Research on the Mechanical Properties and Damage Model of Cemented Sand under Uniaxial Compression

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Abstract. Using cement to solidify the sand is an effective way to prevent sand from erosion in the sea bank. To investigate the mechanical properties of cemented sand with different cement content, a series of unconfined compression tests were performed. In addition, to better describe the damage constitutive relation of cemented sand, a damage model with volume change considered were deduced. The results indicate that the unconfined compressive strength and deformation modulus increases linearly with the increase of cement content. The constitutive model with volume change considered can effectively fit the curves obtained from the test and describe the damage process of cemented sand.

1. Introduction
Guangdong province has the longest coastline in China, accounting for about 1/5 of China's total coastline. In addition, Guangdong province is the most frequent landfall Province in China, and the landing of the typhoon is a serious threat to the safety of the people's life and property. Sea dike, as the most direct and effective sea defense engineering measure, has been widely used in the coastal areas. According to statistics, about 1/3 seawall in Guangdong province is constructed by sand. However, Due to the characteristics of easy erosion of sand, there are many problems such as low moisture proof standard and fragile destruction in sand built sea embankment.

In recent years, with the increasing investment in water conservancy construction, a large number of old sea dikes were reinforced. However, due to lack of clay material in the sandy area, sand is still a major material in sand embankment reinforcement engineering. In order to prevent sand loss, the concrete board is built on the sea side as a protective face, and a layer of geotextile is placed between the sand and concrete surface. It is found that the damage degree of the seawalls build by sand is still far higher than by clay. The main reason for the destruction of sand embankment is the separation between concrete slab and sand which caused by sand loss, as shown in figure 1. A small amount of cement can solidify sand effectively, which greatly reduces the sand loss and ensures the safety of seawall. Therefore, research on cement sand materials is of great significance.
Since the 1970s, scholars have been researching cemented sand, and made great progress in this field [1-3]. Trad et al [4] carried out triaxial testing and DEM simulation on sand which were cemented by cement and gypsum separately, the results show that density, confining pressure and cement ratio are three main factor in the mechanical properties of cemented sand. Consoli et al. [5-7] conducted a great quantity of mechanical tests on cement sand, and established an empirical expression of compressive strength based on curing time, porosity and cement content. Wang et al. [8] carried out triaxial test and quantitative chemical test on cemented sand with different mixing ratio of calcium oxide. The effect of calcium oxide content on the physical and mechanical properties of cemented sand was analyzed. A chemical index reflecting the amount of cementation is defined, which modifies the Mohr Coulomb strength theory.

As a complex mixture, cemented sand has obvious heterogeneity. Its macroscopic failure can be regarded as the superposition of the average utility of many microscale failures. The damage theory assumes that the internal defects of the rock and soil materials obey random distribution in the micro and mesoscopic level, and a damage constitutive model which can well reflect the relationship between the damage process of rock and the stress-strain relationship is established [9-11]. The cemented sand has a large number of initial pores, and new gaps will be formed for the damage after loading. Therefore, the volume change of the cemented sand deformation is obvious in the process of deformation [12]. Damage constitutive model of cemented sand should be modified in consideration of volume change.

In this study, a series of unconfined compression tests were performed on cemented sand specimens with different cement content, and the affecting of cement content on the mechanical behaviour of cemented sand were researched. In addition, to describe the damage constitutive relation of cemented sand reasonably, a damage model with volume change considered were deduced.

2. Materials and Methods
The sand used in this test were taken from a beach in Guangdong Province, as shown in Figure 2, with specific gravity $G_s = 2.78$. The grain size distribution is shown in Figure 2 the mean grain size $D_{50} = 0.18$ mm, the coefficient of uniformity $C_u = 1.75$, and the coefficient of curvature $C_c = 0.89$. The minimum and maximum dry density are 1.47 and 1.63, respectively. The minimum and maximum void ratios can be calculated by Formula 1 and formula 2. The compacted dry density $\rho_d$ was 1.97 g/cm$^3$, the stabilizer used in this test was Portland cement and the water was distilled water.

$$e_{\text{max}} = \frac{\rho_d G_s}{\rho_{\text{dmin}}} - 1$$
\[ e_{\text{min}} = \frac{\rho_{\omega} G_s}{\rho_{\text{dmax}}} - 1 \]  

(2)

Where \( e_{\text{max}} \) is maximum void ratios, \( e_{\text{min}} \) is minimum void ratios, \( \rho_{\omega} \) is water density, \( \rho_{\text{dmax}} \) is maximum dry density, \( \rho_{\text{dmin}} \) is minimum dry density.

The specimens were prepared by mixing sand with a prescribed amount of cement. A relevant amount of water were mixed subsequently. Specimens were manually compacted in five layers in a cylindrical mould (80mm in height and 39.1mm in diameter) with a controlled thickness of compacted layer of 16mm. The specimens preparing time was controlled within half an hour. The specimen was cured in the mould for about 24 hours, then the specimen was removed from the mould and stored in maintenance room for additional curing.

![Image](a) Camera figure  
(b) SEM figure  

Fig 2. Sand used in the test

![Image](a) Camera figure  
(b) SEM figure  

Fig 3. Grain size distribution of sand.

The unconfined compression tests were performed on cemented sand with different cement content (cement mass fraction are 1%, 2%, 3%, 4% and 5% respectively), the curing period is 28d. All tests were performed in the condition of strain controlled loading, and the strain rate is 0.1mm/min.

3. Results and Discussion

Figure 4 presents the typical axial stress-axial strain behaviours for different cement contents at the unconfined compression condition. The full deformation and failure process of cemented sand can be divided into four stages. In the first stage, the original microfracture and pore in the cemented sands were gradually compacted under axial stress, the slope of the curve increased. In the second stage, the stress is directly proportional to the stress and the cemented sand is in the stage of elastic deformation,
with the increase of cement content, the slope of curve increases, and the elastic modulus of cemented sand has greater elastic modulus. In the third stage, the deformation of cemented sand gradually changes from elastic to plastic. With the cement content decrease, the plastic deformation is more obvious. When the cemented sand reached peak unconfined compressive strength, the strength decreases with the strain increased. The post peak residual strength increases with the increase of cement content.

Taking the peak strength as the compressive strength $\sigma_c$. With the cement content increases $\sigma_c$ increase approximately, as shown in Figure 5. There is a distinct linear relationship between $\sigma_c$ and cement content, it can be expressed as

$$\sigma_c = \alpha C_c$$

(3)

Where, $C_c$ is cement content, $\alpha$ is a test coefficient which indicates the rate of $\sigma_c$ increases with $C_c$ increase, $\alpha=247$ kPa in this test.

The tangent modulus at the point of $\sigma_c=0.5\sigma_c$ is employed as the initial tangential modulus $E_0$ of cemented sand. The relationship between $E_0$ and cement content $C_c$ is shown in Figure 6, it can be concluded that $E_0$ rapidly increased with an increase in $C_c$, the relationship between $E_0$ and $C_c$ is linear.

**Fig 4.** Axial stress-axial strain relationship for different cement content at the unconfined compression condition

**Fig 5.** Variation of unconfined compressive strength for different cement content.

**Fig 6.** Variation of deformation modulus for different cement contents.
The creation of cracks at the failure of the specimens for the unconfined compression test differ with the cement content, as shown in Figure 7. In the condition of low content cement (2%-4%), the main crack path is inclined and initiated at the upper boundary, and the crack abruptly appears with almost no secondary cracks along its path. When cement content is high (5%-6%), the main crack path is vertical, and numerous secondary cracks are produced during crack growth.

![Fig 7. Failure patterns](image)

(a) Low cement content  (b) High cement content

4. Statistical damage constitutive model

According to the Lemaitre strain equivalence hypothesis [13], the strain produced by damaged materials under effective stress is equivalent to the strain produced by the same material when it is nondestructive. It can be obtained,

\[ \sigma = \sigma^* (1 - D) = E(1 - D)\varepsilon \]  (4)

Where \( \sigma \) is the stress, \( \sigma^* \) is the effective stress, \( D \) is the damage variable, \( \varepsilon \) is the strain.

Cao [12] take the volume change during the deformation process into account, the Eq. (4) can be rewrite as,

\[ \sigma = \sigma^* (1 - D)\beta = E\varepsilon(1 - D)\beta \]  (5)

Where \( \beta \) is the parameter related to pore.

As the strength of cemented sand obeys the statistical distribution of Weibull, it is considered that the damage parameter \( D \) also obeys the distribution. \( D \) can be written as,

\[ D = 1 - \exp \left[-\left(\frac{\varepsilon}{a}\right)^m\right] \]  (6)

Where \( a \) and \( m \) are shape and scale parameters, respectively. Plug Eq. (5) into Eq. (6), it can be obtained,

\[ \sigma = E\varepsilon\beta \exp \left[-\left(\frac{\varepsilon}{a}\right)^m\right] \]  (7)
Take the derivative of strain,

\[
\frac{d\sigma}{d\varepsilon} = E \exp \left[ -\left( \frac{\varepsilon}{a} \right)^m \right] \left[ 1 - m \left( \frac{\varepsilon}{a} \right)^m \right] \beta
\]  

(8)

In the peak point,

\[
\begin{cases}
\varepsilon = \varepsilon_c \\
\sigma = \sigma_c \\
d\sigma / d\varepsilon = 0
\end{cases}
\]  

(9)

Plug Eq. (9) into Eq. (8),

\[
0 = E \exp \left[ -\left( \frac{\varepsilon_c}{a} \right)^m \right] \left[ 1 - m \left( \frac{\varepsilon_c}{a} \right)^m \right] \beta
\]  

(10)

Since \( E \neq 0 \), \( \exp \left[ -\left( \frac{\varepsilon_c}{a} \right)^m \right] \neq 0 \), \( \beta \neq 0 \), then,

\[
1 - m \left( \frac{\varepsilon_c}{a} \right)^m = 0
\]  

(11)

Eq. (11) can be rewrited as,

\[
a = \frac{\varepsilon_c}{\left( \frac{1}{m} \right)^m}
\]  

(12)

Plug Eq. (12) into Eq. (7),

\[
m = \frac{1}{\ln \left( \frac{E\beta\varepsilon_c}{\sigma_c} \right)}
\]  

(13)

The comparison of theoretical curve with test curves under different cement content were shown in Figure 8, and the measured parameters were list in Table 1. It can be seen that the constitutive model and parameters given in this paper can effectively fit the curves obtained from the test and describe the damage process of cemented sand effectively, which has a certain reference value for the engineering analysis and design.
Table 1. Measured parameters of damage constitutive models under uniaxial compression

| Cement content | Initial tangential modulus/MPa | Peak stress/MPa | Peak strain/10^{-2} | m     | a     | β     |
|----------------|-------------------------------|-----------------|---------------------|-------|-------|-------|
| 2%             | 50                            | 0.53            | 2.45                | 1.0   | 0.024 | 1.18  |
| 3%             | 83                            | 0.75            | 2.25                | 0.99  | 0.023 | 1.10  |
| 4%             | 123                           | 1.0             | 2.15                | 0.97  | 0.021 | 1.05  |
| 5%             | 157                           | 1.25            | 2.05                | 1.03  | 0.020 | 1.03  |
| 6%             | 198                           | 1.44            | 1.95                | 0.99  | 0.019 | 1.01  |

Fig 8. Comparison of theoretical curve with test curves under different cement content
5. Conclusion
A series of unconfined compression tests were performed to investigate the mechanical behaviour of cemented sand with different cement content, and deduced a damage model with volume change considered. The following conclusions were obtained

1) The unconfined compressive strength and deformation modulus increases linearly with an increase in the cement content.
2) Constitutive model given in this paper can effectively fit the curves obtained from the test and describe the damage process of cemented sand.

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