Experimental Study on Compression Behavior of Solidified Silt in Corrosive Site

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Abstract. The use of cement is a common technique to improve the bearing capacity of muddy coast foundation, and the determination of compression parameter of cemented soft clay is of great importance in the design process of solidification engineering. One-dimensional consolidometer was used to measure the vertical compression of cemented clay at different cement content and curing time. Test results indicate that cemented clay formed under seawater condition is a kind of strongly-structured soil with a relatively low compressibility. Yield stress increases with cement content and curing time, while compressibility decreases with the increase of cement content and curing time. The compress deformation is rather small with less vertical load, but significant compress deformation occurs when vertical load is greater than yield stress. Statistical data show that the yield stress can be used to represent the effect of cement content and curing time on compressibility of cemented clay. And a power function relationship exists between compressibility and the yield stress within the range considered in this study.

1. Introduction

In recent years, with the deepening of coastline resource development in China, more and more coastal ports construction projects are facing the problem of muddy foundation with poor natural water depth and geological conditions. Soils deposited in muddy coast are mainly composed of silt and clay with high water content, low shear strength and high sensitivity, and cement or lime cementitious materials are often used to improve its bearing capacity prior to construction[1-3]. However, the formation and use of cemented-soil in ocean engineering are always in contact with sea water. Therefore, it is of great practical significance to carry out the research on compression characteristics of solidified marine clay for the construction of coastal engineering.

Much work has been done regarding the physical and mechanical properties of cemented clay. And the research results show that cement content and curing time are the main factors affecting the strength property of cemented soil[4-6]. The micro-mechanism of strength increase and the corresponding strength calculation model are revealed and established[7-10]. But the influence of cement and water content on compression properties is mainly studied under routine conditions without erosion[11-13]. While the formation and service of cemented foundation are subjected to erosion under marine environment. The decomposition of the hydrate gel may cause the macroscopic change and strength deterioration of the reinforced body eventually[14-15]. And the long-term
stability of the cemented soil will be affected once the erosion accumulates to a stated point. The objective of this study is to present the compression behaviour of cemented clay formed in the environment of seawater corrosion condition, especially the compressibility of cemented clay with different cement content and curing time. And a computational model considering the influence of cement content and curing time on the compressive characteristics of reinforced soil is established. The research results can be used as a theoretical instruction for the reinforcement of muddy foundation.

2. Experimental investigation

2.1. Soil sample
The clay used in this study was collected from the Lianyungang Harbour, which lies to the west coast of the Yellow Sea, China. Lianyungang Port is located at typical muddy coast with deep soft clay stratum. The marine clay is thought to be deposited younger than 11,700 years. The first layer of submarine sedimentary is a kind of soft clay about 12 m thick according to in-situ survey data. And the soil is often distinguished by its high sensitivity and low strength. The clay is highly plastic with a natural water content which ranges from 55.8% to 68.2%. The bulk density of the soil is about 16.0 kN/m³ and the initial void ratio is about 1.6. The specific gravity of the soil is 2.72. The main physical parameters of the tested soil are shown in Table 1.

| Liquid limit (LL) (%) | Plastic value (PL) (%) | Sand particle (%) | Silt particle (%) | Clay Particle (%) | Cohesive force, c_q (kPa) | Internal friction angle (°) |
|----------------------|------------------------|-------------------|------------------|------------------|-------------------------|--------------------------|
| 78.5                 | 38.2                   | 3.6               | 48.2             | 48.2             | 9                       | 0.9                      |

2.2. Specimen preparation
To ensure the uniformity of the specimen, the sample preparation procedure employed in this study was as follows: first, air dry the soil sample collected from the field and sift the soil through a 1.0-mm sieve to remove shell and other impurities. Stir the prepared soil sample with cement power by electrical mixer until evenly dispersed according to the experiment scheme. Then place the mixed material into 61.8 mm diameter by 20 mm height ring-knife which was coated with Vaseline to decrease the friction between the knife and specimen as much as possible. During sampling, the specimen density was monitored carefully and maintained constant. At last, put the ring-knife into airtight cylinder block for vacuum saturation. After saturation, soak the ring-knife in sea water collected from the engineering site in humidity room under temperature of 25 degree Celsius and humidity of 97% until the lapse of different planned curing time.

2.3. Testing methodology
It should be pointed out that a specified dry soil density of 1.0 g/cm³ was selected in order to be consistent with engineering site. A cement content (a_c) of 4, 6, 8, 10 and 12%, and a curing time (T) of 7, 28, 60 and 90 days were selected. The cement content is defined as the ratio between the dry weight of the cement and the soil particles. Generally, the coefficient of compressibility (a_v) within the pressure range of 100 ~ 200 kPa are generally used to measure the compressibility of the soil in engineering practice. Oedometer tests were carried out with a load increment ratio of 1 for all of the load increments. The vertical confining pressure applied is 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa and 1600 kPa. And the vertical deformation of the specimens was monitored simultaneously at the same time.

3. Test results

3.1. Cement content
One dimensional compression test was carried out to study the effect of cement content on the compressibility of cemented clay. Specimens were prepared by using 4, 6, 8, 10, and 12% cement by
weight of dry soil particles. The compression curves during virgin loading are shown in Figure 1.

Figure 1 gives the compression curves of the marine clay–cement mixtures. These curves define the general behavior of cemented clay in terms of compressibility. It is apparent from these compression curves that almost all tested samples show little compression at a low vertical stress level, which indicates that, the specimens are initially much stiffer than its destructured state, and become gradually softer as the vertical stress increases. It can be deduced from the compression curves that some overconsolidation characteristics and a vertical yield stress has developed from mixing the clay with cement.

By taking samples with a 4% cement content in Figure 1(a) as an example, the compression curves with the same cement content but with different curing times define different lines, and the curves do not join to form one unique curve until a final applied loading of 1600 kPa.

Figure 2 gives the curves of coefficient of compressibility versus cement content. We can see that the coefficient of compressibility decreases with the increase of cement content. It can also be seen from the figure that the coefficient of compressibility decreases rapidly with cement content increases from 4% to 6%. But the decreasing trend is not that obvious for specimens with cement content of 8%, 10% and 12%.

The compression curves indicate that the compressibility of marine clay is greatly reduced after
mixing with cement. And the cemented clay is a kind of strongly-structures soil. Take the specimens with 7 days of curing in Figure 2 as an example, the coefficient of compressibility is 1.81 MP\(^{-1}\) with cement content of 4\% which belongs to high compressive soil. The coefficient of compressibility is 0.27 MP\(^{-1}\) with cement content of 12\% which belongs to high medium compressive soil. Take the specimens with 90 days of curing as an example, the coefficient of compressibility decreases from 0.63 MP\(^{-1}\) to 0.06 MP\(^{-1}\) with the increase of cement content. It can be seen that the soil change from high compressive soil to low compressive soil.

The vertical yield stress at which the soil starts to develop a large strain was determined from Figure 1 using the graphical procedure of Casagrande (1936) is shown in Figure 3. As can be seen from Figure 3, vertical yield stress increase with cement content. And the higher the cement content is, the greater the vertical yield stress is. This indicates that a commensurate amount of particle bonding formed in the clay as the result of hydration products cementation. The vertical compression leads to shear deformation under the condition that the lateral displacement is completely constrained. The small vertical deformation indicates that the cemented soil maintains strong shear resistance capacity. The variation of vertical yield stress with the increase of cement content is consistent with that reflected by compression curve.

3.2. Curing time

Figure 4 gives the curves of coefficient of compressibility versus curing time with different cement content added. It can be seen from Figure 4 that the coefficient of compressibility decreases with the increase of curing time. The test curves also state clearly that the decreasing trend is more significant within the first 28 days of curing. And the decreasing trend, while still present, becomes less and less significant at long curing time.

![Figure 4. Influence of curing time to coefficient of compressibility](image)

![Figure 5. Influence of curing time to vertical yield stress](image)

Based on analyzing the obtained data, we find that the coefficient of compressibility decreases from 1.81 MP\(^{-1}\) to 0.28 MP\(^{-1}\) when the curing time increases from 7 to 90 days with a cement content of 4\%. The soil change from high compressive to medium compressive. While the coefficient of compressibility decreases from 0.28 MP\(^{-1}\) to 0.06 MP\(^{-1}\) with a cement content of 12\%. The test results prove that the curing time is also an important parameter determining the compression behaviour of cemented clay.

The vertical yield stress of cemented clay with different curing time is shown in Figure 5. According to the test data given above, it can be seen that the vertical yield stress increase with curing time under different cement content condition. After mixing cement into soil, exchange reaction and aggregation between hydration products and vivacious clay minerals enhances the interparticle bonding and fabric combination. Figure 5 also shows out that the increasing trend of vertical yield stress slows down as the curing time increases. This mainly due to the hydration reaction of the cement and water at the primary curing ages and the pozzolanic reactions between the lime released by the cement and the clay minerals. Hydration and pozzolanic reaction products harden with time, thereby enhancing the strength of cement mixes.
4. Compressibility and yield stress
Cement content and curing time are decisive factors for strength and compression behaviour of cemented clay. Test results of the study show that the strength increases and the compressibility decreases with the increase of cement content and curing time. The curve about the coefficient of compressibility and vertical yield in different conditions is shown in Figure 6.

Figure 6. Change of coefficient of compressibility with vertical yield stress
Figure 6 shows out that the coefficient of compressibility decreases with increasing vertical yield stress. It can also be seen from the figure that the reduction extend is bigger when the vertical yield stress is small. And then the reduction goes down with the increase of vertical yield stress. The coefficient of compressibility falls from 1.81 MPa$^{-1}$ to 0.3 MPa$^{-1}$ as the vertical yield stress increases from 144.3 kPa to 600 kPa. While the coefficient of compressibility goes down to 0.06 MPa$^{-1}$ as the vertical yield stress increases to 1300 kPa. This means the economy of reducing settlement and deformation of soft foundation by increase adding quantity gradually deteriorates when the compressibility drops to a certain extent.

For this kind of marine clay mixed with cement, the coefficient of compressibility may be correlated to vertical yield stress by the following relationship:

\[ a_v = m \times \left( \frac{\gamma'}{p_0} \right)^n \]  

where \( p_0 = 1 \) kPa, \( \gamma' \) is vertical yield stress, and \( m \) and \( n \) are experimentally fitted values. For this kind of cement-treated marine clay, \( m = 2025 \) and \( n = -1.4 \), and the coefficient of determination \( R^2 \) is 0.89. Eq. (1) states clearly the potential use of yield stress in evaluating the compressibility of cement treated clay.

It can be concluded that the vertical yield stress reflects the influence of cement content and curing time on the compressibility of cemented clay. Previous studies showed that there is a linear function relationship between yield stress and unconfined compressive strength[16]. Then it seems reasonable to deduce that there exists a functional relationship between the coefficient of compressibility and unconfined compressive strength. Moreover, unconfined compressive strength is an easy to get parameter in the field, and it can be used to predict the compression characteristic of the soil.

5. Conclusion
This paper presents results of the laboratory one-dimensional compression test for Lianyungang marine clay admixed with cement under seawater erosion condition. The main objective of this study is to research the compressibility and its changing rule for marine clay with different cement content and curing time. The following conclusions can be drawn based on this research:

1. Cement content and curing time are the main factors affecting the compression behavior of cemented clay. And the coefficient of compressibility decreases with the increase of cement content and curing time.

2. The compression behaviour of cemented marine clay is significantly different before and after yield. The compressibility is small before yield but increases dramatically after yield.

3. Vertical yield stress increases as the cement content and curing time increases. And the higher the cement content and the longer the curing time, the greater the vertical yield stress.
(4) Vertical yield stress can reflect the influence of cement content and curing time on the compressibility of cemented clay. There is a power relationship between compressibility and the yield stress for cemented clay within the range considered in this study.

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