

1.2.2. Sand cushion reinforcement:

The sand cushion is a mixture, including sand between two layers of geotextile. The sand cushion, like the geotextile, functions as a drainage border, forcing the rapid pore water pressure to release rapidly.

1.2.3. Cement reinforcement

This technique combines cement and soil in a particular proportion to form a soil-cement mixture with a greater load capacity. The cement and aggregate mixture considerably increase the strength and bearing capability of the clay via the hydration process. This technique is also used to reduce settlement.

1.3. The urgency of the research

Using riverbed soil instead of sand for backfill material has brought numerous benefits, particularly in the South of Viet Nam. Significantly this solution can help to solve the problem of lacking sand in many road constructions. However, riverbed mud exhibits low characteristics. Reinforcement techniques, including geotextiles, sand cushions, and cement, have been explored and developed to improve soil capacity.

1.4. Specification of road embankments

1.4.1. Road classification

Rural roads are defined and categorized by TCVN 10380:2014 [6].

1.4.2. Road embankment specifications:

TCVN 4054:2005[7] specifies the regulations for the pavement layer.

1.5. Literature review

1.5.1. International research:

a) Using riverbed soil as a backfill material for road construction:

It is common practice to use riverbank soil for road construction and land reclamation [8]–[10]. Methods of reinforcement are utilized to strengthen the strength and speed the consolidation of this backfill soil [13], [14].

b) Side friction in one-dimensional consolidation test

The standard of the one-dimensional consolidation test specifies a minimum specimen diameter-to-height ratio, D/H_0, of 2.5 to reduce the effects of side friction [20]. For geotextile and sand cushion, the samples are usually high. The side friction would significantly reduce the applied consolidation pressure, [21]–[24]. Thus, it is crucial to evaluate the side friction as well as the uniform void ratio condition when D/H_0 is greater than 2.5.

c) Geotextile reinforcement method:

Geotextile reinforcement is widely used due to its essential qualities, which include filtration, drainage, separation, and reinforcing of soil layers [34].

d) Sand cushion reinforcement method:

Numerous studies confirm the drainage function of geotextiles and sand cushions in enhancing the structure's load capacity and stability [17], [19]..

e) Soil cement

Cement is commonly used to increase soft soils' strength, stiffness, and stability [56]. The shear strength of the soil-steel interface was evaluated utilizing the modified direct shear test apparatus. The most commonly used shear test apparatus was a conventional direct shear box with the lower portions of the box replaced with an interface plate [79], [80], [82]–[84]. However, prior research rarely assessed the shear strength of the cement-treated soil-steel interface.

1.5.2. National research:

Geotextiles, sand cushions, and cement have been widely researched for basement applications, for example: Vinh [85], Nguyen Minh Duc et al. [89], Nguyen et al. [93]…

1.5.3. Comments:

Although there were some studies about the soil reinforced by geotextile, sand cushion, and cement, these methods were not entirely investigated.

1.6. RESEARCH OBJECTIVES

1.6.1. Goals of dissertation

The research objectives are:

- Consolidation behavior of clay under the effects of side friction: analysis of friction pressure and non-uniform void ratio.
- Effect of *geotextile reinforcement* on swelling, CBR value, UU shear strength in saturated and unsaturated conditions, and saturated soil consolidation.
- Effect of *sand cushion reinforcement* on swelling, CBR value, UU shear strength in saturated and unsaturated conditions, and saturated soil consolidation.
- Effect of *cement reinforcement* on swelling, CBR value, UU shear strength in saturated and unsaturated conditions, and saturated soil consolidation. Additionally, direct shear tests were performed to investigate the behavior of

the shear strength of soil cement and the interface shear strength between soil cement and steel under consolidated, drained conditions.

1.6.2. Research scope

This research just investigated the soil from Cai Lon River, Kien Giang Province. The outcome of the research would be the basic theory to enhance the soft soil from riverbeds for the backfill.

CHAPTER 2: MATERIALS – THEORIES- MODIFIED DEVICES

2.1. MATERIAL

2.1.1. Riverbed soil

a) Soil properties

This study utilized soil collected from the CaiLon River in southern Vietnam. The ignition loss was 3.96% at about 900^0C at which was decarbonatation would be completed [99], indicating the minimal organic content.

b) Process of remoulding soil

2.1.2. Geotextile

A nonwoven needlepunched Polyethylene terephthalate geotextile was utilized.

2.1.3. Uniform quart sand

Sand is classified as clean sand: few fine particles, and poor gradation. Its type is SP according to the Unified Soil Classification System.

2.1.4. Ordinary Portland cement

Normal Portland cement PC40 with a specified density of 3 g/cm^3 was used in this study (ASTM C188 [100]).

2.2. EXPERIMENTAL THEORIES

2.2.1. California Bearing Ratio test:

2.2.2. One-dimensional consolidation theory

a) Consolidation process: the process of lowering the volume of water in saturated soil due to the lack of grain rearrangement.

b) One-dimensional consolidation test

The minimum specimen diameter-to-height ratio shall be 2.5 to reduce the impact of friction between the specimen's periphery and the inside of the ring.

c) Determine the coefficient of consolidation C_v and permeability coefficient k_v

2.2.3. Triaxial compression test – Modified triaxial apparatus:

a) Triaxial compression test:

A triaxial compression test is performed to calculate the c, ϕ under drainage circumstances and construction durations.

b) Modified triaxial apparatus:

A modified triaxial schematic is introduced, in which there is a small pipe from the middle of the sample to the device to measure the pore water pressure.

c) Unconsoililidated- Undrained test (UU)

- The strain rate in UU tests is typically 1% per minute.

2.2.4. Direct shear test

2.3. Modified shear box for friction between the soil and steel

2.3.1. Modified shear box for friction between the soil and steel

A modified shear box was developed to evaluate the shear strength of the interface between untreated or cement-treated soil and stainless steel. The upper shear box is filled with soil, while the original lower shear box has been replaced with a stainless steel plate.

2.3.2. Friction between the soil and steel measured by modified shear device:

The effective friction angle of the clay, and the interface friction angle between the clay and the stainless steel, ϕ'_{int}, were 27.6^0 and 16.5^0, respectively.

2.4. Modified oedometer apparatus for side friction pressure measurement

A modified oedometer apparatus was developed to measure the side friction between the soil and the consolidation ring, as shown in the following figure:

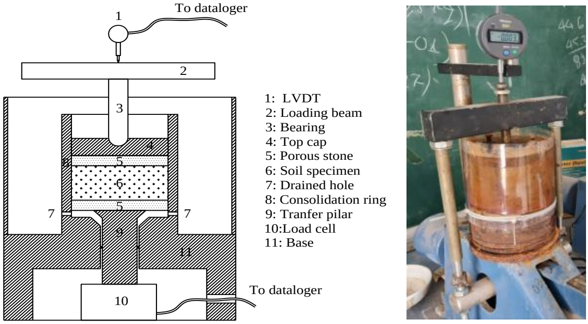

Figure 2.1: Modified oedometer apparatus for side friction pressure measurement

CHAPTER 3: BEHAVIOR OF SOIL REINFORCED BY GEOTEXTILE UNDER CBR, UU, AND CONSOLIDATION TEST

3.1. INTRODUCTION

The research objectives of this chapter are:

- Effect of nonwoven geotextile on soil's swelling and CBR value in unsaturated and saturated conditions by the CBR test.
- Effect of nonwoven geotextile on the UU shear strength in unsaturated and saturated conditions by triaxial test to evaluate the soil capacity.
- Effect of side friction on the consolidation behavior of clay. A modified Taylor's method is presented to predict the friction pressure and determine the void ratio distribution without requiring the specimen height at the end of the tests. Furthermore, the study proposed an analytical equation to evaluate the COV values to quantify the degrees of uniformity of the void ratio along the depth of the specimens in the one-dimensional consolidation experiments.
- Effect of geotextile under the one-dimensional consolidation test.

3.2. EXPERIMENTAL PROGRAM

3.2.1. CBR specimens

There were totally 10 specimens for soaked and unsoaked conditions:

- Unsoaked condition: soil sample and geotextile-soil samples.

- Soaked condition: the compacted specimens were soaked for 96 hours.

In every group, there were unreinforced samples and geotextile-reinforced samples with 1, 2, 3, and 5 layers.

3.2.2. Unconsolidated-Undrained shear strength samples in triaxial test

Unconsolidated-undrained (UU) shear strength was determined by testing a total of 20 samples, including unreinforced samples, 1-layer, 2-layer, and 3-layer reinforced samples, with two initial conditions and compression pressure:

- *Unsaturated samples*: samples will be tested at lateral pressure at 50 kPa, 100 kPa, 150 kPa, and 200 kPa, respectively.
- *Saturated samples*: samples will be saturated at 500 kPa pressure and tested at 300 kPa of lateral pressure.

3.2.3. Consolidation samples

a) Samples to investigate the soil consolidation behavior under the effects of side friction:

The remoulded clay samples were made using clay powder at 54.7% of water content. The height of the soil was 10, 20, 30, 40, and 50 mm. The diameters of the samples were 50 and 75 mm.

b) Samples to investigate the effect of nonwoven geotextile on the soil consolidation process.

There were 4 samples, including unreinforced soil and soil reinforced by 1, 2, and 3 geotextile layers.

3.3. Behavior of soil and geotextile-soil under the swelling and CBR test

3.3.1. Influence of nonwoven geotextile on the swell behavior of clay

The swell process did not reach equilibrium within 96 hours of soaking.

At the initial time, the percent swell of unreinforced specimens was smaller than that of reinforced specimens. After 96 hours, the final swell of reinforced specimens was observed to be reduced with the number of reinforcement layers. The swell velocity of reinforced specimens is observed to be higher than that of unreinforced specimens in 10 hours of soaking. The reduction in dry unit weight of clay specimens reinforced by a geotextile layer is smaller than that of unreinforced soil. As a result, after soaking, the clay in reinforced specimens would be denser than that of the unreinforced soil due to the strength of nonwoven geotextile.

3.3.2. CBR behavior of unreinforced and reinforced with geotextile in un-soaked & soaked condition:

The higher the number of reinforcements, the higher the bearing capacity of reinforced specimens. The nonwoven geotextile improved the bearing capacity of soaked clay more effectively than that of unsoaked clay specimens.

The optimum ratio between reinforcement spacing and the diameter of the load piston, D for the highest strength ratio was about 0.8 (equivalent to the specimen reinforced by 2 reinforcement layers) due to confinement and membrane effect.

3.4. Behavior of soil and geotextile soil on UU shear strength in triaxial test

3.4.1. The swelling of soil and geotextile soil

The swelling of soil reinforcement was lower than that of unreinforcement, and these results were the same as those of in the CBR test.

3.4.2. The shear strength behavior of soil unreinforced and reinforced with geotextile in the unsaturated condition:

a) Shear strength behavior of soil unreinforced and reinforced by geotextile in the unsaturated condition

The deviation stress increased as the lateral pressure σ_3 and the number of geotextile layers increased. The reinforced geotextile sample had the same internal friction angle as the unreinforced sample. Still, the cohesive force was much higher, especially 3 times higher in the case of 3-geotextile layers.

b) The shear strength increasement R_{uf} in the unsaturated condition:

Results indicated that R_{uf} was greater than 1, showing that the reinforcement layers can increase the soil's strength. The R_{uf} value decreased as lateral pressure increased. The R_{uf} value increased as the number of fabric layers increased.

3.4.3. The shear strength behavior of soil unreinforced and reinforced by geotextile in the saturated condition.

a) Shear strength behavior of soil unreinforced and reinforced by geotextile in saturated conditions.

As the number of geotextile layers increased, the UU shear strength and the excess pore water pressure increased. In the strain range of 1% to 3%, the reinforced sample generated a higher water pressure than the unreinforced sample, as the geotextile prevented lateral expansion of the sample. As the strain increased, the soil sample developed lateral strain (sliding between the soil and geotextile), which decreased the water pressure.

b) The shear strength increasement R_f in the saturated condition:

The R_f index increased as the number of layers surged.

3.4.4. Shear strength reduction of the soil and soil reinforced by geotextile:

The results showed that the shear strengths of saturated samples were much lower than those of unsaturated ones, about 46.04 % - 82.38%.

3.5. Consolidation behavior of clay under effects of side friction

3.5.1. The one-dimensional consolidation behavior under the effects of side friction pressure

a) The strain of specimens:

The smaller axial strain was observed in the soil specimens with the higher initial height and the smaller diameter due to side friction.

b) The coefficient of consolidation: the higher the average consolidation pressure, the lower the coefficient of consolidation.

c) The void ratio at the end of the primary consolidation (EOP):

The void ratio at EOP of the specimens with the initial height, $H_0 \geq 30$mm, was significantly higher than those with lower H_0. It illustrates that for the cases of $H_0 \geq 30$mm, the friction between the soil and the ring was high enough to cause a significant reduction in the actual consolidation pressure.

d) Coefficient index:

The compression curves of all the soil specimens converged in a unique curve. It was because the effects of side friction on reducing the compression pressure were eliminated when using the average consolidation pressure to correct the compression curves (*e*-log*p*)

3.5.2. The total friction pressure and the friction pressure loss ratio

The value of T slightly increased with consolidation time. It would be due to the increment in the effective stress caused by water pressure dissipation. As a result, the effective lateral earth pressure rose and induced an increment in the total friction pressure, T. The higher total friction pressure was obtained for specimens with higher thicknesses and smaller diameters.

3.5.3. Modified Taylor's method to evaluate friction pressure loss ratio:

The height of soil specimens at end of primary consolidation (EOP), *H*, can be estimated by:

$$H = \alpha\left(1 - \frac{C_c}{1+e_0} log\frac{P}{P_0}\right) H_o \qquad (3.1)$$

In which $\alpha = \dfrac{1}{1-\frac{C_C}{1+e_0}\frac{2H_0}{D\ ln\ 10}K_0\ tan\ \varphi'_{int}}$ (3.2)

e_0 is the void ratio equivalent to the pre-consolidation pressure, P_0.

The friction pressure loss ratio, *r* (ratio between the difference in thi top and bottom pressure and the top pressure), would be modified:

$$r_{EOP} = 1 - e^{\frac{-4H_0}{D}\alpha\left(1-\frac{C_C}{1+e_0}log\frac{P}{P_0}\right)K_0\ tan\ \varphi'_{int}} \qquad (3.3)$$

3.5.4. The non-uniform density in the specimens caused by the side friction:

The void ratio of soil at depth z could be determined:

$$e_z = e_P + \frac{4z}{D\ ln\ 10}K_0\ tan\ \phi'_{int}C_c \qquad (3.4)$$

in which e_p: the void ratio under the compression pressure P acting on the top of the specimen. The average value of the void ratio:

$$e_{EOP\_predicted} = e_P + C_c\frac{2H_0}{D\ ln\ 10}\alpha K_0\ tan\ \phi'_{int} \qquad (3.5)$$

When considering constant K_0 and $tan\phi'_{int}$, the void ratio would increase proportionally with the depth.

3.5.5. The coefficient of variation, *COV*:

The coefficient of variation, *COV* (the ratio between the standard deviation and the average void ratio at EOP), could be evaluated:

$$COV = \frac{2H}{\sqrt{3}\, ln\, 10De_{EOP}} K_0 \tan\varphi'_{int} C_c \qquad (3.6)$$

The specimens subjected to a higher compression pressure, *P*, would exhibit a greater coefficient of variation. The requirement of $D/H_0 \geq 2.5$ not only ensures the homogeneity void ratio in the specimens (i.e., COV<1.2%), but it also limits the loss of consolidation pressure at EOP due to side friction to less than 21%.

3.6. Behavior of soil and geotextile-soil in one dimensional consolidation test

3.6.1. Primary consolidation

Consolidation time was reduced by approximately 1.5 to 2 times when adding a layer of geotextile. Geotextile enhanced the process of dissipating the excess pore water pressure. Due to the side friction, the average compression pressure was ultilised instead of the load compression.

3.6.2. Consolidation coefficient C_v:

The consolidation coefficient C_v increased due to its enhanced permeability. However, as the load developed, the C_v reduced.

3.7. Conclusion

A Series of tests, including CBR, UU triaxial, and consolidation test, were performed to investigate geotextile's effect on soil improvement due to the soaking process. The results illustrated that the side friction was significantly for soil with D/H < 2.5 and the critical role of reinforcement inclusion in enhancing bearing capacity and consolidation in both soaked and un-soaked conditions.

CHAPTER 4: BEHAVIOR OF SOIL REINFORCED BY SAND CUSHION UNDER CBR, UU, AND CONSOLIDATION TEST

4.1. Introduction

The research objectives of this chapter are:

- Effect of sand cushion on soil's swelling and CBR value in unsaturated and saturated conditions by the CBR test.
- Effect of sand cushion on the UU shear strength in unsaturated and saturated conditions by triaxial test to evaluate the soil capacity when constructed fast.
- Effect of sand cushion under the one-dimensional consolidation test.

Each objective corresponds to a type of test.

4.2. Experimental program

4.2.1. CBR specimens

8 specimens were reinforced with cushion sand for soaked and unsoaked conditions. The thickness of the sand cushion varied from 10mm to 15mm, 20mm, and 40 mm.

4.2.2. Unconsolidated-Undrained shear strength samples in triaxial test

There were 15 sand cushion samples with sand thicknesses ranging from 5mm to 10 mm and 20 mm. There were 2 types of tests, as follows:

- *Unsaturated samples*: samples will be tested at lateral pressures of 50 kPa, 100 kPa, 150 kPa, and 200 kPa.
- *Saturated samples*: samples will be saturated at 500 kPa pressure and tested at 300 kPa lateral pressure.

4.2.3. Consolidation samples

A layer of 10mm and 20mm sand was placed between geotextiles in the middle of the soil. The total height of the specimens was 40mm.

4.3. Behavior of soil and sand cushion-soil under the swelling and CBR test

4.3.1. Influence of the sand cushion on the swell behavior

In the first 30 hours, the percentage swell of reinforced specimens is higher than that of unreinforced specimens. However, at the end, the swells of the reinforced specimens were slightly smaller than those of the unreinforced specimens. The effect is due to the local lateral confinement from soil-reinforcement interaction.

4.3.2. The CBR behavior of unreinforced and reinforced specimens

Due to the reinforcement, the CBR value of reinforced specimens was higher than that of unreinforced specimens. Interestingly, the bearing capacity of the specimens was the highest for the specimens reinforced by a 1.5 cm thickness of the sand cushion, of which the ratio of the height of the topsoil layer, d1, and the diameter of the penetrated piston, B, was equal to 1.

4.3.3. Influences of soaking on the CBR behavior of unreinforced and reinforced specimens

Compared to the unsoaked specimens, the CBR value of the soaked specimens was much smaller, demonstrating the extreme reduction of the strength when saturated. The sand cushion not only enhanced the bearing capacity under both conditions but also minimized the strength reduction of the soil after soaking.

4.4. Behavior of soil and sand cushion soil on UU shear strength under triaxial test

4.4.1. The swelling of soil reinforced by sand cushion:

The swelling of soil reinforcement was lower than that of unreinforcement clay, and these results were the same as those in the CBR test.

4.4.2. The shear strength behavior of soil reinforced with a sand cushion in the unsaturated condition.

a) Shear strength behavior of unsaturated soil reinforced by a sand cushion:

The deviation stress increased as the lateral pressure σ_3 and the thickness of the sand cushion increased. When the 5 mm sand cushion was present, the cohesive force increased rapidly (about 2.7 times), but only slightly increased when the thickness of the sand cushion was increased fourfold. Similarly, the angle of internal friction increased from 15.7^o to 16.0^o and to 16.7^o when the ratio between the sand and soil dried weight increased to 0.053, 0.111, and 0.250, respectively.

b) The shear strength increasement Ruf in the unsaturated condition.

R_{uf} was greater than 1 at all lateral pressures, showing that the reinforcement can increase the soil's strength. The R_{uf} value decreased as lateral pressure increased. The R_{uf} value increased as the thickness of the sand increased.

4.4.3. The shear strength behavior of soil reinforced by a sand cushion in saturated conditions.

a) Shear strength behavior of the saturated soil reinforced by sand cushion.

Deviation stress increased when the axial strain and the thickness of the sand cushion increased. As the thickness of the sand cushion increased, the UU shear strength and the excess pore water pressure increased, as the sand cushion prevented lateral expansion of the sampls.

b) The shear strength increasement Rf in the saturated condition.

The strength increase index R_f when comparing the strength of unreinforced and reinforced soil, increased as the thickness of the sand increased.

4.4.4. Shear strength reduction T of soil and soil reinforced by sand cushion:

After soaking, the shear strength decreased. The larger the lateral stress and the thickness of the sand were, the higher the strength reduction T was.

4.5. Behavior of soil and sand cushion-soil under consolidation test

4.5.1. Estimate the height and the bottom of sand cushion under load:

Based on Section **Error! Reference source not found.Error! Reference source not found.**, the height (h_{sand}) and the bottom pressure (P_{b_sand}) of sand cushion under compression load P_{t_sand} were predicted, with an error under 7%.

4.5.2. The average pressure in soil and sand cushion

Due to the side friction between the soil, specifically sand, and the ring, the lost compression pressure must be considered.

The friction pressure in the sand cushion layer was much higher than that of the upper and lower soil, up to 1.9 times, leading to a high loss pressure in the average compression pressure, about 20%. The significant difference was due to the different materials. The average compression pressure was required for the consolidation procedure to be carried out.

4.5.3. The effect of the sand cushion on the soil consolidation process

a) Primary consolidation: The results indicated that consolidation was accelerated in the reinforced samples.

b) Consolidation coefficient C_v: The consolidation coefficient C_v rose due to its increased permeability. As the load increased, the C_v decreased.

4.6. Conclusion:

A series of tests, including CBR, UU triaxial, and consolidation tests, were performed to investigate the sand cushion's effect on soil improvement due to the soaking process. The results illustrated the critical role of reinforcement inclusion in enhancing bearing capacity and consolidation in both soaked and unsoaked conditions.

CHAPTER 5: BEHAVOIR OF SOIL REINFORCED BY CEMENT UNDER CBR, UU, CONSOLIDATION, AND SHEAR TEST

5.1. Introduction

The research objectives of this chapter are:

- Effect of cement ratio on soil's swelling and CBR value in unsaturated and saturated conditions by the CBR test.
- Effect of cement ratio on the UU shear strength in unsaturated and saturated conditions by triaxial test to evaluate the soil capacity.
- The behavior of soil cement on the one-dimensional consolidation test.
- The effects of cement content and curing time on the shear strength behavior of the cement-treated clay and steel interface. In addition, grain size analysis was conducted on the treated soil samples to reveal the effects of cement treatment on improving their structure, which led to an increase in shear strength. Using the peak and residual strength values, the brittleness of the treated soi was also evaluated. In addition, a correlation equation would be proposed to quantify the rate of shear strength and interface shear strength development in cement-treated soil specimens with curing time.

The cement content is defined as the mass ratio of cement to dry soil expressed as a percentage.

5.2. Experimental program

5.2.1. CBR specimens

Three specimens were reinforced with cement under wet conditions. The dried weight ratio of soil to cement was 3%, 5%, and 10%.

5.2.2. Unconsolidated-Undrained shear strength samples in triaxial test

The dried weight ratio of cement to soil was 3%, 5%, and 10%. The water was then added to the dried mixture at 24.5% water content and stored in the chamber for 28 days before testing. There were two types of tests, as follows:

- *Unsaturated samples*: samples will be tested at lateral pressures of 50 kPa, 100 kPa, 150 kPa, and 200 kPa, respectively.
- *Saturated samples*: samples will be saturated at 500 kPa pressure and tested at 300 kPa lateral pressure.

5.2.3. Consolidation samples

There were 4 specimens with dry cement at 3%, 5%, 7%, and 10%. The mixture and water were blended at 24.5% water content and then poured into the mold, which was 50mm in diameter and 20mm in height. The dry density of the soil in the samples was 1.25 g/cm^3.

5.2.4. Driect shear and interface shear samples

The number of samples were displayed as in the following table:

Table 5.1: Testing program

Material	Cement content, c_m (%)	Effective normal stress (kPa)	Curing period (days)
Type of test: Direct shear test under consolidated drained condition			
Untreated soil	0%	50, 100, 150, and 200	0
Cement treated soil	10%	200	3, 7, 14, 28, and 56
Cement treated soil	3%, 5%, 7%, and 10%	50, 100, 150, and 200	28
Type of test: Interface shear test under consolidated drained condition			
Untreated soil vs. stainless steel	0%	50, 100, 150, and 200	0
Cement treated soil vs. stainless steel	10%	200	3, 7, 14, 28, and 56
Cement treated soil vs. stainless steel	3%, 5%, 7%, and 10%	50, 100, 150, and 200	28

5.3. Behavior of soil cement under the swelling and CBR test

5.3.1. Influence of cement on the soil's swell behavior

At the initial time, the percent swell of unreinforced specimens was smaller than that of reinforced specimens. However, after about 20 hours, more swell was found in the unreinforced specimens. After 96 hours, the final swell of reinforced specimens was observed to be reduced with the higher ratio of cement.

5.3.2. The CBR behavior of unreinforced and reinforced specimens

For soaked specimens, at 28 days of curing time, the bearing capacity of the soil was significantly improved when reinforced by cement. The higher the cement content was, the higher the bearing capacity of reinforced specimens would be.

When the cement ratio increased to 3%, 5%, and 10%, the CBR values went up 1.7, 3.4, and 3.8 times.

5.4. Behavior of soil cement on UU shear strength under triaxial test

5.4.1. The shear strength behavior of unsaturated soil cement:

a) Shear strength behavior of unsaturated soil reinforced by cement:

When the cement content increased, the sample exhibited brittle failure with minimal deformation at the horizontal pressure of 50 kPa. As lateral pressure rose, the strain at failure increased. When the cement content increased, its strength increased dramatically.

When cement was presented, the cohesive force increased rapidly (about 3.6 times), especially nearly 6 times with a 5% cement ratio. In contrast, the angle of internal friction was nearly unchanged, about 20.5^0 with 3% and 5% cement, before increasing double to 46.5^o at 10% cement.

b) The shear strength increasement R_{uf} in the unsaturated condition.

Results indicated that R_{uf} was greater than 1 at all lateral pressures, showing that the soil's strength was improved. The R_{uf} value decreased as lateral pressure increased. The R_{uf} value increased as the cement content increased.

5.4.2. The shear strength behavior of soil cement in saturated condition.

a) Shear strength behavior of saturated soil reinforced by cement.

Deviation stress increased when the axial strain and the cement content increased. The larger the strain and the cement content were, the higher the deviation was. Because the soil cement samples failed at minimal strain (1%-2%) with brittle failure, excess pore water pressure went up slightly (about 6.5 kPa) before dropping significantly.

b) The shear strength increasement R_f in the saturated condition.

The strength increment index R_f was the ratio between deviations of soil cement and soil at failure. The cement index R_f increased with the cement ratio increment.

5.5. Behavior of soil cement under consolidation test

The results showed that the soil cement settles quickly and stabilizes after approximately 30 minutes. It is not possible to determine the consolidation time and consolidation coefficient C_v according to Taylor and Cassagrade's methods due to the limitations of these methods. Instead, secant modulus [64] was the characteristic of soil cement. It showed that the modulus of soil cement increased slightly, about 2 times, when the cement ratio increased from 3% to 7%, but the modulus in the case of 10% cement was 6 times higher than that of 3% cement at 23.74 kPa.

5.6. Grain size distribution of soil cement

In general, the particle size of the treated soil was larger than that of the untreated soil. It revealed a transition from predominantly clay-sized particles to silt-sized particles due to hydration and pozzolanic processes. β, the coefficients account the effects of cement on intergrate the fines particle to the sand size particles, was found. It increased from 0.018 to 0.135 when increasing the cement content from 3% to 10%. In other words, up to 13.5% of the fines content in the soil was transferred to sand size particles when treated with 10% of cement contents.

5.7. Interface shear strength behavior of cement treated soil under consolidated drained conditions:

5.7.1. Shear stress-strain behavior of cement stabilized soil under consolidated drained conditions

After 28 days of curing under various effective normal stresses, at the effective normal stress range of 50-200kPa, the peak shear strength of cement-treated soil specimens was substantially higher than that of untreated soil. More cement content increases the shear strength of treated soil sample. In addition, cement treatment shifted the stress-strain behavior of the untreated and treated soil specimens from ductile to brittle failure, respectively.

5.7.2. Behavior of interface shear strength between cement treated silty soil and steel under consolidated drained conditions.

After 28 days of curing, the interface shear strength of cement-treated soil with steel was greater but reached its maximum value at a smaller shear displacement than that of untreated soil and steel. Moreover, the increase in cement content led to an increase in peak interface shear strength and a reduction in peak shear displacement.

5.7.3. Result of effect of cement content on the shear strength and interface shear strength of cement treated soil.

The small effective cohesion of the untreated soil illustrated that the soil was under the normal consolidated condition. For the shear strength of the cement treated soil, it was manifested by relatively small increases in effective cohesions and significant increases in effective friction angle. Similarly, both the peak and residual effective interface friction angles, ϕ'_{int_max} and ϕ'_{int_res}, were higher when increasing the C_m value. In contrast, the slight increase in effective cohesion under consolidated drained shearing may expose weak particle bonding.

In addition, there was a significant difference between the peak and residual shear strength of cement-treated soil sample. Althought there was a little difference (about 2kPa) between the peak and residual effective cohesiveness of the cement-treated soil, c'_{max} and c'_{res}, a significant difference between the peak and residual effective residual friction angles, ϕ'_{max} and ϕ'_{res}. The difference would be greater as the cement content increased.

The strength ratio of cement-treated soil could also be evaluated using w/C_m:

$$R_s = \frac{15.191}{(w/C_m)^{1.019}} \tag{5.1}$$

5.7.4. Effect curing period on the shear strength and the interface shear strength of cement treated soil.

The lengthening of the curing period caused the shear and interface shear behavior of the treated soil to become more brittle.

A strong correlation ($R^2 = 0.981$) was found between the curing period and the strength development ratio of peak and residual strength derived from shear strength and interface shear strength of the treated soil samples:

$$R_{SD} = \frac{\tau_D^{max}}{\tau_{28}^{max}} = \frac{\tau_D^{res}}{\tau_{28}^{res}} = \frac{\tau_D^{int\_max}}{\tau_{28}^{int\_max}} = \frac{\tau_D^{res\_int}}{\tau_{28}^{res\_int}} = 0.2108\, ln(D) + 0.2833 \qquad (5.2)$$

in which

τ^{max}_{D}, τ^{res}_{D}, $\tau^{int\_max}_{D}$, and $\tau^{int\_res}_{D}$ are the peak shear stress, residual shear stress, peak interface shear stress, and residual interface shear stress after D days of curing period, respectively,

τ^{max}_{28}, τ^{res}_{28}, $\tau^{int\_max}_{28}$, $\tau^{int\_res}_{28}$ are the peak shear stress, residual shear stress, peak interface shear stress, and residual interface shear stress after 28 days of curing period, respectively.

5.8. Conclusion

A series of laboratory tests were conducted to examine the characteristics of cement-treated silty soil. Due to cement's hydration and pozzolanic reaction, the swelling, the CBR value, UU shear strength, the settlement and shear strength of the treated soil improved significantly.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1. Summary:

The primary goal of this research was to evaluate the capacity of reinforcements, including geotextile, sand cushion, and cement, to improve the soil's properties. The results confirmed that these methods could enhance soil characteristics, including swelling, strength, and consolidation. Besides, the modified oedometer apparatus and the modified Taylor's method were recommended to forecast the friction pressure and find the void ratio distribution. An analytical equation to evaluate *COV* values was suggested to quantify the level of uniformity of the void ratio along the depth of samples in one-dimensional consolidation experiments. Furthermore, by a modified direct shear test, the effects of effective normal stress, cement content, and curing period on the shear strength, and the interface shear strengt were investigated.

The minimum requiment of CBR load capacity for rural roads is 6 for the top 30 cm and 4 for the following 50 cm. Thus, soil after soaking was not satisfied for backfill. However, after being reinforced by geotextile, sand cushion, and cement, the swelling and the strength of the reinforced soil improved, which can replace sand for the road basement.

The main conclusions of this research were as follows:

a) Percentage of swelling

These methods reduced the swelling of the soil. They also reduce density loss after soaking. For the soil reinforced by geotextiles and sand cushion, the permeable reinforcement accelerates swelling by increasing the drainage path within the reinforced specimens. In the soil cement the hydration process occurred and blinded the soil grain together, leading to a decrease in the swell. A less percent expansion was observed as the number of geotextile layers, the sand cushion thickness, and the cement ratio increased. The reduction in dried unit weight due to soaking decreases.

b) CBR behavior

After soaking, the CBR values of the soil decreased dramatically. By using geotextile, sand cushion, and cement, the CBR value was improved significantly. Interestingly, for the geotextile-soil, the highest CBR value was obtained when the ratio between reinforcement spacing, and the diameter of the load piston achieved the optimum value of about 0.8 (2 geotextile layers samples). The observation can be explained by the mechanisms of reinforced soil under the load of a piston, including confinement effect and membrane effect. Under sand cushion reinforcement, again, the maximum improvement happened at soil with

15 mm of sand cushion, of which the ratio of the height of the topsoil layer, d1, and the diameter of the penetrated piston, B, got an optimum value equal to 1. The CBR increase in soil reinforced by geotextile and sand cushion in the case of soaking is greater than in the case of unsoaking.

For the soil cement, after 28 days of soaking, the CBR value of soil reinforced by 3%, 5%, and 10% cement was 1.7, 3.4, and 3.8 times higher than that of soaking soil. The increase was due to the hydration process, which blinded the soil grains together and increased their strength.

c) UU shear strength

After soaking, the UU shear strength of the soil decreased dramatically, from 46.04 % to 82.38%. Geotextile, sand cushion and cement improved UU shear strength for both unsaturated and saturated samples

The shear strength reduction decreased when the lateral pressure decreased. and the the number of geotextile layer and sand cushion thichness increased. In constract, in the case of unsoaked samples, the deviation stress increased. Additionally, the reinforced sample had the same internal friction angle as the unreinforced sample. Still, the cohesive force was much higher, especially 3 times higher in the case of 3-geotextile layers. Similarly, the cohesive force rose quickly (about 2.7 times) when a sand cushion existed, but slightly increased when the thickness of the sand cushion was increased fourfold.

For saturated samples, as the number of geotextile layers increased, the UU shear strength and the excess pore water pressure increased with the small strain as reinforcements can restrain the lateral deformation or the potential tensile strain of the soil. After that, the pore water pressure decreased.

The soil cement showes a brittle failure with minimal deformation. As the concentration of cement increased, its strength significantly increased. The cohesive force increased quickly as the cement ratio increased, whereas the angle of internal friction remained nearly the same. With the saturated samples, the results indicated that deviation stress increased when the axial strain and the cement content increased.

d) Consolidation

When estimating the consolidation behavior of cohesive soils with a D/H_0 greater than 2.5, evaluating the side friction is essential.

In this study, a modified oedometer apparatus was created to determine the side friction between the soil and the consolidation ring. The total side friction pressure grew marginally as consolidation time rose, but this resulted in an important reduction in the average consolidation pressure at the end of primary consolidation (EOP). As D/H_0 increases, the friction pressure loss ratio at EOP decreases. Furthermore, it declined as the compression pressure was raised. Besides, the proposed analytical method can accurately predict the values of r_{EOP} and e_{EOP} for clay within the normal consolidation pressure range without requiring the height of test specimens.

The void ratio at the conclusion of primary consolidation increases proportionally with depth due to side friction. Using COV values of the void ratio, the degree of soil sample uniformity at the EOP was determined. The COV values increase as the friction pressure loss ratio increases.

Regarding the effect of geotextile and sand cushion, the consolidation time significantly declined compared to that of soil, 1-2 times for geotextile samples and 3.5- 5 times for sand cushion samples. Thus, the geotextile and sand cushion, as a drainage path, can improve the soil's capacity and the consolidation process.

When the soil was added to cement, after roughly 30 minutes, the soil cement settled rapidly and stabilized. The secant modulus was displayed as one of the characteristics of soil cement. When the cement ratio increased, the modulus of soil cement increased. Furthermore, the settlement of the mixture decreased significantly, leading to an increase in the void ratio.

e) The effects of cement content and curing time on the shear strength behavior of the cement-treated clay and steel interface

Due to cement's hydration and pozzolanic reaction, the shear strength and interface shear strength of the treated soil specimens improved significantly. The remaining findings were as follows:

- The cement caused the treated soil's particle size to increase. Particularly, after 28 days of curing, the percentage of sand in soil treated with 10% cement decreased two-fold. That increment was due to the intergration of fines to sand size particles (about 13.8% at 10% of cement content) which was a result of cement treatment.
- The treated soil's shear strength and interface shear strength exhibited the brittle shear-strain and stick-slip phenomena, respectively. The increase in effective friction angle mostly contributed to the improvement in shear strength of the soil cement. In contrast, the treated soil exhibited an insignificant increase in effective cohesion.
- The higher the cement content, the greater the shear strength ratio of the soil treated with cement. For specimens containing 3-10% cement, the peak and residual average shear strength ratios ranged from 1.28 to 2.40 and 1.16 to 1.80, respectively. The cement also enhanced the soil-steel interface's strength parameters. At its peak, the average interface efficiency factor was approximately 1.55 when 10% cement content was added.

The proposed equation may be used to predict the rate of shear strength and interface shear strength development of cement-treated silty soil with curing period.

6.2. Limitations and recommendations:

The outcome of this study would be a fundamental theory to enhance rural road design by using reinforced clay as backfill instead of costly sandy soil for rural road foundations. Although the experimental findings cannot be directly used in the design of reinforced earth structures, they offer a method that is efficient, quick, and cost-effective for investigating and comprehending the behavior of reinforced soil. Thus, there needs to be more applied research about techniques, machines, and the small-scale model so that the methods can be widely used.