Increased sand content and its effect on the strength of cement-solidified soft clay

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Abstract: The clay minerals in the studied soft clay mainly include illite and montmorillonite. This clay has unfavorable geologic properties, such as a loose structure, fine-grained particles, a high water content, high compressibility, low strength, and a long drying time. Furthermore, this clay is easily deformed. In coastal areas where little land is suitable for development, the solidification of clay to enable the use of materials for engineering purposes has practical significance. In consideration of the economic and engineering aspects of the clay’s problem, a study on clay solidification was conducted. This paper presents the results of the research on the strength of Portland cement-stabilized soft clay with 5%, 10%, and 15% added sand. The results showed that the compressive strength of the cement-solidified clay increased as the sand content increased. The unconfined compressive strengths of the clay solidified with 5% cement and 5%, 10%, and 15% added sand were 49.91, 53.88, and 67.85 kPa, respectively. The unconfined compressive strengths of the clay solidified with 10% cement and 5%, 10%, and 15% sand were 86.00, 107.40, and 129.20 kPa, respectively. When the cement content was 5% and cylindrical samples of solidified clay were compressed uniaxially, the samples showed plastic failure. No strong skeletal structure was observed in the samples. When the cement content was 10% and the sand content was 15%, the samples exhibited strength and brittle failure. With 10% cement and 15% sand, the added constituents worked together with silt to form a strong structural skeleton.

Keywords: Sand content, Compression strength, Cement-solidified, Soft clay

1 Introduction

With the rapid development of China’s economy, increasing numbers of construction projects, such as water conservancy, land reclamation, port development, and waterway construction, have been observed. These projects involve the excavation of substantial amounts of soft clay (Wang, 2015). The disposal of soft clay requires a considerable area of cultivated land for stacking and storage. Hydraulic reclamation and dredging also produce large amounts of soft clay, which leads to increasingly serious environmental pollution and wasting of cultivated land by clay disposal.

The clay minerals in soft clay mainly include illite and montmorillonite; clay has a loose structure with very small mineral grains, a high water content, high compressibility, and low strength. In addition, clay is easily deformed and has a long drying time. Solidification is the main large-scale method used to modify clay for its use for engineering purposes (Shen et al., 1998; Zhu et al., 2014). Clay stabilization is an important method that aids in engineering construction (Huang et al., 2012; Xiong et al., 2011), especially in coastal areas with little land suitable for development (Xu et al., 2013; Xu et al; Wang et al., 2013; Jin et al., 2014).

After considering the economic and engineering aspects of clay stabilization, we added 5%, 10%, and 15% sand to clay containing 5% or 10% Portland cement for experiments on the compressive strength of cement-stabilized soft clay. Using the results of laboratory tests, this paper explored changes in the mechanical properties of soft clay and expanded our knowledge of the utilization of soft clay.
resources.

2 Test Materials, Design, and Testing Procedures

2.1 Materials
The cement used in the tests was 32.5 “Zuanpai” composite Portland cement. The soil was obtained from an embankment at the Qingyi River Basin project in Anhui Province, China, and the sand was ordinary river sand from Guanting reservoir, Hebei Province, China.

Table 1 lists the principal physical properties of soft clay tested as determined by relevant test procedures.

Table 1 Physical properties of the Qingyi River soft clay samples used in the experiments

| Material  | $W_0$ (%) | $\rho$ (g/cm$^3$) | $k$ (cm/s) | $W_l$ (%) | $W_p$ (%) |
|-----------|-----------|-----------------|-------------|-----------|-----------|
| Soft clay | 40        | 1.82            | $1.0 \times 10^{-6}$ | 32.10     | 20.40     |

2.2 Test design
According to a stability analysis report prepared for the Qingyi River flood diversion project, the maximum moisture content of the soft clay is 40%. For the tests we conducted, soils with 20% moisture were mixed with different proportions of cement and sand after the soil moisture content was increased to 40%. During sample preparation, the Code for Design of Cement Soil Mixing Proportions (JGJ 233-2011) and the Technical Manual for Mix Proportion Design and Test of Highway Engineering were referred to. To determine the effects of sand-cement mixing ratios on the sample strength, we carried out unconfined uniaxial compressive strength tests on the samples containing 5%, 10%, or 15% sand mixed with two different cement mixtures, namely, those with water-to-cement ratios of 5% and 10%. The samples were cured for 7 days before testing.

X-ray diffraction spectra for the clay-bearing soil samples showed that the minerals in the soil were mainly quartz, potassium feldspar, plagioclase, dolomite, amphibole, and clay minerals, with clay minerals accounting for 27.4% of the total mineral content. Illite comprised 28% of the clay minerals, and montmorillonite was not detected. Therefore, we excluded the influence of clay mineralogy on the test results.

Table 2 lists the cement and sand mixing ratios, sample densities, and curing times.

Table 2 Curing agent mixing ratios, sample densities, and curing times for the tested samples

| Mixing ratio of curing agent | Number of groups | Sample preparation density (g/cm$^3$) | Curing time (days) |
|-----------------------------|------------------|--------------------------------------|-------------------|
| Sand 5%                     | 2                | 1.89                                 | 7                 |
| Cement 5%                   |                  |                                      |                   |
| Sand 10%                    | 2                | 1.89                                 | 7                 |
| Sand 15%                    | 2                | 1.89                                 | 7                 |
| Sand 5%                     | 2                | 1.89                                 | 7                 |
| Cement 10%                  |                  |                                      |                   |
| Sand 10%                    | 2                | 1.89                                 | 7                 |
| Sand 15%                    | 2                | 1.89                                 | 7                 |

2.3 Testing procedures
The tests were carried out in accordance with the Design of Cement Soil Mixing Proportions (JGJ
T233-2011), technical manual for mix proportion design and test of highway engineering, specification of soil test (GB/T50123-2019), technical code for building foundation treatment (JGJ 79-2012), and with reference to relevant data from soft clay solidification tests carried out for similar projects.

To prepare a sample for the test, we mixed the cement, sand, and soft clay of appropriate moisture contents evenly in a container for 10 min. The mixed sample was placed in a mold and cured in a moisture- and temperature-controlled cabinet at 18 °C and 88% humidity. The sample was maintained in accordance with the requirements of T0845-2009, Test Method for Curing Inorganic Binder Stabilized Materials in JTG E51-2009 Test Code for Stable Materials of Highway Engineering. After 7 days, the sample was tested in accordance with 0805-1994, Test Method for Unconfined Compressive Strength of Inorganic Binder Stabilized Materials.

2.4 Test equipment
The unconfined compression test equipment, testing methods, and procedures were carried out in accordance with the Chinese National Standard GB/T50123-2019 for soil testing. A SANS Universal Testing Machine was used for the unconfined compression tests using an axial displacement rate of 1.0 mm/min. When the dynamometer reading reached its peak value, or the reading was stable, loading was continued to 3%–5% of the sample’s axial strain, and the test was stopped. If the reading was unstable, the sample was loaded to 20% of its axial strain.

3 Analysis of Test Results
As described previously, the soil samples tested for unconfined compressive strength contained 5%, 10%, or 15% sand and 5% or 10% Portland cement. The samples were cured for 7 days before testing. Figure 1 shows the uniaxial displacement and axial pressure curves for the samples; Table 3 lists the stress and strain data.

For soft clay with 5% or 10% cement, the results showed that the compressive strength of solidified soft clay increased with the increase in sand content. The average unconfined compressive strengths of the clay samples with 5% cement and 5%, 10%, and 15% sand were 49.91, 53.88, and 67.85 kPa, respectively. The average unconfined compressive strengths of the solidified soft clay samples with 10% cement and 5%, 10%, and 15% sand were 86.00, 107.40, and 129.20 kPa, respectively.

The stress–strain curves in Figure 1 show that in addition to different stress peaks, the slopes of the curve varied significantly after the samples exhibited failure.

When the curves for the solidified soils with 10% cement and 15% sand reached their peaks, the
Pressure drops were large, declines were steep, and brittleness was evident. When an additional pressure was applied, the stress decreased rapidly, indicating brittle failure with high strength and less deformation. When the cement content was 5%, except for the low strength, the stress–strain curves were relatively smooth and showed no distinct peak value. These findings indicate a plastic failure with low strength and considerable deformation. When the cement content was 10%, 5% sand and 10% sand, after the stress–strain curves reached their peaks, the declining curves showed no steep drops, implying that the samples were plastic. When additional pressure was applied, the stress decreased slowly, and the type of failure was between plastic and brittle.

Table 3 Measured and average unconfined compressive strengths of the tested samples

| Mixing ratio of curing agent | Mixing ratio of sand (%) | No. | Curing time (days) | Unconfined compressive strength (kPa) | Mean unconfined compressive strength (kPa) |
|---------------------------- |--------------------------|-----|--------------------|----------------------------------------|--------------------------------------------|
| 5%                         | 5                         | 1   |                    | 55.60                                  | 49.91                                      |
|                            |                           | 2   |                    | 44.21                                  |                                            |
|                            |                           | 3   |                    | 64.73                                  |                                            |
|                            |                           | 4   |                    | 99.02                                  |                                            |
|                            |                           | 5   |                    | 72.98                                  |                                            |
|                            |                           | 6   |                    | 67.85                                  |                                            |
|                            |                           | 7   |                    | 99.02                                  |                                            |
| 10%                        | 10                        | 9   |                    | 107.84                                 | 107.40                                     |
|                            |                           | 10  |                    | 106.96                                 |                                            |
|                            |                           | 11  |                    | 153.28                                 |                                            |
|                            |                           | 12  |                    | 105.11                                 |                                            |

Table 1 shows that given the same sand content, the unconfined compressive strength of solidified soil with 10% cement was significantly higher than that of soil with 5% cement; the 10% cement soil’s strength was approximately twice as high.

When the sample contained 5% cement and 5%, 10%, or 15% sand (Figures 2–4), the sample failed plastically. Thus, given these sand contents and a low cement content, the solidified soft clay acquired moderate strength, but no strong skeletal structure was formed in the soil.

Figure 2 Sample with 5% cement and 5% sand before (left) and after (right) testing
Figure 3 Sample with 5% cement and 10% sand before (left) and after (right) testing

Figure 4 Sample with 5% cement and 15% sand before (left) and after (right) testing

Figure 5 Sample with 10% cement and 5% sand before (left) and after (right) testing

Figure 6 Sample with 10% cement and 10% sand before (left) and after (right) testing
When the sample contained 10% cement and either 5% or 10% sand, the solidified soil’s stress–strain curve inflection points were relatively smooth (Figure 1). Several portions of the sample failed plastically, whereas the others underwent brittle failure. (Figures 5 and 6). These results indicate that for the samples with a high cement content, the cement combined with sand to form a strong skeleton in the soft clay soil to improve the soil strength. When the sample contained 10% cement and 15% sand (Figure 7), the failure mode was brittle failure, and the samples showed increased strength and less deformation before failing. These findings indicate that the cement and sand formed an improved and stronger structural skeleton in the soil, and the cement- and sand-bearing clayey silt was stronger than the other samples.

4 Conclusions

1. The results showed that the compressive strength of solidified soft clay soil with 5% or 10% Portland cement increased when the sand content increased. The average unconfined compressive strengths of solidified soft clay samples with 5% cement and 5%, 10%, and 15% sand content were 49.91, 53.88, and 67.85 kPa, respectively.

2. When the cement content was 10%, the unconfined compressive strengths of soft clay samples with 5%, 10%, and 15% sand were 86.00, 107.40, and 67.85 kPa, respectively. Given the same sand content, the unconfined compressive strength of solidified soil samples with 10% cement was approximately twice as high as that of samples with 5% cement.

3. When the cement content was 5%, no overall substantial structure was formed in the soil. However, when the cement content was 10% and the sand content was 5% or 10%, the soil revealed an increased strength to a certain extent, and when compressed, the failure mode was between plastic and brittle failures. When the cement content was 10% and the sand content was 15%, the cement and sand formed a stronger and more rigid framework. The clayey silt soil samples with 10% cement and 15% sand were stronger, and when compressed, they failed with brittle fractures.

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