Research on Unconstrained Compressive Strength and Microstructure of Calcareous Sand with Curing Agent

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Abstract: In the South China Sea, calcareous sand, as a natural foundation, has the features of low mechanical properties, including its compressive strength. With the development of South China Sea islands, the problems of calcareous sand foundation are encountered in the process. However, the experience of traditional pile foundation engineering could not be applied to calcareous sand. In this study, different proportions of curing agents were added to calcareous sand to improve the compressive strength. The quantitative analysis of the relationship between the unconfined compressive strength and microstructure of solidified calcareous sand is discussed. The unconfined compressive strength was gauged from unconfined compressive strength tests. Microscopic images, acquired using a scanning electron microscope (SEM), were processed using the Image-Pro Plus (IPP) image processing software. The microscopic parameters, obtained using IPP, include the average equivalent particle size (Dp), the average equivalent aperture size (Db), and the plane pore ratio (e). This research demonstrates that the curing agent could improve the compressive strength, which has a relation with the three microstructure parameters. The curing agent, through hydration reaction, generates hydration products, i.e., calcium silicate hydrate, calcium hydroxide, and calcite crystals. They adhere to the surface of the particles or fill the space between the particles, which helps increase the compressive strength. In addition, there is a good linear relationship between the macroscopic mechanics and the microscopic parameters. Using the mathematical relation between the macroscopic and microscopic parameters, the correlation can be built for macro-microscopic research.

Keywords: calcareous sand; curing agent; unconfined compressive strength; microstructure; SEM

1. Introduction

In the South China Sea, calcareous sand, as a geotechnical medium formed by marine organisms, is widely distributed. In the construction of the South China Sea project, calcareous sand, as a natural foundation, is characterized by low bearing capacity of foundation and small building load. However, with China’s strategic goal of “building a strong ocean power”, China will enhance the construction of the South China Sea island, including wharfs, airport runways, and various civil buildings. During the construction process, it will meet the problem of calcareous sand foundation [1–6].

A large number of studies have shown that calcareous sand is a kind of rock and soil material with internal porous, an irregular shape, and is easy to break. Among them, Wang [2] discussed the physical properties of calcareous sand. Wei [4] analyzed the internal pore characteristics of calcareous sand structure. Coop [5], Xiao [6], and Donohue [7] discussed the particle breakage of calcareous sand. Therefore, the mechanical properties of calcareous sand are different from those of common sand.

In addition, the traditional foundation treatment methods include mechanical compaction, chemical grouting, replacement treatment, and so on. Lehane [8] carried out the experimental study of
calcareous sand model piles, which indicated that the traditional pile foundation engineering may not be used in calcareous sand. Therefore, we need to implement measures to enhance the mechanical properties of calcareous sand foundation.

Nowadays, numerous scholars have performed a lot of research on enhancing the mechanical properties of calcareous sand. One of the methods is to use microbially induced calcite precipitation (MICP) technology for foundation treatment [1,3,9–17]. Ivanov [18] and Van Paassen [19] have proved that MICP could effectively improve the strength of soil. At the same time, De Jong [20] detected by SEM that MICP cement was calcite, which filled the pores between particles, enhancing the mechanical properties of soil. Xiao [21] carried out cyclic triaxial test on calcareous sand reinforced by MICP and found that microbial grouting could significantly improve the liquefaction resistance of sand columns and model foundations. Though the mechanical properties of the calcareous sand could be improved using MICP, the method is characterized by strict sampling conditions, complex operation, high sample preparation cost, and lack of good economic benefits. In the study, the curing agent was added to calcareous sand to improve the compressive strength. This method is not only simple to operate, but also can effectively improve the mechanical properties of calcareous sand. In addition, there is little quantitative research on its macroscopic and microscopic properties, and the majority of them could only determine the changing trend between the macroscopic and microscopic parameters, lacking good correlation. However, the research demonstrates the quantitative relationship between the unconfined compressive strength and microstructure of the solidified calcareous sand. Using the mathematical relationship between the macroscopic and microscopic properties, the correlation can be built for macro-microscopic research.

In this paper, by adding the curing agent to the calcareous sand, the mechanical properties of soil are improved, including its compressive strength. The effects of curing time and curing agent contents on solidified calcareous sands are investigated. The compressive strength and microstructural parameters are obtained using compression tests and SEM. Based on these, the quantitative dependence of the macroscopic and microscopic parameters is established, not just the trend between them, so as to explain how the macroscopic parameters change as the microscopic parameters change more reasonably and intuitively.

2. Materials and Methods

2.1. Sample Preparation

The calcareous sand used in this study is from an island reef in the South China Sea. In order to achieve easy compaction during sample preparation and to obtain the maximum degree of compactness, it is necessary to obtain the optimum soil water content using compaction testing. The moisture content was 20%, the specimens were separated into four groups, and the curing agent contents were 6%, 8%, 10%, and 12%. The mold size for filling test soil sample was 70.7 mm × 70.7 mm × 70.7 mm. To determine the quantitative relationship between the macroscopic and microscopic properties, the curing ages for the samples were 7 days, 14 days, 21 days, 28 days, 35 days, 42 days, 56 days, 72 days, 90 days, and 180 days. This is because the sample changes significantly during the early periods of curing, while it changes little in the later periods of curing. Therefore, the intervals between the early periods of curing are short, but the ones between the later periods are longer.

The compaction tests, following standard GB T50123-1999, involved placing the soil into a compaction cylinder and striking the soil with a hammer according to the prescribed drop distance for a certain number of times, during which the relationship between the moisture content and the dry density was measured. When the dry density reached the maximum value, the corresponding moisture content was the optimum water content.

Before the preparation of soil samples, the soil was cleaned and dried to remove a few large particle impurities in the undisturbed sand. The mean particle diameter $d_{50} = 0.31$ mm, the inhomogeneity
coefficient $C_u = 2.19$, the curvature coefficient $C_c = 0.91$, the maximum pore ratio $e_{\text{max}} = 1.74$, and the minimum pore ratio $e_{\text{min}} = 1.28$.

During sample preparation, curing agent with contents of 6%, 8%, 10%, and 12% were added to the calcareous sand following standard GB 50010-2010. Then, water was added (until a water content of 20% was reached) and the soil was mixed well. In addition, the mixed soil sample was placed in a mold. The sample was tampered down with a tamping rod. After this, the entire soil sample and the mold were placed in the curing box at 20 °C and 99% humidity. The curing period was 7 days, 14 days, 21 days, 28 days, 35 days, 42 days, 56 days, 72 days, 90 days, and 180 days. Finally, the sample was removed from the curing box to continue the follow-up experiment.

The curing agent used in the test is a self-made curing agent, which contains a variety of materials, including ordinary Portland cement, lime (CaO), sodium sulfonate, acrylamide, and so on. The main components of the cement are reported in Table 1.

Table 1. Main Components of the Cement (%).

| Component | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | K₂O | Na₂O | P₂O₅ | TiO₂ | SO₃ |
|-----------|------|-------|-------|-----|-----|-----|------|------|------|-----|
| Value     | 21.04| 6.94  | 2.36  | 61.27| 1.32| 1.02| 0.27 | 0.12 | 0.38 | 2.31|

2.2. Test Method

The entire experimental process is illustrated in Figure 1. First, curing agents (6%, 8%, 10%, and 12%) were added to the calcareous sand from an island reef in the South China Sea to prepare samples. Then, the samples were placed in the curing box. In addition, the unconfined compressive test was conducted to determine the compressive strength of a sample. Meanwhile, microscopic images were obtained using a SEM. Next, the microscopic images were processed using the IPP processing software, and the microstructural parameters were obtained. Based on the above-described macroscopic and microscopic data, the corresponding microstructure and compressive strength were respectively taken as the X-axis and the Y-axis for a certain curing period and curing agent. Then, a rectangular coordinate system was established, and a fitting curve was drawn. Finally, the quantitative relationship between the compressive strength and the microstructural parameters was discussed.

Three samples were tested for each curing age (7 d, 14 d, 21 d, 28 d, 35 d, 42 d, 56 d, 72 d, 90 d, and 180 d) and curing agent content (6%, 8%, 10%, and 12%). For a certain curing age and curing agent content, the unconfined compressive strength and microscopic parameters of the three samples were measured respectively. The average value of each parameter was taken as the final measurement result. Table 2 shows the experimental scheme for each curing age and curing agent content.

The machine used in the unconfined compression test is shown in Figure 2. The type of the machine is DYE-2000. The experimental process of the unconfined compression test following standard GB T50123-1999 is as follows.

1. The sample was taken from the curing box and was placed on the base of the machine. The handwheel was turned so that the pressure plate was slowly dropped to just contact with the sample, and the dynamometer reading was adjusted to zero.
2. The switch of the machine was turned on and the sample was pressurized until the soil was broken. The test should be completed within 8 to 10 minutes.
3. When the dynamometer reading peaked or stabilized, the data were recorded, and the test was completed.
The entire experimental process is shown in Figure 1. The experimental scheme for each curing age and curing agent content is presented in Table 2.

**Figure 1.** The entire experimental process.

**Table 2.** The experimental scheme for each curing age and curing agent content.

| Sample (70.7 x 70.7 x 70.7 mm) | Unconfined Compressive Strength | Average Value | Sample (10 x 10 x 20 mm) | Microscopic Parameters | Average Value |
|-------------------------------|---------------------------------|---------------|---------------------------|------------------------|---------------|
| 1                             | √                               |               | 1                         | √                      |               |
| 2                             | √                               | √             | 2                         | √                      | √             |
| 3                             | √                               |               | 3                         | √                      |               |

**Figure 2.** The machine for the unconfined compression test.
The SEM analysis was conducted using a field emission scanning electron microscope (FE-SEM) made in Japan. The following SEM analytical procedure was used.

1. Soil samples were removed from the curing box. Then, the soil samples were removed from the mold, and cut into small $10 \times 10 \times 20$ mm samples with a knife.
2. The samples were dehydrated for one day before the scanning electron microscopy analysis. The oven drying method was adopted to dehydrate the samples.
3. After dehydration and drying, the specimens were broken, and the SEM analysis was performed on the flat fracture surface. If the surface of a sample was not flat enough, the brightness of the SEM image deviated, and the resulting image was not clear enough.
4. Because the samples were not conductive, it was necessary to conduct the gold sputtering on the samples. When the sputtering was being treated, we were careful to control the spraying time. Spraying for too long leads to an excessively thick gold film on a sample’s surface, which may cover the undisturbed structure of the solidified calcareous sand. Spraying for too short a time results in insufficient conductivity and unclear images. In this test, the sputtering speed was $10$ mm/min and the sputtering time was $60$ s.
5. The sample was treated by sputtering before the scanning electron microscopy was conducted.

The microscopic images of the solidified calcareous sand were processed and analyzed using IPP. Gu et al. [22], Vito et al. [23], and Yang et al [24,25] introduced these specific practices. The processing steps are as follows.

1. Image segmentation is defined as the binarization of an image, which converts the image into a black and white image by determining a threshold. At present, there is no standard method for the binarization of microscopic images, so only a certain range of thresholds can be determined. In this study, through constant adjustment of the threshold, the binary image, which best reflects the true appearance of the solidified calcareous sand, was selected as the object of analysis.
2. Image morphology processing was conducted in order to remove the isolated highlights and black spots during image acquisition and processing, without destroying the original image structure.
3. The measuring units were calibrated. The image is in pixels, but our research requires an area size, so we need to add new rulers using the software. It can be calibrated using the scale of the SEM image.
4. The measurement parameters for the measurement were selected. The number and area of the pores and particles need to be calculated in this study.
5. The measurement data were extracted. After the measurement was completed, the measurement data were extracted and analyzed.

3. Test Results

3.1. Compression Test and SEM Results

The unconfined compressive strength values of the solidified calcareous sands for different curing periods and curing agent contents are reported in Table 3. As the curing period and curing agent content increase, the compressive strength of the solidified calcareous sand increases.

The relationship between the unconfined compressive strength and the curing period is reported in Figure 3. Figure 3 illustrates that for the same curing agent content, the compressive strength of the solidified calcareous sand will increase with the increase of curing time, and the compressive strength will not increase after 90 days of the curing period.
Table 3. The unconfined compressive strength of the solidified calcareous sand (MPa).

| Curing Period T (d) | Content of Curing Agent λ (%) | 6   | 8   | 10  | 12  |
|---------------------|-------------------------------|-----|-----|-----|-----|
| 7                   |                               | 1.596 | 2.574 | 3.906 | 4.771 |
| 14                  |                               | 1.885 | 2.752 | 4.120 | 5.178 |
| 21                  |                               | 2.228 | 3.122 | 4.685 | 5.727 |
| 28                  |                               | 2.427 | 3.707 | 4.975 | 5.967 |
| 35                  |                               | 2.512 | 3.889 | 5.112 | 6.022 |
| 42                  |                               | 2.594 | 3.968 | 5.201 | 6.113 |
| 56                  |                               | 2.643 | 4.026 | 5.286 | 6.179 |
| 72                  |                               | 2.661 | 4.065 | 5.329 | 6.217 |
| 90                  |                               | 2.670 | 4.079 | 5.354 | 6.239 |
| 180                 |                               | 2.672 | 4.082 | 5.360 | 6.243 |

Figure 3. Relationship between the unconfined compressive strength and the curing period.

It is due to the hydration reaction of the curing agent. The hydration reaction equation is as follows:

\[
3\text{CaO} \cdot \text{SiO}_2 + 7\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{Ca(OH)}_2, \\
2\text{CaO} \cdot \text{SiO}_2 + 5\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{Ca(OH)}_2
\]

The calcium silicate hydrate is hydrated by the hydration reaction. Its microstructure is flocculent, and it possesses strong cementation. The calcium hydroxide, which has a flaky microstructure, adheres to the particle surfaces or fills in the pores, so it plays a role in solidifying the calcareous sand.

In addition, the prismatic calcite crystal is produced by the reaction of the calcium hydroxide and the carbon dioxide. The calcite crystal, which has strong cementation, connects loose soil samples into a whole structure.

The hydration products are flocculent calcium silicate hydrate (Figure 4a), flaky calcium hydroxide (Figure 4b), and prismatic calcite crystal (Figure 4c). Based on the above analysis, by adding the curing agent to the calcareous sand, the hydration products, produced by the hydration reactions, help improve the compressive strength of the solidified calcareous sand.
where:

- $d$ is the diameter of the equivalent circle equal to the area of the particle unit ($\mu m$); $A_i$ is the area of the particle unit ($\mu m^2$); and $n$ is the number of particles in the analyzed area.

The microscopic appearance of the solidified calcareous sand is shown in Figure 5. Figure 5 indicates that the curing agent added to the soil generates hydration products through the hydration reaction of the curing agent. The hydration products adhere to the surface of the particles and fill the voids between the particles. Thus, the surface of the particles becomes rougher, which contributes to the increase in compressive strength.

The microscopic appearance of the solidified calcareous sand is shown in Figure 5. Figure 5 indicates that the curing agent added to the soil generates hydration products through the hydration reaction of the curing agent. The hydration products adhere to the surface of the particles and fill the voids between the particles. Thus, the surface of the particles becomes rougher, which contributes to the increase in compressive strength.

The average equivalent particle size $D_p$ is the average value of the equivalent diameter of all of the particles in the analyzed area.

The calculation formula is as follows:

$$D_p = \frac{\sum d_i}{n}$$  \hspace{1cm} (1)

$$d_i = 2\pi \frac{1}{2} A_i^{\frac{1}{2}}$$  \hspace{1cm} (2)

The average equivalent particle sizes of the solidified calcareous sand for different curing periods and curing agent contents are reported in Table 4. According to Table 4, as the curing agent content increases, the average equivalent particle size also increases.
Table 4. The average equivalent particle size of the solidified calcareous sand (µm).

| Curing Period T (d) | Content of Curing Agent λ (%) | 6  | 8  | 10 | 12 |
|---------------------|-------------------------------|----|----|----|----|
| 7                   |                               | 2.63 | 2.86 | 3.15 | 3.44 |
| 14                  |                               | 2.71 | 2.95 | 3.23 | 3.57 |
| 21                  |                               | 2.88 | 3.06 | 3.35 | 3.66 |
| 28                  |                               | 2.94 | 3.24 | 3.49 | 3.77 |
| 35                  |                               | 3.02 | 3.32 | 3.56 | 3.82 |
| 42                  |                               | 3.09 | 3.38 | 3.64 | 3.89 |
| 56                  |                               | 3.14 | 3.42 | 3.69 | 3.94 |
| 72                  |                               | 3.17 | 3.45 | 3.76 | 3.97 |
| 90                  |                               | 3.20 | 3.47 | 3.80 | 3.99 |
| 180                 |                               | 3.21 | 3.47 | 3.83 | 4.01 |

The average equivalent aperture size \( D_b \) is the average value of the equivalent diameter of all of the pores in the analyzed area.

The calculation formula is as follows:

\[
D_b = \frac{\sum d_i}{N}, \tag{3}
\]

\[
d_i = 2\pi \frac{1}{2} A_i^{\frac{3}{2}} \tag{4}
\]

where: \( d_i \) is the diameter of the equivalent circle that is equal to the area of the pore unit (µm); \( A_i \) is the area of the pore unit (µm²); and \( N \) is the number of pores in the analyzed area.

Table 5 shows the average equivalent aperture sizes of the solidified calcareous sands for different curing period and curing agent contents. As the content of curing agent increases, the average equivalent aperture size decreases.

Table 5. The average equivalent aperture size of the solidified calcareous sand (µm).

| Curing Period T (d) | Content of Curing Agent λ (%) | 6  | 8  | 10 | 12 |
|---------------------|-------------------------------|----|----|----|----|
| 7                   |                               | 2.11 | 2.08 | 1.93 | 1.86 |
| 14                  |                               | 2.01 | 1.99 | 1.85 | 1.79 |
| 21                  |                               | 1.92 | 1.87 | 1.71 | 1.62 |
| 28                  |                               | 1.83 | 1.79 | 1.64 | 1.57 |
| 35                  |                               | 1.77 | 1.73 | 1.58 | 1.52 |
| 42                  |                               | 1.73 | 1.68 | 1.53 | 1.48 |
| 56                  |                               | 1.69 | 1.64 | 1.49 | 1.43 |
| 72                  |                               | 1.67 | 1.61 | 1.46 | 1.41 |
| 90                  |                               | 1.65 | 1.59 | 1.44 | 1.39 |
| 180                 |                               | 1.65 | 1.58 | 1.43 | 1.38 |

The plane pore ratio \( e \) is the ratio of the total area of the pores to the total area of the particles in the analyzed area.

The calculation formula is as follows:

\[
e = \frac{S_b}{S_p}, \tag{5}
\]

where: \( e \) is the plane pore ratio; \( S_p \) is the particle area in the analyzed area (µm²); and \( S_b \) is the pore area in the analyzed area (µm²).

The plane pore ratio of the solidified calcareous sands for different curing time and curing agent contents are reported in Table 6. As the increase in curing agent content rises, the plane pore ratio decreases.
4. Relationships Between the Unconfined Compressive Strength and the Microstructural Parameters

The compressive strength of the solidified calcareous sand for different curing periods and curing agent contents can be obtained based on the results of the unconfined compression tests. Furthermore, the microscopic images were obtained from the SEM analysis. After the images were processed using IPP and computed, the microscopic parameters of the solidified calcareous sand were obtained for different curing periods and curing agent contents. Based on the above macroscopic and microscopic data, for a certain curing period and curing agent content, the corresponding microscopic parameters and compressive strength were obtained. Then, they were used as the X-axis and Y-axis, respectively, the image coordinates were established, and the fitting curves between these parameters were drawn. Using this process, the quantitative dependence between the compressive strength and the microscopic parameters were obtained.

Based on the above methods, the microscopic parameters (x-axis) and the compressive strength (y-axis) of the solidified calcareous sand for diverse curing periods and curing agent contents are shown in Tables 7–9.

The relationship between the unconfined compressive strength and the average equivalent particle size is shown in Figure 6. According to Figure 6, for the same curing agent content, as the average equivalent particle size increases, the unconfined compressive strength increases linearly. Based on the analysis of the previous SEM images, due to the hydration reaction of the curing agent, hydration products, i.e., calcium silicate hydrate, calcium hydroxide, and calcite crystal, are attached to the surface of the particles, resulting in an increase in the average equivalent particle size. Therefore, the increased bonding force between the soil particles contributes to the increase in compressive strength.

Table 6. The plane pore ratio of the solidified calcareous sand.

| Curing Period T (d) | Content of Curing Agent λ (%) |
|---------------------|-------------------------------|
|                     | 6    | 8    | 10   | 12   |
| 7                   | 0.433| 0.426| 0.411| 0.401|
| 14                  | 0.415| 0.409| 0.395| 0.386|
| 21                  | 0.397| 0.388| 0.373| 0.367|
| 28                  | 0.379| 0.369| 0.355| 0.347|
| 35                  | 0.364| 0.354| 0.341| 0.333|
| 42                  | 0.351| 0.342| 0.332| 0.318|
| 56                  | 0.343| 0.334| 0.326| 0.309|
| 72                  | 0.339| 0.329| 0.322| 0.305|
| 90                  | 0.337| 0.326| 0.320| 0.303|
| 180                 | 0.336| 0.325| 0.319| 0.302|

Table 7. The average equivalent particle size (x-axis) and the compressive strength (y-axis).

| Curing Period T (d) | Content of Curing Agent λ (%) |
|---------------------|-------------------------------|
|                     | 0    | 2    | 4    | 8    |
| 7                   | (2.63,1.596)| (2.86,2.574)| (3.15,3.906)| (3.44,4.771)|
| 14                  | (2.71,1.885)| (2.95,2.752)| (3.23,4.12)| (3.57,5.178)|
| 21                  | (2.88,2.228)| (3.06,3.122)| (3.35,4.685)| (3.66,5.727)|
| 28                  | (2.94,2.427)| (3.24,3.707)| (3.49,4.975)| (3.77,5.967)|
| 35                  | (3.02,2.512)| (3.32,3.889)| (3.56,5.112)| (3.82,6.022)|
| 42                  | (3.09,2.594)| (3.38,3.968)| (3.64,5.201)| (3.89,6.113)|
| 56                  | (3.14,2.643)| (3.42,4.026)| (3.69,5.286)| (3.94,6.179)|
| 72                  | (3.17,2.661)| (3.45,4.065)| (3.76,5.329)| (3.97,6.217)|
| 90                  | (3.2,2.67)| (3.47,4.079)| (3.8,5.354)| (3.99,6.239)|
| 180                 | (3.21,2.672)| (3.47,4.082)| (3.83,5.36)| (4.01,6.243)|
Table 8. The average equivalent aperture size (x-axis) and compressive strength (y-axis).

| Curing Period T (d) | Content of Curing Agent λ (%) | 0  | 2  | 4  | 8  |
|---------------------|-------------------------------|----|----|----|----|
| 7                   | (2.11, 1.596)                | 2.08, 2.574 | 1.93, 3.906 | 1.86, 4.771 |
| 14                  | (2.01, 1.885)                | 1.99, 2.752 | 1.85, 4.12 | 1.79, 5.178 |
| 21                  | (1.92, 2.228)                | 1.87, 3.122 | 1.71, 4.685 | 1.62, 5.727 |
| 28                  | (1.83, 2.427)                | 1.79, 3.707 | 1.64, 4.975 | 1.57, 5.967 |
| 35                  | (1.77, 2.512)                | 1.73, 3.889 | 1.58, 5.112 | 1.52, 6.022 |
| 42                  | (1.73, 2.594)                | 1.68, 3.968 | 1.53, 5.201 | 1.48, 6.113 |
| 56                  | (1.69, 2.643)                | 1.64, 4.026 | 1.49, 5.286 | 1.43, 6.179 |
| 72                  | (1.67, 2.661)                | 1.61, 4.065 | 1.46, 5.329 | 1.41, 6.217 |
| 90                  | (1.65, 2.67)                 | 1.59, 4.079 | 1.45, 5.354 | 1.39, 6.239 |
| 180                 | (1.65, 2.672)                | 1.58, 4.082 | 1.43, 5.36 | 1.38, 6.243 |

Table 9. The plane pore ratio (x-axis) and the compressive strength (y-axis).

| Curing Period T (d) | Content of Curing Agent λ (%) | 0  | 2  | 4  | 8  |
|---------------------|-------------------------------|----|----|----|----|
| 7                   | (0.433, 1.596)               | 0.426, 2.574 | 0.411, 3.906 | 0.401, 4.771 |
| 14                  | (0.415, 1.885)               | 0.409, 2.752 | 0.395, 4.12 | 0.386, 5.178 |
| 21                  | (0.397, 2.228)               | 0.388, 3.122 | 0.373, 4.685 | 0.367, 5.727 |
| 28                  | (0.379, 2.427)               | 0.369, 3.707 | 0.355, 4.975 | 0.347, 5.967 |
| 35                  | (0.364, 2.512)               | 0.354, 3.889 | 0.341, 5.112 | 0.333, 6.022 |
| 42                  | (0.351, 2.594)               | 0.342, 3.968 | 0.332, 5.201 | 0.318, 6.113 |
| 56                  | (0.343, 2.643)               | 0.334, 4.026 | 0.326, 5.286 | 0.309, 6.179 |
| 72                  | (0.339, 2.661)               | 0.329, 4.065 | 0.322, 5.329 | 0.305, 6.217 |
| 90                  | (0.337, 2.67)                | 0.326, 4.079 | 0.325, 5.354 | 0.303, 6.239 |
| 180                 | (0.336, 2.672)               | 0.325, 4.082 | 0.319, 5.36 | 0.302, 6.243 |

Figure 6. Relationship between the unconfined compressive strength and the average equivalent aperture size.

Table 10 illustrates the linear dependence of the unconfined compressive strength and the average equivalent particle size. The compressive strength and the average equivalent particle size are linearly related for curing agent contents of 6%, 8%, 10%, and 12%. Consequently, the average equivalent particle size can be defined for a given curing agent content and curing period, and then, the compressive strength could be computed using the above linear formula.
size can be defined for a given curing agent content and curing period, and then, the compressive strength could be computed using the above linear formula.

### Table 10. Linear dependence of the unconfined compressive strength and the average equivalent particle size.

| Average Equivalent Particle Size $D_p$ (µm) | The Linear Relationship between the Unconfined Compressive Strength and the Average Equivalent Particle Size $D_p$ | $R^2$ | Slope |
|-------------------------------------------|-------------------------------------------------------------------------------------------------|-------|-------|
| Curing Agent Content $\lambda$ (%)        | $y = 1.7758x - 2.9367$                                                                       | 0.9475| 1.7758|
| 6                                         | $y = 2.5541x - 4.7051$                                                                       | 0.9825| 2.5541|
| 8                                         | $y = 2.1229x - 2.6034$                                                                       | 0.9264| 2.1229|
| 10                                        | $y = 2.4946x - 3.6289$                                                                       | 0.9237| 2.4946|
| 12                                        |                                                                                               |       |       |

The relationship between the unconfined compressive strength and the average equivalent aperture size is reported in Figure 7. Figure 7 illustrates that for the same curing agent content, as the average equivalent aperture size decreases, the unconfined compressive strength increases linearly. Combining the previous analysis of the SEM images, the hydration products fill the macropores and the small pores between the particles. Compared to the filling rate of the small pores, the filling rate of the large pores is slower because the space in the large pores is larger. Therefore, the increase of the contact area between the particles contributes to the compressive strength.

Figure 7. Relationship between the unconfined compressive strength and the average equivalent aperture size.

The linear relationship between the compressive strength and the average equivalent aperture size is reported in Table 11. Table 11 also shows the linear formulas describing the relationship between the compressive strength and the average equivalent aperture size for curing agent contents of 6%, 8%, 10%, and 12%. Similarly, the compressive strength of the solidified calcareous sand could be deduced using these linear relationships.

### Table 11. Linear relationship between the unconfined compressive strength and the average equivalent aperture size.

| Average Equivalent Aperture Size $D_b$ (µm) | The Linear Relationship Between the Unconfined Compressive Strength and the Average Equivalent Aperture Size $D_b$ | $R^2$ | Slope |
|--------------------------------------------|-------------------------------------------------------------------------------------------------|-------|-------|
| Curing Agent Content $\lambda$ (%)        | $y = -2.2779x + 6.4958$                                                                       | 0.9648| 2.2779|
| 6                                         | $y = -3.2848x + 9.3945$                                                                       | 0.9576| 3.2848|
| 8                                         | $y = -2.984x + 9.7251$                                                                        | 0.9746| 2.984 |
| 10                                        | $y = -2.9431x + 10.413$                                                                       | 0.9573| 2.9431|
| 12                                        |                                                                                               |       |       |

The linear relationship between the unconfined compressive strength and the plane pore ratio is shown in Table 12. Table 12 also reveals that there is a linear relationship between the compressive strength and the plane pore ratio for curing agent contents of 6%, 8%, 10%, and 12%. Similarly, the compressive strength can be computed using these formulas.

### Table 12. Linear relationship between the unconfined compressive strength and the plane pore ratio.

| Average Plane Pore Ratio $D_p$ (%) | The Linear Relationship between the Unconfined Compressive Strength and the Average Plane Pore Ratio $D_p$ | $R^2$ | Slope |
|----------------------------------|-------------------------------------------------------------------------------------------------|-------|-------|
| Curing Agent Content $\lambda$ (%) | $y = -2.2779x + 6.4958$                                                                       | 0.9648| 2.2779|
| 6                                | $y = -3.2848x + 9.3945$                                                                       | 0.9576| 3.2848|
| 8                                | $y = -2.984x + 9.7251$                                                                        | 0.9746| 2.984 |
| 10                               | $y = -2.9431x + 10.413$                                                                       | 0.9573| 2.9431|
| 12                               |                                                                                               |       |       |

Figure 8 shows the dependence between the unconfined compressive strength and the plane pore ratio. As the plane pore ratio decreases, the unconfined compressive strength increases linearly. In other words, the microcosmic aspect is the decrease in the plane pore ratio, while the macroscopic aspect is the linear increase in the compressive strength. The reason is that the hydration products change the pore structure and the soil properties. Therefore, the compressive strength increases.

The linear relationship between the unconfined compressive strength and the plane pore ratio is shown in Table 12. Table 12 also reveals that there is a linear relationship between the compressive strength and the plane pore ratio for curing agent contents of 6%, 8%, 10%, and 12%. Similarly, the compressive strength can be computed using these formulas.
Table 11. Linear relationship between the unconfined compressive strength and the average equivalent aperture size.

| Curing Agent Content λ (%) | The Linear Relationship between the Unconfined Compressive Strength and the Average Equivalent Aperture Size $D_b$ | $R^2$ | Slope |
|----------------------------|---------------------------------------------------------|-------|-------|
| 6                          | $y = -2.2779x + 6.4958$                                 | 0.9648| 2.2779|
| 8                          | $y = -3.2848x + 9.3945$                                 | 0.9576| 3.2848|
| 10                         | $y = -2.984x + 9.7251$                                  | 0.9746| 2.984 |
| 12                         | $y = -2.9431x + 10.413$                                 | 0.9573| 2.9431|

Figure 8 shows the dependence between the unconfined compressive strength and the plane pore ratio. As the plane pore ratio decreases, the unconfined compressive strength increases linearly. In other words, the microcosmic aspect is the decrease in the plane pore ratio, while the macroscopic aspect is the linear increase in the compressive strength. The reason is that the hydration products change the pore structure and the soil properties. Therefore, the compressive strength increases.

The linear relationship between the unconfined compressive strength and the plane pore ratio is shown in Table 12. Table 12 also reveals that there is a linear relationship between the compressive strength and the plane pore ratio for curing agent contents of 6%, 8%, 10%, and 12%. Similarly, the compressive strength can be computed using these formulas.

Table 12. Linear relationship between the unconfined compressive strength and the plane pore ratio.

| Curing Agent Content λ (%) | The Linear Relation between the Unconfined Compressive Strength and the Plane Pore Ratio $e$ | $R^2$ | Slope |
|----------------------------|---------------------------------------------------------|-------|-------|
| 6                          | $y = -10.372x + 6.2201$                                 | 0.9467| 10.372|
| 8                          | $y = -15.729x + 9.2921$                                 | 0.9629| 15.729|
| 10                         | $y = -15.781x + 10.447$                                 | 0.9791| 15.781|
| 12                         | $y = -12.701x + 10.158$                                 | 0.8788| 12.701|
In conclusion, for a larger average equivalent particle size ($D_p$), a smaller average equivalent aperture size ($D_b$), and a smaller plane pore ratio ($e$), as the curing time increases, the unconfined compressive strength increases. These results, combined with the microscopic analysis of the previous SEM images, indicate that the increase in the compressive strength may be caused by the hydration products, i.e., calcium silicate hydrate, calcium hydroxide, and calcite crystal, which change the pore structure and soil properties.

5. Discussion

In this paper, we demonstrate that the unconfined compressive strength of the solidified calcareous sand has a good linear correlation with the three microstructural parameters. Based on this trial, we conclude that the microstructural parameters can be defined based on the curing agent content (6%, 8%, 10%, and 12%) and curing time (7 d, 14 d, 21 d, 28 d, 35 d, 42 d, 56 d, 72 d, 90 d, and 180 d). Therefore, the unconfined compressive strength can be computed using the macroscopic-microscopic relationship obtained from the experiment. In addition, the curing agent could improve the compressive strength of the calcareous sand. This is because the hydration products, i.e., calcium silicate hydrate, calcium hydroxide, and calcite crystal, which are produced by the hydration reaction, adhere to the surface of the particles or fill the space between the particles. Therefore, the change in the pore structure and the compactness of the particles helps increase the compressive strength. It also indicates that the mechanical properties of calcareous sand could be effectively improved by adding curing agent.

The study of Xiao [18] lacks quantitative analysis of the relationship between the macroscopic and microscopic parameters. Moreover, the scholar’s method to improve the calcareous sand is microbial induction method, which is complex to operate, with harsh sample preparation conditions and high cost of materials. However, our study on the use of curing agents is simple and cost-effective, and could also improve the mechanical properties of the calcareous sand.

The past studies have demonstrated that the experience of traditional pile foundation engineering could not be used in the calcareous sand. The methods of the past studies are only qualitative analysis between the macroscopic and microscopic research. In this study, we determined the numerical relationship between the macroscopic and microscopic parameters, not only the basic trend of their relationship. Thus, we can explain the relationship between the compressive strength and the microstructural parameters more reasonably and intuitively.

Though there are important discoveries revealed in this paper, there are also limitations. Firstly, the research is based on the unconfined compressive strength test, the test conditions are unconfined, but the actual project is limited. Therefore, the research provides a theoretical basis. Secondly, the amount of curing agent used in the study is only 6%, 8%, 10%, 12%, which needs to be further expanded.

Finally, one subject that remains to be explored is how to better apply the method of adding the curing agent to engineering construction, and whether the elements of the calcareous sand particle breakage will influence the study results.

6. Conclusions

In this study, the unconfined compressive strength of the solidified calcareous sand was obtained from the unconfined compressive strength test. The microscopic SEM images were analyzed using IPP. The quantitative analysis of the relationship between the unconfined compressive strength and the microstructural parameters was determined. Based on our results, we have reached the following conclusions.

1. Curing agent can improve the mechanical properties of calcareous sands. The curing agent, through hydration reactions, generates the hydration products, i.e., calcium silicate hydrate, calcium hydroxide, and calcite crystals. They adhere to the surface of the particles or fill the space between the particles and help increase the bonding strength between the soil particles. Therefore, the compressive strength improves.
2. The unconfined compressive strength has a strong linear correlation with the three microstructural parameters. By establishing the quantitative relationship between the macroscopic and microscopic parameters, the microstructural parameters can be defined based on the curing agent content (6%, 8%, 10%, and 12%) and the curing period (7 d, 14 d, 21 d, 28 d, 35 d, 42 d, 56 d, 72 d, 90 d, and 180 d). Using the mathematical relation between the macroscopic and microscopic parameters, the unconfined compressive strength can be calculated, and the correlation can be built for macro-microscopic research.

The mechanical properties of the solidified calcareous sand, obtained adding the curing agent to the calcareous sand, need more sufficient experimental studies, which contribute to the application of adding the curing agent to the construction of calcareous sand foundation in the South China Sea.

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