International Journal of GEOMATE, Jan., 2020, Vol.18, Issue 65, pp. 49 - 54
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2019.64.19076
Geotechnique, Construction Materials and Environment

EFFECT OF CEMENT AND BENTONITE MIXTURE ON THE CONSOLIDATION BEHAVIOR OF SOFT ESTUARINE SOILS

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*Corresponding Author, Received: 13 Sept.. 2019, Revised: 04 Oct. 2019, Accepted: 29 Oct. 2019

ABSTRACT: In order to study the effect of mixed cementitious materials on the consolidation behavior of soft estuarine soils in South East Queensland, a series of oedometer tests were performed in the geotechnical laboratory. To fulfill the objectives, specimens were prepared with different additive content of stabilizing agents and were cured for 7 and 28 days, in which cement content remained at 10 % while the content of bentonite was varied from 2.5% to 7.5%. The testing results indicate that both cement-treated and cement-bentonite treated samples represented a significant decrease in compressibility compared with untreated samples, in which cement-bentonite mixture shows higher effect on soil stabilization than cement only. However, with the increase of bentonite content, the consolidation behavior of cement-bentonite treated samples did not change consistently which indicates that the effectiveness of cement-bentonite mixture has no linear relationship with the bentonite content and the optimum bentonite content is around 5%.

Keywords: Soft Estuarine Soil, Cementitious Materials, Cement Stabilization, Bentonite Content, Curing Time

1. INTRODUCTION

Attributing to the rapid growth of population and urbanization, the scarcity of land resources has become a serious worldwide issue, especially in regions adjacent to estuaries where soils with poor geotechnical conditions are commonly encountered, for example South East Queensland and Northern New South Wales in Australia. Substantial infrastructure is required to be constructed in these regions, such as road embankments sitting on soft compressible estuarine soils can be common [2,3]. The most generally employed ground improvement techniques in these regions are prefabricated vertical drains or stone columns which involve the installation of pore pressure release mechanisms to accelerate consolidation [2,3]. The objective of this study is to investigate the suitability of the in-situ soil mixing method in this region and to investigate the optimum additive content of cementitious materials and to estimate suitable curing period.

A considerable amount of studies have proved that in-situ soil mixing method is the most suitable ground improvement technique to deal with soft soils, in which cement stabilization is one of the most commonly employed treatment methods due to the low cost, high efficiency and easy to obtain [6-9]. Cement stabilization is to improve the engineering properties through the flocculation, aggregation and reticulation effects between the soil particles and cementitious products which are produced by the hydration and pozzolanic reaction, for instance, increase strength and stiffness, decrease the compressibility, permeability, moisture content, etc [10-15]. Among them, soil compressibility is one of the most intuitive and important parameters generally investigated by means of oedometer test.

South East Queensland is a typical sedimentary area in Australia where the soft estuarine soils are commonly deposited [1-2,16]. However, the studies on the improved soft estuarine soils in this region are limited, especially the consolidation behavior of treated samples. Previous studies mainly investigated the effect of different additive content and curing period on the strength and stiffness of the treated SEQ soft soils by means of triaxial test and unconfined compressive strength test [2-3, 17-19]. However, the limitation of this research is that only strength and stiffness were investigated where the consolidation properties of improved soils hadn't been taken into account. Furthermore, only single type of cementitious material such as cement or lime was employed in their research without any other stabilizing agent or multiple mixing agent. Therefore, considering the previous experimental data and the cost, this study will investigate the consolidation behavior of improved SEQ soft estuarine soils which treated with 10% of cement and varying additive content of bentonite.

2. GEOLOGY OF SOUTH EAST QUEENSLAND AND SOIL PROPERTIES

Large areas of estuarine deposits are present throughout the South East Queensland area, generally occur on the lower lying coastal plains and often encountered to varying depths up to 30 meters. These estuarine deposits can be geologically classified as the sediments origin in the Holocene age since the end of the last ice age and as such have not been subjected to high pre-consolidation pressures. Figure 1 indicates the Geology of the study area in South East Queensland in which the area Q with bright green color represents the Holocene sediments [1]. Although this map does not indicate the deposits of soft estuarine soils, however, it shows the exact sites of Holocene deposits where soft estuarine soils are likely to be encountered.

The types of estuarine deposits that fall within the scope of this journal are the soft compressible estuarine soils deposited in a sedimentary form, which were collected from the Port of Brisbane. As shown in Figure 1, this study area is located near the Brisbane River and has deposited a large amount of soft and alluvial soils which has low strength and high potential in the settlement [1]. Furthermore, a motorway upgrade project in this area is currently in progress and appropriate ground improvement techniques are required to deal with the soft estuarine soils.

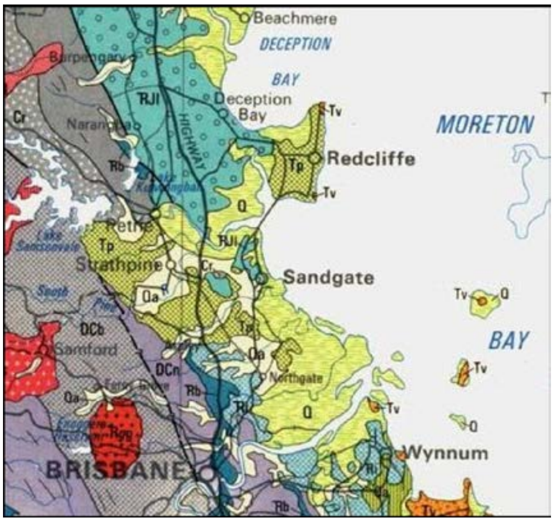

Fig. 1 Distribution of Holocene Deposits in Brisbane [1]

After the initial field tests, some undisturbed samples were collected from the study area and sealed in the heavy duty bag. Afterward, a series of laboratory tests were performed at the Geotechnical Laboratory.

The physical properties of soil samples from South East Queensland are summarized in Table 1.

Table 1 Physical properties of South East Queensland soil samples

Physical Properties	SEQ Soft Soil
Sand Content	57%
Clay Content	35%
Silt Content	8%
Liquid Limit	100%
Plastic Limit	35%
Plasticity Index	65%
Natural Moisture Content	60%-120%
Liquidity Index	0.96
Activity	2.64
Undrained Shear Strength	10-15 (KPa)
Compression Index	0.4-0.5
Coefficient of Consolidation	0.1-0.3
Creep ratio	>1
Colour	Dark brown – Dark grey
Organic Content	<10
Sensitivity	High

3. TESTING PROGRAM

Table 2 indicates the testing program of conventional oedometer tests. Based on the previous studies of SEQ soft estuarine soils and took the cost of materials into consideration, 10% of cement could be an appropriate additive content [2,3]. Remain the cement content constant and add varying content of bentonite to evaluate the effect of cement-bentonite mixture on soil stabilization.

Table 2 Testing Program of Conventional Oedometer test

Cement Content	Curing Time		
	7 Days	14 Days	28 Days
0%	x		x
10%	x		x
Cement Content	Bentonite Content	Curing Time	
		7 Days	28 Days
10%	2.5%	x	x
	5%	x	x
	7.5%	x	x

3.1 Sample Preparation

The samples need to be treated with stabilizing agents and cured for a specific period before the commencement of the consolidation tests. The processes of sample preparation are as follows:

The first step is to prepare the appropriate amount of bulk sample and stabilizing agents to perform the required tests at the target moisture content and additive content. The bulk sample is required to be thoroughly mixed by means of a mixing blender for 5 minutes to ensure a homogenous moisture condition before the addition of the stabilizing agents. The amount of required stabilizing agents was calculated on a percentage by dry weight basis and then mixed with water to form a slurry using a water-cement ratio of 0.5. Afterward, the cement slurry was added into the mixing blender and further mixed for 10 minutes. It should be noted that the blender should be stopped several times during the mixing process to allow mixing samples to be removed from the upper edge of the mixing bowl and mixing blade to ensure a homogeneous soil-cement blend.

After the mixing process, the thoroughly mixed sample was removed from the mixing blender and placed in a steel mold to produce a sample 100 mm in length and 50 mm in diameter. The amount of soil-cement mixture which required to produce a target bulk density is measured and split into three layers. Each layer is compacted to fill a measured volume of sample and the interface of each subsequent layer is achieved by ramming with a 10 mm rod. Samples were then removed from the prepared mold and placed in a thin-walled consolidation ring with 63.5 mm diameter. Afterward, the specimen was carefully trimmed, weighed, recorded and prepared for curing.

Specimens were then wrapped in waxed paper to ensure that there is no moisture ingress or egress during the curing process. The sealed and identified samples were then stored in a 100% humidity cupboard with 22 degrees centigrade for the specific curing period.

3.2 Test Equipment

The oedometer apparatus (Figure 2) consists of a thin walled retaining ring (which gives a lateral restraint to the sample), porous plates (which will placed on the top and bottom surface of the specimen and provide an axially drainage) and a cell base (which is a cast metal bottom sealed cylinder of sufficient depth to ensure the specimen and porous disks are covered by de-aired water during the test).

The top platen is seated beneath a lever loading system with a ten to one loading ratio and masses are applied at the end of the loading bar. A linear variable displacement transducer (LVDT) is located above the loading bar and connected with a data-logger which allows the measurement and record of vertical displacement.

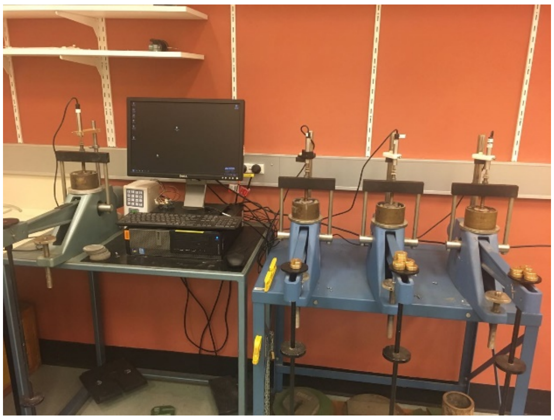

Fig. 2 Conventional Oedometer Apparatus

3.3 Testing Procedure

According to ASTM D2435-11 [5], place the assembled consolidation cell on the loading device and apply a seating load of 6 kPa to confirm seating errors were removed adequately. Apply the load based on the load increment ratio (LIR) by doubling the pressure on the specimen which commenced at 12.5 kPa and continued in doubling steps up to 1600 kPa. The standard unloading schedule should use the same ratio as LIR by halving the pressure. If desired, skip a decrement and unload as a ratio of one-forth. The standard loading increment duration shall be 24 hours or multiples thereof, depending on whether the primary consolidation of specimen is completed or not (Usually a period of 24 hours was employed). The deformation readings of specimen height and its corresponding time were collected by means of the linear variable displacement transducer (LVDT) and the data-logger and recorded by computer at set time intervals. At the end of the unloading phase, rebound the specimen back to the seating load and maintain it overnight, which can minimize the specimen swelling during dismantlement.

4. RESULTS AND DISCUSSION

4.1 Cement Treated Soft Soil

Figure 3 presents the typical e-log P curves of the cement-treated SEQ soft estuarine soils with the curing period of 7 and 28 days. It can be seen that the pre-consolidation stress of cement-treated soil is evidently higher than that of untreated soil, which attributes to the increase of the cementing bonds between cement and soil particles. When the applied stress exceeded the pre-consolidation stress, the curves of cement-treated soil are roughly parallel to that of untreated soil. The occurrence of this similar consolidation behavior was due to the fracture of cementing bonds between cement and soil particles. In conclusion, the increment of cement content will result in decrease incompressibility and increase in strength, however, beyond the pre-consolidation stress of the treated sample a similar but slightly reduced consolidation behavior can be anticipated to the untreated sample.

The effect of the curing period on consolidation properties of samples can be evaluated by comparing those two curves which have different curing time. A slight increase of pre-consolidation stress and a decrease of overall consolidation can be found, which indicates that the compressibility of soil samples decreases as the curing period increase. Meanwhile, it can be noted that the consolidation properties of the cement-treated sample improved substantially with a short curing period of 7 days, while 28 days curing didn't express a significant improvement. The reason was that the primary cementitious compounds which were produced by primary reaction provided higher strength than the secondary cementitious products, while this primary hydration process can be almost completed within a short curing period.

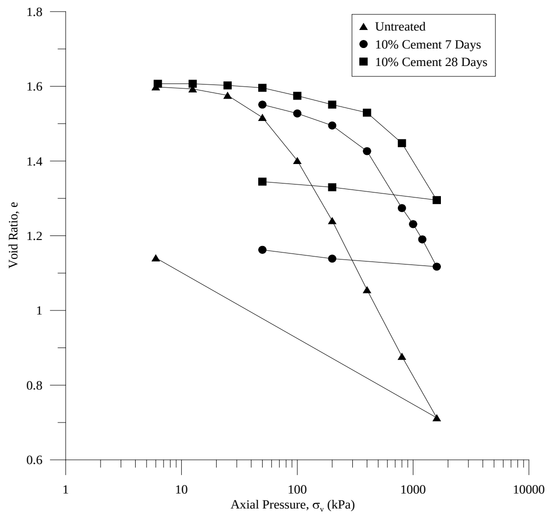

Fig. 3 Typical e-log P Curves of Cement Treated SEQ Soft Soils

The relationship between void ratio difference (Δe) and axial pressure (σ_v) of cement-treated soil was presented in Figure 4. Attributing to the cementation process in cement-treated soils, the initial void ratio of treated specimens is lower than those of untreated clay samples and compressibility is lower as well. Therefore, the void ratio difference Δ e decreases with the increment of cement content.

Before the pre-consolidation stress was reached, the slope of the void ratio difference curve of treated sample is lower than that of untreated specimens and increased gradually with the increment of applied stress. Eventually a similar changing behavior of void ratio difference occurred and the curves of treated samples were paralleled to the untreated one. As for the effect of curing time on Δ e-log P relationships of cement-treated clay, although longer curing period resulted in a decrease of void ratio difference however it didn't affect too much.

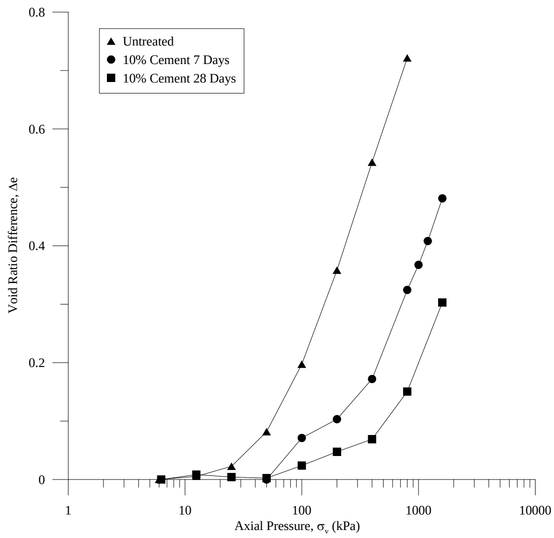

Fig. 4 Δ e-log P Relationships of Cement Treated Samples

4.2 Cement-Bentonite Treated Soft Soil

Plots of void ratio versus axial pressure in logarithmic scale were presented in Figure 5. It can be seen that the compressibility of cement-bentonite treated soil has a significant decrease comparing with untreated sample. However, with the increase of bentonite content, the consolidation behavior of samples did not change linearly. It is noted that the initial void ratio of samples with 5% bentonite content is much lower than those of samples with 2.5% and 7.5% bentonite content. Furthermore, the overall consolidation of samples with 5% bentonite content is the lowest as well. This phenomenon might attribute to that bentonite-water mixtures are generally used as a bonding agent when mixing with a small amount of water to improve the rigidity of soil mixture rather than plasticity. Clem and Doehler [4] found that the additive content of bentonite in a soil mixture, which used as a bonding agent, should generally be less than 5% by weight. However, in this study, 5% bentonite content became the optimum additive content which probably attributes to the higher natural moisture content of samples in this study area.

As for the effect of the curing period of cement-bentonite treated estuarine soil, the specimens had roughly the same pre-consolidation stress and the consolidation behavior except the overall consolidation. Longer curing period generally resulted in a smaller overall consolidation which was because the pozzolanic reaction in the stabilization process is a continuous reaction and generally takes a long time to react.

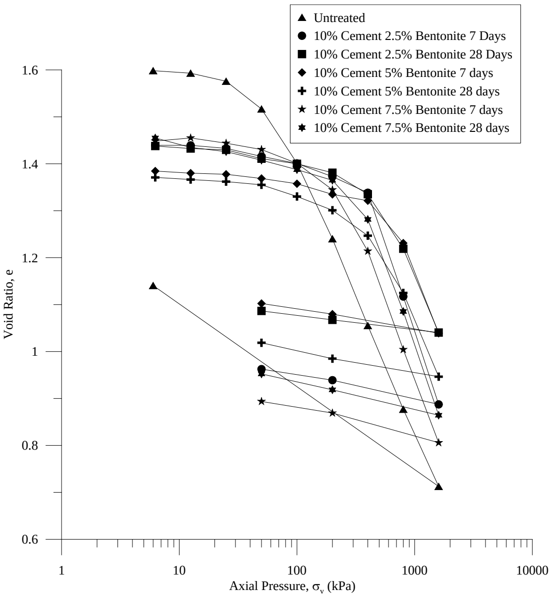

Fig. 5 e-log P Curves with 10% Cement and Varying Bentonite Contents

By referring to the curves in Figure 6, it can be noted that the behavior which was mentioned previously for cement-treated soil exists in the cement-bentonite treated specimens. However, the amounts of consolidation did not increase linearly with the increment of bentonite content. The specimens treated with 2.5 and 5% bentonite showed a reduction in void ratio difference at higher axial pressure, while the specimen with 7.5% bentonite content showed an increase in void ratio difference. This phenomenon indicates that the addition of bentonite accelerates the fracture of the cementing bonds in the sample when the applied stress exceeds the pre-consolidation stress which results in a higher overall consolidation. The consolidation behavior of these samples is almost the same until reaching the pre-consolidation pressure, which indicates that the acceleration in deconstruction of cementing bonds is not evident during stabilizing process.

By referencing the results summarized in Table 3, it can be found that the pre-consolidation stress of cement-bentonite treated estuarine soil is relatively higher than that of soil treated with cement only. Furthermore, the initial void ratio of cement-bentonite treated samples is lower as well which indicates that cement-bentonite treated clay shows higher effect on sample stabilization.

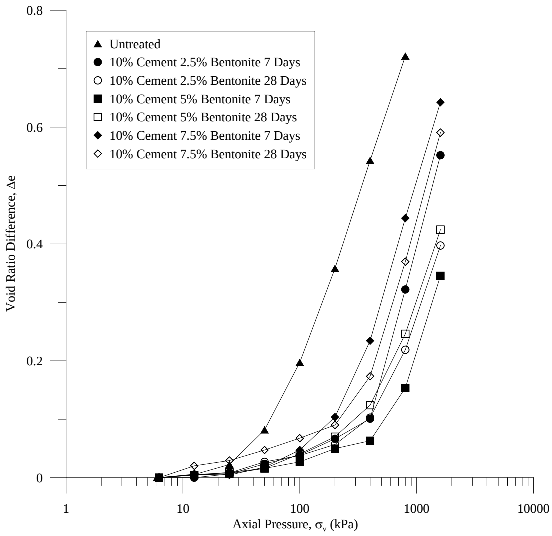

Fig. 6 Δ e-log P Relationships of Cement-Bentonite Treated Samples

4.3 Comparison between Cement Stabilization and Cement-Bentonite Stabilization

However, by analyzing the void ratio difference in Table 3, an interesting phenomenon can be found. The overall consolidation of cement-bentonite treated soil with 2.5% and 7.5 % bentonite content is higher than that of samples treated with cement only, while for the samples with 5% bentonite content the amounts of consolidation decrease. This indicates that the addition of bentonite accelerates the deconstruction of cementing bonds beyond the pre-consolidation stress and exhibits higher overall consolidation compared with samples which treated with cement only. A useful result might be come up with from these tests that the optimum additive content of bentonite should be around 5%.

Table 3 Summary of Testing Data

		Initial void ratio *e*		Pre consolidation pressure (kPa)		Void ratio difference *Δe*	
Cement Content		7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
Untreated		1.60		72		0.88	
10%		1.55	1.60	320	480	0.45	0.32
Cement content	Bentonite content	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
10%	2.5%	1.43	1.42	400	550	0.55	0.40
	5%	1.38	1.36	490	580	0.36	0.42
	7.5%	1.45	1.45	380	400	0.65	0.60

5. CONCLUSION

Both cement and cement-bentonite mixture express a positive effect on soil improvement which proves the suitability of In-situ Soil Mixing Method in South East Queensland region.

Higher cement content and longer curing period result in an increase in strength and decrease in compressibility, while the curing period has a limited effect on sample stabilization compared with additive content.

Cement-bentonite mixture shows a higher effect on sample stabilization compared to the samples which treated with cement only, for example the pre-consolidation stress of cement-bentonite treated clay is higher and the initial void ratio is lower than that of cement-treated soil. The effectiveness of cement-bentonite treated soil is depended on the additive content of bentonite which the optimum additive content is around 5%.

6. FURTHER RESEARCH

As for the further research recommendation, pore water pressure dissipation will be taken into account in the future tests by means of Rowe consolidation cell to obtain more reliable consolidation properties. Furthermore, more experiments with different types and content of cementitious materials (such as cement, lime, bentonite, fly ash, etc.) will be performed to figure out the optimum additive content and the most suitable stabilizing agent which can be used to deal with the soft estuarine soils in South East Queensland.

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