Study on fluidity and strength of dredged sludge under water curing condition

Yupeng Cao1,*, Jing Zhang1, Shuai Zhang2, Guizhong Xu3 and Jianwen Xu1
1 College of Transportation, Shandong University of Science and Technology, Qingdao, China
2 Company of Guangzhou Municipal Engineering Design and Research Institute, Guangzhou, China
3 Geotechnical Research Institute, Yancheng Institute of Technology, Yancheng, China

*Corresponding author e-mail: paradise456917@163.com

Abstract. Dredged sludge can be used in engineering by treating with flowing solidification method underwater, but the flow solidification characteristics of dredged sludge in underwater curing condition are not clear. The influence of initial water content, cement content and curing age on the fluidity and strength of solidified sludge was discussed through laboratory tests. The results show that the strength of solidified sludge under water curing situation increase linearly with cement content, decreases linearly with the initial water content, and increases logarithmically with the curing age. The relationship of unconfined compressive strength with liquid limit and initial water content for dredged sludge at 28 days curing age was proposed and verified, which provides an important basis for field application and strength prediction of flow solidification treatment.

1. Introduction
A large number of dredged sludges is produced every year in China with the development of water conservancy projects and water environment control projects. Dredged sludge has high water content, low strength, high compressibility, and is difficult to use directly in engineering [1, 2]. In the actual treatment, most of them are dumping and filling in the yard, which occupies a large amount of land resources for a long time, and the treatment cost is extremely high. In recent years, the treatment method of sludge resource utilization has developed rapidly. According to the characteristics of dredging construction, relevant scholars have put forward the flow solidification technology of sludge treatment [3, 4]. That is, some specific solidified materials are fully mixed with dredging sludge to form a kind of mixture that can be pumped in the flow state, so that it has a certain fluidity at the initial stage and can be quickly consolidated and hardened to form strength at the later stage. However, at present, the research on solidified sludge mainly focuses on the mechanical properties, solidified materials and soil properties, and the experimental research on strength and fluidity of dredged sludge under water curing condition is not studied. Water curing is the most commonly used maintenance method in the construction site, which can prevent water loss, make a humid environment, and ensure the full hydration of cement [5, 6]. The maintenance method of cast-in-place solidified sludge in construction site is quite different from indoor standard maintenance, so it is necessary to carry out experimental study on the fluidity and strength characteristics of dredged sludge under water curing condition.
In this paper, two kinds of common dredged sludge (Changzhou soil and Haimen soil) are studied by fluidity characteristic test and unconfined compressive strength test. The main influencing factors and changing rules of fluidity and compressive strength characteristics of solidified sludge are analyzed. The prediction method of compressive strength at 28 days age under the condition of water curing is proposed and verified.

2. Materials and test method

2.1. Sludge properties

The sludge for the test is taken from Changzhou and Haimen areas of Jiangsu Province, respectively, and its basic physical and mechanical properties are shown in Table 1. The liquid limit and plastic limit are determined by butterfly liquid limit instrument and rolling strip method [7], respectively. Both soil samples are high liquid limit clay. The cement is ordinary Portland cement, which is taken from Nanjing Jiangnan Cement Plant, and the strength grade is 42.5. Considering the connection of dredged sludge construction and the water content is between 2.0-3.0 times liquid limit after sedimentation, initial water contents are set as 2.0, 2.5 and 3.0 times liquid limit. The cement contents are 100, 150, 200 and 250 kg/m³. The design proportion of solidified sludge is shown in Table 2.

| Name of soil sample | Initial water content w₀ (%) | Cement content α_c (kg/m³) | Curing age t(d) |
|---------------------|------------------------------|-----------------------------|-----------------|
| Changzhou soil      | 73.8, 92.25, 110.7           | 100, 150, 200, 250          | 3, 7, 14, 28    |
| Haimen soil         | 91.0, 113.75, 136.5          | 100, 150, 200, 250          | 3, 7, 14, 28    |

2.2. Test method for fluidity and strength

The special polyethylene cylinder with diameter and height of 8cm was used for the fluidity test. During the test, first place the test cylinder on a flat and clean plexiglass plate, then fill the test cylinder with the uniformly stirred solidified sludge mixture, scrape the surface with a scraper, then lift the test cylinder quickly, measure the maximum and minimum diameter of the mixture spread, and take the average value of the two as the liquidity index. As shown in the Figure 1 (a) and (b).

In the unconfined compressive strength test, a special polyethylene mold with diameter of 39.1 mm and height of 80 mm was used. A thin layer of Vaseline is applied on the inner wall of the mold before sample preparation to facilitate demolding. The soil sample is put into the mold in three layers, and each layer shall be vibrated to discharge bubbles. After vibration, the surface shall be scraped flat.
After sample preparation, water storage and maintenance shall be carried out for the sample. The so-called water storage and maintenance means that the mold is placed neatly in the plastic bucket for water storage (the sample should be submerged in the water), and then the bucket is placed in the curing box for maintenance (the temperature of the curing box is set to $20 \pm 2 ^{\circ}C$). Demolding shall be carried out after the soil sample is fixed and formed, and water storage and maintenance shall be continued after demolding (generally, demolding can be carried out on the second day of sample preparation, and demolding shall be carried out one or two days later for the soil sample with high initial water content). As shown in the Figure 1 (c). The unconfined compressive strength test was carried out in 3 days, 7 days, 14 days and 28 days, and the axial strain control rate was 1 mm/min [6]. Two parallel tests were conducted in each group. Unconfined compressive strength test is shown in Figure 1 (d).

3. Analysis of test results

3.1. Analysis of silt fluidity

Figure 2 and 3 show the changing law of fluidity with different water content and cement content. From Figure 2 (a) and (b), it can be seen that the fluidity increases approximately linearly with the increase of the initial water content of the sludge, and decreases linearly with the increase of the cement content.

![Fluidity and initial water content curve](image1)

(a) Fluidity and initial water content curve  (b) Fluidity and cement content curve

**Figure 2. Fluidity of Haimen soil**

![Fluidity and initial water content curve](image2)

(a) Fluidity and initial water content curve  (b) Fluidity and cement content curve

**Figure 3. Fluidity of Changzhou soil**

Figure 3 shows that the change rule of fluidity is consistent with that of Haimen soil. According to the construction requirements of flow solidification in Japan [8], the minimum fluidity shall not be less than $(18 \pm 2)$ cm, and 16 cm is taken as the lower limit of fluidity solidification construction. Based on the results of fluidity experiment, the fluidity of Haimen soil and Changzhou soil is less than but close
to the lower limit of fluidity when the cement content is 250kg/m³ under 2.0 times liquid limit. The flow radius of the two kinds of soil is greater than 16cm under the other initial water content and cement content, which shows that the flow solidification construction can be carried out under the cement content of 100-250 kg/m³. In Figure 2, 100C presents that the cement content is 100kg/m³, and the other symbols are similar. According to the analysis of the relationship between the fluidity and the initial water content in Figure 2 (a) and 3(a), it can be seen that for different cement content, the fluidity and the initial water content not only have a good linear relationship, but also have a parallel linear slope. This is consistent with the test results of Ding et al. [9].

3.2. Stress-strain properties of solidified sludge

The destructive character and destructive strain are key problems that must be considered in practical application of solidified sludge. The magnitude of destructive strain has a direct impact on the use of silt solidified materials in filling engineering [10].

The change law of stress-strain of solidified sludge with different initial water content is shown in Figure 4. The deformation form shows stress softening characteristics obviously. With the increase of initial water content, the stress-strain curve changes from brittle failure to plastic state, which shows low strength and small deformation. This phenomenon can be explained by cement hydration of solidified sludge. When the cement content reaches a certain degree (150 kg/m³), the skeleton strength of soil is relatively high and forms a unified whole. Under the action of external force, the cemented soil particles bear the pressure together as a community, which shows the softening characteristics of decreased failure stress and reduced failure strain on the macro level.

3.3. Analysis of strength influencing factors

Figure 5 shows the relationship between unconfined compressive strength and cement content at 28 days curing age of solidified sludge. It can be seen that the strength increases linearly with the increase of cement content. Under different initial water content, there is a minimum cement content (50 kg/m³). When the cement content is lower than 50kg/m³, there is no solidification effect.

![Figure 4. Stress-strain curve](image)

![Figure 5. Relationship between unconfined compressive strength and cement content](image)
Figure 6 shows the relationship between the solidified sludge strength and $w_0/w_L$. From the changing rule, it can be seen that the initial water content has a great influence on the solidified strength, and the relationship between the water content and the solidified strength is inversely proportional. Figure 7 shows the influence of age on the strength of solidified sludge. With the increase of age, the strength showed a logarithmic growth law. The factors influencing the solidification strength of sludge are close to the research results of other scholars [11-15].

![Figure 6. Relationship between $q_u$ and $w_0/w_L$.](image1)

![Figure 7. Relationship between $q_u$ and age.](image2)

### 4. Strength prediction

Compressive strength is an important mechanical performance index of geotechnical materials, and also is a key factor to be considered in construction engineering. Therefore, it has practical significance to predict the compressive strength of solidified sludge [16-17]. This paper mainly studies the influence of initial water content and cement content on the strength of sludge under the condition of water maintenance. According to the test results of unconfined compressive strength, the formula of strength with initial water content and cement content can be obtained, as shown in formula (1).

$$q_u = (6.27 - 1.40) \alpha \left( \frac{w_0}{w_L} \right)^{1.12 + 1.54}$$

(1)

![Figure 8. Relationship between predicted value and measured value.](image3)

According to this formula, the strength of solidified sludge can be easily estimated. In order to verify the validity of the prediction formula, unconfined compressive strength test was carried out on dredged sludge ($w_L = 45.5\%$) in Haimen under the condition of water maintenance. The results are shown in figure 8. The predicted values of compressive strength were in according with the measured values, which shows that the prediction formula is reasonable.

### 5. Conclusions

1. The fluidity has a good linear relationship with the initial water content and cement content. The fluidity index of dredged sludge meets the 16 cm fluidity solidification standard.
(2) Under the condition of water curing, the unconfined compressive strength increases linearly with cement content, and decreases linearly with initial water content. With the increase of age, the compressive strength shows a logarithmic growth law.

(3) The unconfined compressive strength prediction formula of solidified sludge at 28 days curing age under water maintenance is established, which has certain guiding significance for treatment of dredged sludge in the field.

6. Acknowledgments
This research was supported by National Natural Science Foundation of China (Grant No. 51608312).

References
[1] Y.P. Cao, J.W. Xu, B. Xia, G.Z. Xu, Effect of clogging on large strain consolidation with prefabricated vertical drains by vacuum pressure, KSCE Journal of Civil Engineering. 23 (2019) 10 4190-4200.
[2] M.T. Wu, Y.L. Li, Q. Guo, D.W. Shao, M.M. He, T. Qi, Harmless treatment and resource utilization of stainless steel pickling sludge via direct reduction and magnetic separation, Journal of Cleaner Production. 240 (2019) 1-7.
[3] J.P. Bao, W. Zhu, W.H. Min, Technology of dredging and sludge treatment in small and medium-sized river regulation, Water Resources Protection. 31 (2015) 01 56-62+68.
[4] Q. Lu. Experimental research on fluidity and strength behavior of solidified clays under sea water environment, Jiangsu university, Zhenjiang, 2016.
[5] Y.F. Zhang, B. Bai, H.Y. Guan, Some symmetries, similarity solutions and various conservation laws of a type of dispersive water waves, Advances in Difference Equations. 1 (2019) 1-20.
[6] G. Lorenz, L. Ching, Q. Neng, Motivating household water conservation: A field experiment in Singapore, PloS one.14 (2019) 3.
[7] Ministry of water resources of the people's Republic of China. Standard for soil test method (GB / T 50123-1999), China Planning Press, Beijing, 1999.
[8] J.W. Ding, S. Zhang, Z.S. Hong, Experimental study of solidification of dredged clays with high water content by adding cement and phosphogypsum synchronously, Rock and Soil Mechanics. 31 (2010) 09 2817-2822.
[9] J.W. Ding, Z.S. Hong, S.Y. Liu, Study of flow-solidification method and fluidity test of dredged clays, Rock and Soil Mechanics. 32 (2011) 280-284.
[10] C.L. Zhang, Study of dredged sediments solidification mechanism based on water transfer model, Hohai University, Nanjing, 2007.
[11] J.J. Li, R.W. Liang, Research on compression strength and modulus of deformation of cemented soil, Rock and Soil Mechanics. 30 (2009) 473-477.
[12] F.F. Yuan, Study on engineering properties of solidified tidal silt with high water content, Zhejiang University, Hangzhou, 2017.
[13] S.H. Zheng, Experimental study on the influence factors of strength behavior of cement stabilized clay at high water content, Huazhong University of Science and Technology, Wuhan, 2015.
[14] L.H. Li, C. Wang, L.F. Mei, Y.Y. Pei, M. Gao, Y.J. Chen, S.Z. Luo, Unconfined compression strength characteristics of glass fiber-reinforced cemented clay, Engineering Journal of Wuhan University. 51(2018) 03 252-256.
[15] T.L. Xiao, Y.L. He, Q.F. Li, Z. Ding, J.H. Zhu, C. Zhou, Experimental study on unconfined compressive strength of cemented soil, Journal of Yangtze University (Natural Science Edition). 14 (2017) 05 64-66+87.
[16] D.S. Wang, J.J. Yang, M.R. Dong, X.T. Su, X.J. Wang, Laboratory Test on the Prediction of Cement Soil Strength, Periodical of Ocean University of China. 48 (2018) 07 96-102.
[17] Yoosathaporn, Sada, Tiangburanatham, Poon, Pathom-Aree, Wasu, The influence of biocalcification on soil-cement interlocking block compressive strength, Biotechnologie, Agronomie, Société et Environnement. 19 (2015) 3 262-269.