Strength of deep mixed soft clay with cement

Huaren Dou[1] and Y. Wang[1]

[1] China Road and Bridge Corporation (Hong Kong), Units 6-11, 23A/F, K. Wah Centre, 191 Java Road, North Point, Hong Kong, China

ABSTRACT

Deep mixing method is often used to treat soft clay under the sea if it is not dredged or removed, which enhances the engineering properties of weak soils to provide sufficient strength and bearing capacity for supporting seawalls, reclamations and other intended structures. Deep soil mixing (DSM) with addition of binder, such as cement, lime, fly ash, has been widely used in Asia and worldwide. The Author has recently been involved in a practical ground improvement project in Hong Kong, using this method. Ordinary Portland cement was used as binder material for this project. Wet mix method was adopted when mixing the binder with soil. The DSM was carried out by rigs mounted on barge, which formed cement-soil clusters composed of four columns in-situ. For areas under seawall, typically underground "walls" were formed by a series of clusters, which are to provide shear resistance for lateral stability of the seawall. In the general platform area of reclamation behind the seawall, individual clusters in a regular square pattern were installed. To evaluate the performance of the stabilized soil, full core along selected clusters was conducted to recover the cement-soil mix samples for laboratory tests that include unconfined compressive strength and other tests such as moisture content, chemical component, and content of organic matter. This paper presents some findings of the characteristics of the cement-soil mixture that was formed in-situ by the deep mixing equipment under water. The paper focuses on the assessment of the unconfined compressive strength of the stabilized soil. It is found that the strength increases with increasing quantity of binder dosage injected into the treated soil. The tests show the stabilized soil gains strength with time.

Keywords: cement; binder; soft clay; deep mixing; stabilization; strength

1 INTRODUCTION

Deep mixing method was first developed in Japan in the late 1960s and applied for practical use in the middle of the 1970s (Kitazume and Terashi 2013; Okumura 1996). The method has been expanded to other countries in Asia and elsewhere since late 1970s. The deep mixing method (DSM) has been used to improve soft clays or organic soils for different purposes, for example, enhancing bearing capacity for foundation soils and stability, reducing compressibility of the weak soil, and improving excavation support. The deep mixing method is to stabilize the in situ soil by blending a binder into the soil to form a mixture of the two, formulating a soil-binder column (cluster). The binder is added into the soil to cement the soil solids, hence improving the strength and stiffness. The characteristics of the improved soil in the cluster will depend on the properties of the soil, mixing method, and features of binder. The binder materials are typically cementous materials such as cement or lime, which could be introduced into the ground either in "wet" (binder-water slurry) or "dry" (dry powder) forms. Other binder materials including fly ash and ground granulated blast furnace slag, either alone or combined with cement in proportions, have also been utilized in practice (Tastan el al. 2011)

The deep mixing method has gained popularity in Hong Kong since 2016. Since then, a few local and rather large scale reclamation projects have taken place, which involve reclamation without dredging in which the soft marine clay was left in place and treated in situ by using the deep soil mixing method. The authors were involved in a ground improvement project that was completed in 2018, which required tens of thousands of deep mixing clusters to be installed. In this project, the binder material is primarily cement, thus it was also referred to as "deep cement mixing" (DCM) method in the local practice. This paper presents some findings of tests on unconfined compressive strength of the cored samples recovered from coring though the cluster.

2 GROUND CHARACTERISTICS

The site of the proposed reclamation project is located near Lantau Island, in the southwest of the Hong Kong Special Administrative Region. The seabed levels generally vary between -5 mPD to -7.5 mPD (meters relative to principal datum), with a natural seawater of approximately 6 m in depth. Marine clay, with local pocket of sands, was encountered at the seabed level, which is underlain by alluvial deposits followed by completely decomposed granite and moderately to slightly decomposed granite. This paper focuses on the improvement of the soft marine clay, the characteristics of which is described herein.

The marine clay varies between 10 m and 35m in thickness across the site, which is grey in color, very soft to soft, and contains shell fragments ranging from less than 0.1 mm to 20 mm in size. Thin lenses or localized pockets of loose sands were found in the marine clay stratum occasionally. The marine clay of high to very high plasticity has an undrained shear strength from less than 3 kPa to 20 kPa in general. It has water content of 40% to over 90% and liquid limit of 50% to 85% and plasticity index between 15% and 30%.

3 METERIALS AND INSTALLATION

3.1 Binder materials

Ordinary Portland cement (OPC) is used as binder material for the deep cement mixing in the field. The proposed OPC complies with BS EN 197-1:2000, being of Type CEM I and strength class of 52.5N. No other additives were added into the binder.

3.2 Field installation and sampling

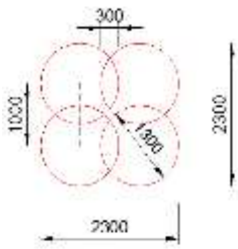
Field installation of deep mixing for the project is briefly discussed below. The installation of deep mixing with cement-water slurry (i.e. wet mix method) was carried out by rigs mounted on barge. Sea water was used for preparation of the cement slurry. Typically three rigs are mounted on the barge at one end, each rig comprising four auger drills. A typical DCM barge is illustrated in Fig. 1.

Fig. 1. Deep cement mixing barge

During installation, four columns with overlap are installed that form a “cluster”. The augers of a rig is shown in Fig. 2. The numbers of blade on each auger and distance between them and the angle are specifically designed to suit the contract requirements and the achievement of the performance of the improved ground. For example, in the penetration, mixing and withdrawal process, the targeted total revolutions or rotations within a certain depth are to be accomplished in order to break up the soil completely and to achieve an even and homogeneous mixing of the cement-soil medium. The number of rotation would in part depend on the soil stiffness or strength. A trial program was carried out to evaluate the auger performance and adjust its configuration as necessary in order to achieve the performance specification.

Fig. 2. Augers of a drill rig on barge

The installed clusters generally range from 10 m to 25m in length below the seabed. A cross section of the design cluster is demonstrated in Fig. 3. Each column has a diameter of 1.3 m and is spaced at 1.0 m to each other, with an overlap of 0.3 m along the centers of the columns. The cluster has an overall dimension of 2.3 m by 2.3 m (i.e. 2,300 mm by 2,300 mm), with a sectional area of 4.62 m^2.



(unit: mm)

Fig. 3. Cross Section of Typical Cluster

Selected clusters were cored and samples along the full length of the cluster were tested in the laboratory after a certain period of installation of the DCM cluster and gain of in-situ strength, to verify the performance and quality of the installed clusters and evaluate amount of dosage to be used for mass production. A photograph showing the core recovery is presented in Fig. 4. The duration, after which the coring is carried out, could range from 20 days to over 120 days, depending on the testing schedule that is intended. The core was typically in 1.0 m long section with a diameter of 100 mm. After the cores were transported to designated laboratory, specimens were then selected and cut into 200 mm in length, which were cured in a controlled environment of temperature ranging between 17ºC to 23ºC and humidity of 95% prior to laboratory testing at the specified curing time. The core specimens were typically tested for UCS at 28, 60, 90 days and even longer.

Fig. 4. Photograph of Core

3 ANALYSIS OF STRENGTH

The UCS tests were performed on cored cement-soil mix samples in laboratory in accordance to the "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens" in ASTM D2938-95 (ASTM 1995). The achieved unconfined compressive strength of the stabilized soil using deep mix method depends on various factors which include, but not being limited to, type of soil, binder material, binder content (dosages), curing method, and mixing duration. Other conditions such as temperature, chemical contents of soil and groundwater, and content of organic matters are also expected to affect the compressive strength. For example, temperature may influence the chemical reaction between the soil and the binder. This paper focuses on the following influencing factors and discusses their effect on the compressive strength of the stabilized soil: initial moisture content of soil, dosages injected, water to cement ratio, and curing time. Test results are presented in the following sections.

3.1 Effect of soil moisture content on strength

A series of unconfined compressive strength tests were performed on marine clay–cement mix samples recovered from the in-situ core along the mixed cluster. The relationship of strength with initial natural moisture content of the soil is illustrated in Fig. 5, which includes those strength data measured at 28 days for cement dosage of 240 kg/m^3 with water to cement ratio of 0.9.

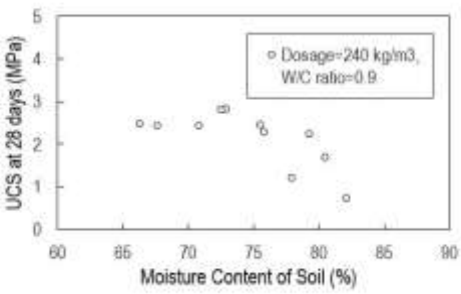


Fig. 5. UCS against initial moisture content of soil

The test results indicate that the UCS values of the stabilized clay range between 0.75 MPa and 3 MPa. The test shows the UCS generally increases with deceasing moisture content of the soil. The strength values do not change considerably over the range of moisture contents of soil between 60% and 75%. However, it drops quickly when the moisture content becomes greater than 75%. Over the test range of the moisture content, the compressive strength decreases by over 70%, from the peak of 3 MPa to the low of 0.75 MPa. The trend of the test results is consistent with the results tested by other researchers (Terashi et al. 1997; Kitazume and Terashi 2013), which demonstrated a reducing UCS of the stabilized soil with increasing moisture content.

3.2 Effect of water to cement ratio on strength

Water to cement ratio is also a parameter that affects the strength of the stabilized soil. The water to cement ratio is defined as the mass of water per unit volume divided by the mass of binder per unit volume. Fig. 6 shows the UCS at 28 days for the cored samples with two different water to cement ratios of 0.8 and 0.9, respectively, for injected dosage of 260 kg/m^3.

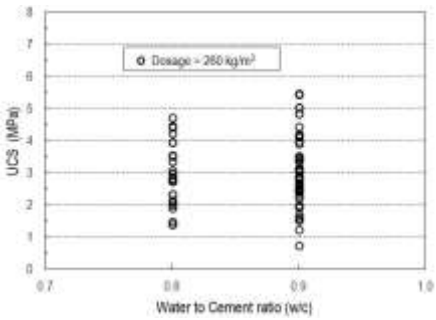


Fig. 6. UCS at 28 days vs water to cement ratio

It is demonstrated that the strength under the two ratios is within the similar range, which does not exhibit a clear trend of the UCS against water to cement ratio. The results indicate that the upper bound of the strength for the higher water to cement ratio is even slightly greater than that for the lower water to cement ratio. The tests for both water to cement ratios postulate a similar mean value of UCS, being 3 MPa. The UCS values for the two water cement ratios do not apparently show the trend such that typically the UCS values would decrease with increasing water to cement ratio as expected. Perhaps, this is because that the two water to cement ratios are so close to each other that the slight difference in amount of water of 12% was not adequate to influence the UCS values, than other factors, such as addition of amount of cement. It is probable that water to cement ratios with greater difference need to be tried to evaluate the effect of different water to cement ratios on the compressive strength.

The test results obtained by the authors show the same conclusion as that demonstrated by Terashi et al. (1997); Kitazume and Terashi (2013); Abbey and Ngambi (2015).

3.3 Effect of amount of cement on strength

Amount of cement slurry injected into the ground is a major factor that governs the strength of the stabilized soil. The amount of slurry used is often referred to as dosage in practice. Fig. 7 shows the trend of UCS values against the cement dosage for water to cement ratio of 0.9. It is observed that the strength values are quite scattered for the same dosage. For dosage of 240 kg/m^3, the UCS varies from 0.75 MPa to nearly 3 MPa with an average of 2.3 MPa, whereas it varies from 1.5 MPa to over 4.1 MPa with an average of 2.8 MPa for dosage of 260 kg/m^3. For dosage of 350 kg/m^3, the UCS is rather high, which measures at a minimum value of 1.5 MPa and maximum value of 5.5 MPa with an average of 3 MPa. It is clearly seen that the higher the dosage, the greater the UCS value.

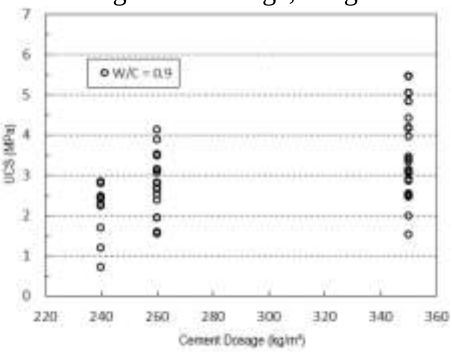


Fig. 7. UCS at 28 days vs cement dosage

The tests for all three dosages yield an overall range of UCS between 0.75 MPa and 5.5 MPa. The general trend of the test results obtained by the Authors are similar to that presented by Abbey and Ngambi (2015).

3.4 Age effect on strength

The cored specimens of the cement-soil mixed clusters were tested at difference ages to study the strength again over time. Fig. 8 illustrates typical relation of UCS vs time for the stabilized soil with cement dosage of 240 kg/m^3 and water to cement ratio of 0.9. It is obvious that the stabilized soil gains further strength with time, where the maximum value is measured to be at 3.8 MPa at 49 days compared to 2.8 MPa at 28 days. The lower bound values of the UCS is also observed to increase from 0.75 MPa at 28 days to 1.3 MPa at 49 days. The average value of the UCS at 49 days is about 1.5 times that at 28 days. Terashi et al. (1997); Abbey and Ngambi (2015) have published their test results which indicated the increasing strength with longer curing age.

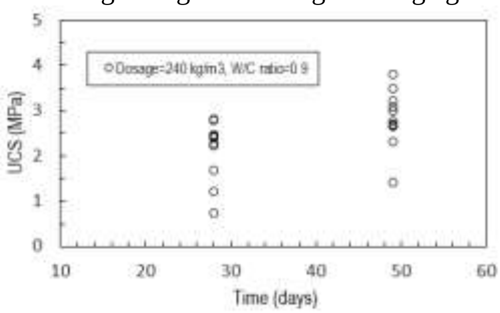


Fig. 8. Strength gain with time

3 CONCLUSION

Soft clay stabilized with cement using deep mixing method under sea was studied based on a practical project in Hong Kong, China. Ordinary Portland cement was utilized as binder material. Improvement of strength to the soft clay is well achieved and demonstrated by laboratory tests on cored samples that were recovered from the stabilized soils. The following conclusions can be drawn from the study:

- The soft marine clay is evidently improved by deep mixing method. The strength of the stabilized clay, being mixed with cement binder, has been significantly increased, with improved UCS ranging from 0.75 MPa to nearly 6 MPa for the various parameters studied.
- The strength of the stabilized clay is influenced by the initial natural moisture content of soil, which is found to decrease with increasing moisture content. The strength values do not vary appreciably over the range of moisture contents of soil between 60% and 75%, whereas it drops quickly when the moisture content becomes greater than 75%. Over the test range of the moisture content, the compressive strength decreases by over 70%, from the peak of 3 MPa to the low of 0.75 MPa.
- The strength of the treated soft clay, to some extent, depends on the water to cement ratios utilized in preparing the cement slurry. The tests show that the lower bound UCS values of the stabilized soil increases with decreasing water to cement ratio.
- The tests further indicate the cement-mixed soil achieves higher UCS values with higher dosages injected into the soil.
- The stabilized soil gains higher strength with time, and the tested 49 days strength is 1.5 times the 28 days strength on average.

REFERENCES

Abby S. and Ngambi S. (2015). Understanding the performance of deep mixed column improved soils – a review. International Journal of Civil Engineering & Technology, 6(3), 97-117

ASTM (American Society for Testing of Materials). (1995). Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens, 1-3. D2938-95. West Conshohocken, PA.

Kitazume, M. and Terashi, M. (2013). *The Deep Mixing Method.* CRC Press, Taylor & Francis Group, Leiden, The Netherlands.

Okumara, T. (1996). "Deep Mixing Method of Japan". *Grouting and Deep Mixing, Proc., IS-Tokyo'96, 2nd International Conf. on Ground Improvement Geosystems*, Vol. 2, Tokyo, Japan, 879-887.

Terashi, M. Okumura, T.&Mitsumoto, T. (1977) Fundamental properties of lime-treated soils. *Report of the Port and Harbour Research Institute*. 16(1), 3–28 (in Japanese).

Tastan, E.O., Edil, T.B., Benson, C.H. Aydilek, A.H. (2011). Stabilization of organic soils with fly ash. Journal of Geotechnical and Geoenvironmental Engineering, 137(9), 819-833.