Strength of Cement Mortar Solidified Soil and Prediction

M Wang1,2, J J Yang1,2, M Q Zhao*, H Liu1,2 and S C Li1,2

1 Key Laboratory of Marine Environment and Ecology, Ministry of Education, Qingdao 266100, China
2 College of Environmental Science and engineering, Ocean University of China, Qingdao 266100, China
Email: zhaomuqiu@126.com

Abstract. Strength is an important index to evaluate the solidification effect of cement soil and engineering design and construction inspection. The unconfined compressive strength test of cement mortar solidified soil was carried out. The results showed that the strength growth rate of cement mortar solidified soil increased linearly with the sand content, which was the maximum at 7d, and tended to be stable after 14d. The strength of solidified soil increased with age, and the initial growth rate was relatively fast. Compared with cement soil, the coefficient of deformation of cement mortar solidified soil did not slow down obviously in the later period. Taking cement mortar solidified soil as cement soil for strength calculation, the strength prediction equation of cement solidified soft soil at full age could well reflect the strength growth rule of cement mortar solidified soil.

Keywords. Cement mortar solidified soil, unconfined compressive strength cement-water ratio, strength prediction.

1. Introduction
Cement soil is a mixture of cement slurry or cement dry powder and the soil to be reinforced, so that the cement and the soil will undergo a physical and chemical reaction to form a solidified body with a certain strength. Because of the simple construction, high efficiency and great flexibility of cement soil, it is widely used in soft soil foundation reinforcement treatment, anti-seepage and water-proof curtains and other projects [1-2]. Cement mortar solidified soil is an improved cement soil with cement mortar as a curing agent. By adding a suitable amount of sand, the cement and soil can be easily mixed, and the mechanical properties of the cement soil are improved.

Regarding the strength characteristics of cement mortar solidified soil, the results of laboratory experiments show that the cement mortar solidified soil exhibits brittle failure or plastic failure. With the increase of age and the increase of sand content, the brittle failure is more significant [3]. Sand can effectively improve the strength of cement mortar solidified soil, especially the early strength. The strength of 28d age sample can reach 67% of the standard value (90d age sample strength) [4]. Different soil has different optimal amount of sand for reinforcement effect, and the optimal amount of sand for clay is between 10%-20% [5-7]. The strength of the solidified soil increases with the increase of the cement mixing ratio, and decreases with the increase of the original soil moisture content [8]. When the original soil moisture content is too high, it is difficult to achieve the desired reinforcement effect by adding sand. The strength of solidified soil is the most...
sensitive to the cement mixing ratio, followed by the water content, and the smaller are the sand content and the particle size of sand material [8]. However, the particle size of sand material has a relatively large impact on the deformation characteristics, the particle size of sand material increases, and the stiffness increases, but the effect of the sand gradation on the strength and deformation is not significant. In practical engineering, the sand material can be used without screening [4, 8-9].

The role of sand are following: to optimize the particle size distribution of soil [10]; form a certain degree of sand skeleton; sand replacement clay indirectly improves the cement mixing content [4,8-9,11]; produce compaction [4,8-10]. Obviously, the above displacement and compaction are different in sample preparation methods. The former takes the sand as the original soil to increase the weight of the soil. In this paper, the sand content is small, the latter method is used.

The strength is a key indicator for the design and construction of cement mortar solidified soil. If the relationship between strength and age of cement mortar solidified soil is known, the number of mix ratio tests and the test cycle can be reduced according to the design strength of the project; Long-term intensity can also be predicted. The current prediction equations for the strength of cement mortar solidified soil are mostly obtained by regression of laboratory test data, as shown in table 1. Among them, the parameters to be determined in equations (1)-(2) are determined by the fitter's own test data and cannot be guaranteed to be applicable to other soil types; the parameters to be determined in equations (3)-(6) require test data to perform a fit to determine.

| Presenter | Equations | number | Remarks |
|-----------|-----------|--------|---------|
| FAN [4]   | \(q_{u,90} = (1.514-1.546)q_{u,28}\) | (1)    | \(q_{u,90}\) Is 90d unconfined compressive strength. |
|           | \(f_{3c} = 57.6 - 4.2[(C + F)/S] - 17.83[F/(C + F)] - 68.3[W/(C + F)]\) |        |         |
| PAN [12]  | \(f_{7c} = 65.4 + 15[(C + F)/S] - 31.2[F/(C + F)] - 83.7[W/(C + F)]\) | (2)    | \(f_{3c,90d}\) Unconfined compressive strength, W, S, C and F are the quality of water, sand, cement and fly ash, respectively. |
|           | \(f_{28c} = 95.6 - 4.45[(C + F)/S] - 6.67[F/(C + F)] - 105.33[W/(C + F)]\) |        |         |
| HE [13]   | \(q_u = be^{αT}\) | (3)    | \(q_u\) Is unconfined compressive strength, \(T=7, 14, 28, 60d\), \(b\) and \(n\) are parameters to be determined. |
| QU [8]    | \(q_u = aS + c\) | (4)    | \(q_u\) Is the unconfined compressive strength under different sand content conditions, \(S=0, 10, 20, 30, 40, 50\%. \(a\) and \(c\) are parameters to be determined. |
| QU [8]    | \(q_u = aω^b\) | (5)    | \(q_u\) Is unconfined compressive strength, \(w\) is moisture content, \(a\) and \(b\) are parameters to be determined. |
| FAN [4]   | \(q_u = a ln T + c\) | (6)    | \(q_u\) Is unconfined compressive strength, \(T\) is age, \(a\) and \(c\) are parameters to be determined. |

Yang Junjie et al. [14-16] put forward the prediction equation of the full age strength of cement soil, which does not contain fitting parameters. Only knowing the strength of the shorter age and the
cement-water ratio, it can predict the full age strength of cement soil, but whether it can be applied to the prediction of the strength of cement mortar solidified soil needs further verification.

In this paper, a series of unconfined compressive strength tests of cement mortar stabilized soil are carried out to study the strength characteristics, and propose a long-term strength prediction method of cement mortar stabilized soil.

2. Experimental study

2.1. Materials

The soil used for the test was taken near Jiaozhou Bay, Qingdao, Shandong Province. The basic physical and mechanical properties are shown in table 2. The grain size analysis is shown in figure 1. According to the Code for Design of Building Foundation [17], the soil sample Silty clay. The sand material was standard quartz sand. The grain size analysis is shown in figure 1. It belongs to medium sand. The cement used in the test was 42.5 ordinary portland cement produced by Weifang Luyuan Building Materials Co., Ltd. The test water was artificially configured seawater, and its main ion concentration was close to the seawater composition of the Jiaozhou Bay site (table 3).

![Figure 1. Grain size analysis.](image)

![Figure 2. Three-phase sketch of cement mortar solidified soil.](image)

![Figure 3. Unconfined compressive strength test instrument.](image)

| Ion               | $Ca^{2+}$ (mg/kg) | $Mg^{2+}$ (mg/kg) | $Cl^{-}$ (mg/kg) | $SO_{4}^{2-}$ (mg/kg) |
|-------------------|------------------|------------------|-----------------|----------------------|
| Artificial        | 300              | 1200             | 14000           | 2400                 |
| Jiaozhou bay seawater | 241.3           | 1149.3           | 13837.2         | 2198.3               |

2.2. Test Scheme

The test scheme is shown in table 4. Cement mixing content aw is the mass ratio of cement to wet soil. Cement mortar mix ratio is the quality ratio of cement, sand, and water. Cement sand mixing content is the mass ratio of cement and sand to wet soil. And the sand content S is defined as the mass ratio of sand and dry soil. The cement mixing content aw was set to 15%, so as to be compared with the cement soil sample, and a sample without sand was designed for the control test. Three parallel samples were tested in each group, and the intensity was averaged.
Table 4. List of testing program.

| Soil          | Moisture content $w_m$ (%) | Curing agent material | Cement mixing content $a_w$ (%) | Cement: sand: water (mass) | Cement-sand mixing content (%) | Sand content $S$ (%) | Cement-water ratio $R$ | Age $t$ (d) |
|---------------|---------------------------|-----------------------|----------------------------------|----------------------------|-------------------------------|---------------------|-----------------------|-------------|
| Soft soil of Jiaozhou bay | 29.3                       | Sand                  | 1704:1023:1366                  | 27.3                       | 13.2                          | 7,                  |                       |             |
|               |                            |                       |                                  |                            |                               |                     | 28,                   |             |
|               |                            |                       |                                  |                            |                               |                     | 60,                   |             |
|               |                            |                       |                                  |                            |                               |                     | 90,                   |             |
|               |                            |                       |                                  |                            |                               |                     | 180                   |             |
|               |                            |                       |                                  |                            |                               |                     | 210                   |             |

2.3. Sample Making and Curing

The soil was uniformly stirred with the seawater and the curing agent, and were divided into three layers into a cylindrical mold with a diameter of 50 mm and a height of 100 mm and coated with vaseline. After each layer was loaded, it was shaken 20 times. After 24 hours of standard curing, released the mold and continued curing to the set age.

2.4. Unconfined Compressive Strength Test

The unconfined compressive strength tester used is shown in figure 2, and the loading rate is 1 mm/min.

3. Strength Characteristics of Cement Mortar Solidified Soil

3.1. Unconfined Compressive Strength Test Results

Figure 4 is the stress-strain curve obtained from the unconfined compressive strength test. Regardless of the type of the curing agent, the cement mixing content, the sand content, and the age, the stress of the cement mortar solidified soil increased with the increase of the strain, and the stress decreased with the increase of the strain after reaching the peak, which belonged to the processing softening curve.

![Figure 4. Different sand content sample stress strain curves.](image-url)
3.2. Strength Characteristics of Cement Mortar Solidified Soil

The peak value of stress-strain curve was defined as unconfined compressive strength, $q_u$.

Figure 5 shows the relationship between unconfined compressive strength and influencing factors, which Sand content of 0% is cement soil. Regardless of the age, because the cement mixing content and the mass of soil were set same in this test, so there was a corresponding conversion relationship between cement-sand mixing content and sand content, the strength of cement mortar solidified soil was slightly higher than cement soil, and the strength increased with sand content or cement-sand mixing content.

The strength growth rate $\Delta s$ of cement mortar solidified soil with the sand content is defined as follows [4]:

$$\Delta s = \frac{(q_{us}-q_{uo})}{q_{uo}} \times 100\%$$  \hspace{1cm} (1)

where, $q_{us}$ and $q_{uo}$ are the unconfined compressive strength of a certain sand content and 0% sand content, respectively.

Figure 5b is the relationship between strength growth rate and sand content. FAN’s [4] data indicates that the strength growth rate first increased and then decreases with the increase of sand content except 14d. In this paper, the experimental sand content was 0% – 13.2%, as shown in the figure, regardless of age, the growth rate of strength increased linearly with the sand content, which was the same as the trend of strength growth rate with the sand content less than 15% in the data of FAN [4].

Figure 5c is the relationship between strength growth rate and age. Regardless of the type of curing agent, the mixing content, and the sand content, the strength growth rate was the maximum at 7d, and tended to be stable after 14d.

Figure 5d is the relationship between the strength of solidified soil and age. Regardless of the type of curing agent, the mixing content, and the sand content, the strength increased with age, and the initial growth rate was relatively fast and then gradually slowed down. The strength growth law of cement mortar solidified soil was not significantly different from that of cement soil. The growth trend of strength before 90d conformed to the growth trend of exponential function with an exponential interval of 0-1 [13].

![Figure 5](image-url)

**Figure 5.** The relationship between $q_u$ and influencing factors.
Defined the half of the stress at the peak of the stress-strain curve and its corresponding strain ratio as the coefficient of deformation, $E_{50}$. $E_{50}$ could be regarded as the secant modulus at this time.

Figure 6 is the relationship between $E_{50}$ and influencing factors. Figure 6a is the relationship between $E_{50}$ and the sand content. Regardless of the age, $E_{50}$ increased approximately linearly with the sand content, which was the same as Terashi’s conclusion [18]. Figure 6b is the relationship between $E_{50}$ and age. Regardless of the type of curing agent, the mixing content, and the sand content, $E_{50}$ increased with age. Compared with cement soil, the $E_{50}$ of cement mortar solidified soil did not slow down obviously in the later period.

4. Strength Prediction of Cement Mortar Solidified Soil

Yang et al [14-17] analyzed the strength data of cement soil and found that the growth law of cement soil strength is related to the cement-water ratio. When the age is less than 180d, the relationship between strength and age conforms to the exponential function form. After 180d, the strength increases slowly, which conforms to the hyperbolic law. Suppose that the exponential function and the hyperbola are connected smoothly at the age of 180d (figure 7), and then the strength prediction equation for the full age of cement soil is obtained-equation (8).

$$R = \frac{1}{c+\frac{mn}{(1+0.09)R_{60}}}$$

$$q_u = \begin{cases} \frac{q_{ut_0}t^R}{t_0^R} & t \leq 180 \\ \frac{q_{ut_0}t}{180^{1-R}R+180^{-R}(1-R)t} & t \geq 180 \end{cases}$$
where, \( q_u \) is the predicted strength of cement soil at \( t \) age under a certain curing condition, and the age is calculated from the completion of sample preparation. \( q_{ut_0} \) is the unconfined compressive strength at \( t_0 \) age obtained from the test under the same conditions, and \( R \) is the cement-water ratio.

For cement soil, the definitions of the cement-water ratio \( R \), the cement mixing content \( \alpha_w \) and the water cement ratio \( C \), and the conversion relationship between \( R \) and other parameters are shown in the table 5. Similarly for cement mortar solidified soil, cement-sand was regarded as curing agent. As shown in table 5, the definitions of the cement-sand-water ratio \( R \), the cement sand mixing content \( \alpha_w \) and the water cement-sand ratio \( C \), and the conversion relationship between \( R \) and other parameters.

**Table 5.** Definition of common parameters of cement soil and cement mortar solidified soil and their conversion relationship with \( R \).

| Curing agent | Cement soil | Cement mortar solidified soil | Cement-sand |
|--------------|-------------|-------------------------------|-------------|
| \( R \)      | \( \frac{m_c}{m_{ws} + m_{wc}} \) | \( \frac{m_c + m_b}{m_{ws} + m_{wc}} \) | \( \frac{m_c}{m_{ws} + m_s} \) |
| \( \alpha_w \) | \( \frac{m_{ws} + m_s}{m_{wc}} \) | \( \frac{m_{ws} + m_s}{m_{wc}} \) | \( \frac{m_{ws} + m_s}{m_{ws} + m_s} \) |
| \( C \)      | \( \frac{1}{m_c} \) | \( \frac{C + \frac{\omega_n}{(1 + \omega_n)\alpha_w}}{m_{ws} + m_s} \) | \( \frac{C}{m_{ws} + m_s} \) |

There were two methods to use the equation (8) to predict the strength of the cement mortar solidified soil. The first one regarded the cement mortar solidified soil as cement soil, and the second one used the cement sand as a curing agent for prediction.

Figure 8 shows the comparison between the predicted value and the measured values when the cement mortar solidified soil is regarded as cement soil, where \( q_{ut_0} \) takes the strength to form a relatively stable 28d age strength. With the cement-water ratio as a variable, it reflects the relationship between cement and water, the main influencing factor of the strength of cement mortar solidified soil. The sand content and physical and chemical properties of soil were comprehensively reflected in \( q_{ut_0} \), the predicted values and the measured values had higher consistency.

Figure 9 is the comparison between the predicted value and the measured values when the cement-sand is regarded as curing agent. When the age is larger, the predicted values deviate greatly from the measured values. When cement sand was used as a curing agent, the continuous increase in the strength of cement mortar solidified soil is mainly due to the reaction between cement and water. Sand is a loose material. It only adsorbed gelling substances and did not react with cement. The produced compaction effect by sand, was a physical effect, could not make the strength of continued growth. Therefore, when the strength of cement mortar solidified soil was predicted, it could be regarded as the strength prediction of cement soil.
**Figure 8.** Comparison of predicted values and measured values when cement is used as curing agent.

**Figure 9.** Comparison of predicted values and measured values when cement mortar is used as curing agent.

Figure 10 shows the relationship between the strength and the age when the cement mortar solidified soil was regarded as cement soil. Equation (8) can better reflect the strength growth of cement mortar solidified soil.

![Graph showing relationship between strength and age](image)

**Figure 10.** The result of equation (8) prediction.

### 5. Conclusion

In this paper, the unconfined compressive strength of cement mortar solidified soil and its prediction were studied, and the following conclusions were obtained:

1. The strength growth rate of cement mortar solidified soil increased linearly with the sand content approximately.
2. The strength growth rate was the maximum at 7d, and tended to be stable after 14d.
3. The strength of solidified soil increases with age, and the initial growth rate was relatively fast and then gradually slows down. The strength growth law of cement mortar solidified soil was not significantly different from that of cement soil.
4. $E_{50}$ increased linearly with the sand content.
5. $E_{50}$ increased with age, compared with cement-soil, the coefficient of deformation of cement mortar solidified soil did not slow down obviously in the later period.
6. Taking cement mortar solidified soil as cement soil for strength calculation, that was, the cement-water ratio was used as a parameter. The predicted value and the measured value had a high consistency, which could better reflect the strength growth law of cement mortar solidified soil.

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