Stabilisation of soft clay by deep cement mixing (DCM) method – A case study

Yanhua Wang, Geng Xie and Huaren Dou
China Road and Bridge Corporation (Hong Kong), Hong Kong, People's Republic of China

ABSTRACT

Soft ground under the sea often presents challenges for supporting seawall or reclamation without treatment if no dredging is implemented. Ground treatment is often required to improve the engineering properties of weak soils to enhance bearing capacity for supporting the intended structures. Deep soil mixing with addition of binder is one of the ground treatment methods that has been widely used in Asia and worldwide. This method was recently adopted by the authors for a practical ground improvement project in Hong Kong. This paper presents the characteristics of cement-soil mixture in the laboratory environment as well as performance of the field mixed soil using the same binder material. A detailed test programme was developed to evaluate the strength and other properties of the cement-soil mixtures by using various amounts of binder and water to binder ratios. A series of unconfined compressive strength (UCS) of the laboratory mixture were performed. The relationship of strength of the cement-soil mixture with binder dosages is developed. Test results of laboratory mixed soils were compared with those of field mixed soils. The relationship of strength between laboratory mixed soils and field mixed soils was derived. Field installation of deep mixing for the project is discussed.

KEYWORDS Cement; binder; soft clay; deep mixing; stabilisation; strength; unconfined compressive strength; ground treatment
CONTACT Huaren Dou warren.dou@crbc.com.hk
Received 30 October 2018

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 and Terashi, 1975). The method has been expanded to other countries in Asia and elsewhere since late 1970s. The deep mixing method has been used to improve soft clays or organic soils for different purposes, for example, enhancing bearing capacity for foundation soils, stability, reduction in settlement and excavation support. The deep mixing method is to stabilise the in-situ soil by blending a binder into the soil to form a mixture of the two, in order to form 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 cluster will reflect the properties of the soil, mixing method and features of binder. The binder materials are typically cementitious materials such as lime or cement, which could be introduced into the ground either in "wet" (binder-water slurry) or "dry" (dry powder) form.

The deep mixing method has gained popularity in Hong Kong since 2016. The major drive is that the local reclamation projects have introduced the deep mixing method for the treatment of soft marine clay (MC). The authors were involved in a practical ground improvement project in Hong Kong waters since 2016. In the project, the binder material is primarily cement, so it was termed "deep cement mixing" (DCM) method. This paper is to present the test results of the laboratory mixed soils and field mixed soils that were treated using DCM method for the project, which comprised installation of DCM clusters to improve the foundation soil for the seawall and formation of reclamation.

2. Background

The project included a reclamation of land and construction of seawalls. As part of the reclamation, DCM technique was adopted to improve the in-situ soil for the purposes of reducing the post construction ground settlement and improving strength of the soft clay to support the seawall and reclamation as non-dredging method was used for the reclamation. The contract under the project involved installation of tens of thousands DCM clusters under a marine environment. As part of the quality and acceptance requirements, selected DCM clusters had to be cored through the entire length and selected samples from the core which needed to be tested for unconfined compressive strength (UCS). For the contract, 90% of the tested segments along the cluster depth was required to achieve no less than the contract required UCS (CRUCS). For example, if a cluster is 20 m in length, it is required that the test results need to have a minimum of 18 segments of 1.0 m in length to pass the CRUCS.

To study the amount of binder required to achieve the CRUCS of the DCM clusters, a trial programme was performed after the award of contract and prior to the mass installation of the clusters. This involved laboratory trial and field trial, which aimed to primarily study the relationship between the quantity of binder (called dosage) added into the soil and soil-cement mixture's UCS at various ages. Based on the trial results, a proper dosage was adopted for the field installation of the DCM with respective targeted UCS specified under the contract.

In this paper, the application of marine DCM is presented in association with a practical project in Hong Kong. The effect of water-cement (W:C) ratio, cement dosage and age on strength of different types of cement-mixed soils are presented and discussed. Prior to field trial, laboratory trials were performed to assist in developing field trial programme and details. The relationship between the strength of laboratory mixed soils and the field mixed soils has been established. The relationship could be utilised to predict the field strength in preliminary design for future projects in similar nature.

3. Ground characteristics

The project is located in the southwest of Hong Kong. The average natural seawater is approximately 6 m deep and average seabed level is between -5 mPD (metres relative to principal datum) and 7.5 mPD. The original seabed is mainly composed of marine deposits underlain by alluvial deposits, followed by the completely decomposed granite and moderately to slightly decomposed granite. A large portion (about 40%) of the project site was excavated to form marine dump pits in 1990's, which was used as an offshore waste disposal area for contaminated muds that were dredged from the project sites of other development elsewhere. The pit was named "contaminated mud pit" (CMP), which was encountered as deep as 29 m below the seabed in the general area.

Ground investigation included marine bore holes with sampling and standard penetration tests (SPTs), cone penetration tests, along with environmental boreholes. Laboratory tests, including physical tests, classification tests, index tests and chemical tests, were carried out on the recovered samples. The ground investigation results indicated that the geological conditions at the project area consisted of four major strata as illustrated in Figure 1.

In the CMP area, the native soils and chiefly MC had been removed and filled with transported contaminated mud wastes in 1990s, which ranges down to a level of -35 mPD. The fill in the CMP primarily consisted of very soft to soft silt and clay with a little to some sand content, occasionally containing boulders, man-made debris or construction waste such as fragments of concrete slabs, steel bars, steel cable strands and rubber tyres. Large size solid wastes presented obstruction to the installation of the marine DCM. The mud fill (MF) in the CMP IVa area was generally of intermediate to high plasticity, having water content from 42%-70%, liquid limit between 32%-56% and a plasticity index typically between 15%-30%. The samples recovered from the MF indicated that it contained organic matters between 0.2%-3.2%.

Marine deposits were encountered at the seabed outside the CMP area, which varied typically between approximately 10 m and 35 m in thickness across the site. The marine deposits primarily consisted of grey, very soft to soft silty clays or clayey silts with a little sand content and shell fragments ranging from less than 0.1 mm - 20 mm in size. Thin lenses or localised pockets of loose sands were found in MC stratum. The MC of high to very high plasticity was very soft, having an undrained shear strength from less than 3 kPa - 20 kPa in general. It has water content of 40%-94%, liquid limit of 50%-85% and plasticity index between 15%-31%.

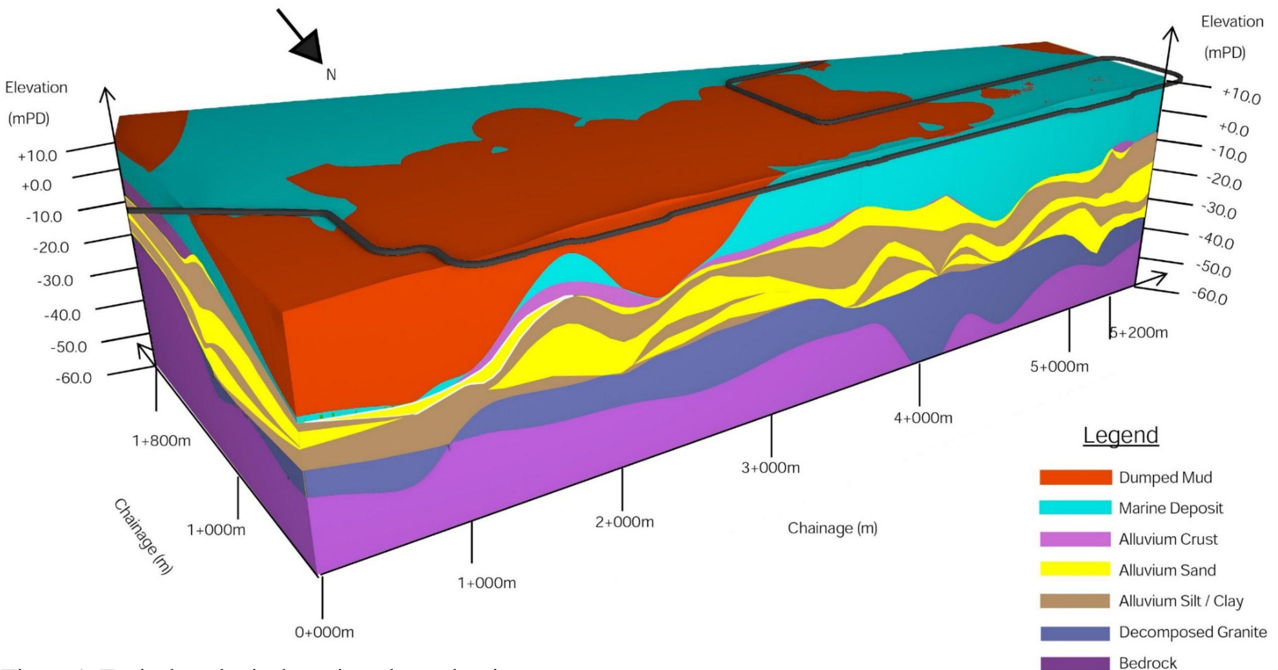

Figure 1. Typical geological stratigraphy at the site.

Table 1. Chemical and physical properties of soils at the site.

Soil type	Unit weight (kN/m^3)	Moisture content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Organic content (%)	Water soluble sulphate content (g/L)	pH
Mud Fill (MF)	15.9-18.1	42-70	32-56	18-37	15-30	0.2-3.2	0.37-0.69	6.9-8.7
Marine Clay (MC)	14.5-19.7	40-94	50-85	24-44	15-31	1.5-2.6	0.53-1.0	7.0-8.1
Alluvial Clay (AC)	14.9-20.8	22-45	30-60	18-35	20-34	0.2-6.6	0.02-0.09	3.9-7.6

Alluvium in the form of clay with a little to some sand content at the site, interbedded with sands at some locations or inclusions of sand pockets, was encountered either below the native marine deposits or the MF in the CMP area at the depth of 29 m maximum below seabed with a thickness of 9.3 m - 34 m. A desiccated alluvium clay (AC) crust was presented at the top of the stratum due to geological loading history, which were typically 2 m - 3 m in thickness. Below the crust was generally firm AC of a few meters, followed by firm to stiff and hard clays. The firm to stiff AC had water content of 22%-45%, liquid limit of 30%-60% and plasticity index of 20%-34%, whereas the firm AC tended to have slightly higher water content as well as higher plasticity index.

Below the alluvium was completely decomposed granite over granite bedrock, which will not be discussed in this paper as the DCM installation is typically terminated within 2 m - 6 m of the AC.

The physical and chemical properties of the various soils at the site are summarised in Table 1.

4. Binder material

The binder material used for the soil mixing for both laboratory tests and the field DCM construction is Ordinary Portland cement (OPC). The proposed OPC complies to BS EN 197-1:2000, being of Type CEM I and strength class of 52.5 N. No other additives were used. Physical and chemical properties of the cement are summarised in Table 2.

Table 2. Cement properties.

Chemical Component	% (by mass)
Calcium oxide content (CaO)	62.8%
Silica content (SiO_2)	20.9%
Alumina content (Al_2O_3)	4.3%
Iron oxide content (Fe_2O_3)	2.9%
Magnesium oxide content (MgO)	2.7%
Tricalcium silicate (C_3S)	56.8%
Dicalcium silicate (C_2S)	16.9%
Tricalcium aluminate (C_3A)	6.5%
Tetracalcium aluminoferrite (C_4AF)	8.9%
Calcium sulphate ($CaSO_4$)	4.1%
Ratio of Calcium oxide content (CaO): Silica content (SiO_2)	1:0.3

5. Test of laboratory mixed soils

The strength of the cement-soil mixture mainly depends on the quantity of dosage, W:C ratio, age and the properties of the soil, if other conditions including adequate agitation, curing environment such as temperature and humidity, and the type of cement are the same. In order to obtain the relationship between the above factors and the strength of the cement-soil mixture, more than 2,000 laboratory cement-soil mixture tests were carried out. For the purposes of the project application, all three superficial soils including MF in the CMP, native MC and AC were sampled from the site, using vibrocore sampling technique. The samples were recovered from 6 m long section of core tubes, operated on the jack-up barge over the sea. The plastic tube was then cut into 1.0 m segment and sealed on both ends before being transported to the designated laboratory for testing.

5.1. Sample preparation and testing

In the laboratory, soil inside each segment of the sampling tube was pushed out by a piston operated mechanically. The soil was then collected into a plastic bag and sealed. The soil in each segment was collectively mixed with cement. The sea water was collected from the project site at 2 m depth below the sea level to make cement slurry in the laboratory based on the designated W:C ratio.

The laboratory mixed soil was prepared according to the procedure of making and curing stabilised soil specimen described in the Japanese Geotechnical Society guideline (Japanese Geotechnical Society, 2009). Specimen preparation and testing procedures are briefly described below.

5.1.1. Soil preparation

1. Take out soil from sealed plastic bag and sieve with a 9.5 mm open sieve to remove the large-sized particles such as shells or gravels.
2. Put adequate sieved soil in a container, then mix it using an electric rotator operated by hand to remould and mix the soil into a homogeneous condition without segregation.
3. Measure the required amount of soil taken out of the container, based on the designated mixing schedule.
4. Place soil in a mixing bowl. The interior surface of the mixing bowl is moistened, but should not have any visible water beads.
5. Mix the soil in the bowl again using a mixing paddle of dough hook type, for a minimum of 10 minutes until the soil are visibly uniform and homogeneous and there are no segregations between water and soil.

5.1.2. Cement slurry preparation

1. Prepare the required amount of dry cement and seawater, based on the designated mixture ratio prepared in the test plan.
2. Blend the dry cement and seawater in a mixing container until thoroughly blended, typically for five minutes. Record the total mixing time and the actual weight of the binder slurry.
3. Pour the cement slurry into the mixing bowl that contains prepared soil samples. Use a rubber spatula to clean the slurry container.

5.1.3. Soil-cement mixing

1. Carry out manual mixing initially to blend the cement into soil.
2. Turn on the automatic rotator to mix the binder slurry and soil inside the mixing bowl for five minutes, as shown in Figure 2.
3. Use a spatula, if necessary, to remove the mixture from the sides of the mixing bowl and push back into the centre of the bowl to ensure adequate mixing.
4. Continue new mixing for another five minutes until the mixture is thoroughly mixed.

Figure 2. Mixer and paddle of flat type.

5.1.4. Soil-cement mixture specimen preparation

The mixture paste was placed inside a cylinder mould (Figure 3), which was made from expanded polystyrene (EPS), for the preparation of the test specimen immediately after the cement-soil was well mixed. The mould measured an inside diameter of 50 mm and a height of 100 mm. Fill the mould in three lifts, lightly tap and poke the sample after each lift as necessary, to remove air bubbles and air pockets. Stop tapping if water begins to separate from the mixture. The objective is to completely fill the mould without air or void while minimising segregation.

Screed the top of the specimen at the top of the mould using a straight edge to produce a flat surface. Cap the specimen immediately to prevent moisture loss. The top surface of the specimen should be covered with a thin plastic sheet or wrapping (sealant). After a batch of moulds have been filled and capped, weigh each mould that was filled with wet cement-soil mixture and record.

The specimens were cured under a controlled environment inside a chamber with a temperature of 20°C - 23°C and the relative humidity of 95% for the target age of 14 days, 28 days, 60 days and 90 days. After achieving the curing time, the specimens (Figure 4) were removed from the chamber for UCS and other testing.

Figure 3. Specimen mould.

Figure 4. Specimens ready for UCS tests.

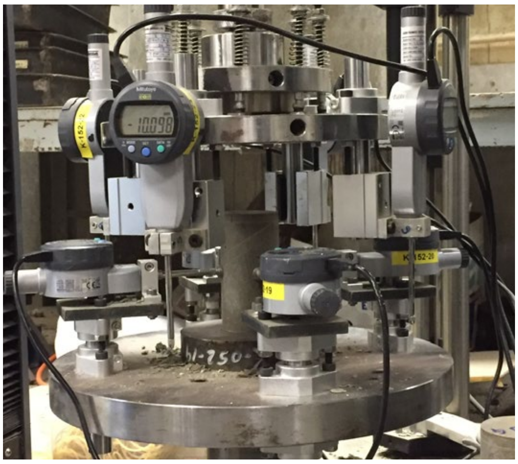

Figure 5. Compression test device.

5.1.5. Apparatus

A loading device with 4.5 kN loading frame, i.e. a compression machine (Figure 5) was used to apply and measure axial load at constant stress rate throughout the test. The stress rate should not be allowed to deviate by more than 10% from the selected rate.

5.1.6. Platens

Two steel platens were used to transfer the axial load to either end of the specimen. They have a hardness of not less than 58 Rockwell C Hardness (HRC). The bearing faces do not depart from a platens by more than 0.0125 mm when the platens are new and are maintained within a permissible variation of 0.025 mm. The platen diameter is at least as big as the specimen diameter, but does not exceed twice the specimen diameter. The platen thickness is at least one-half the specimen diameter.

5.1.7. Spherical seating

One of the platens was spherically seated and the other was a plain rigid platen. The diameter of the spherical seat was at least as large as that of the test specimen, but did not exceed twice the diameter of the test specimen. The centre of the sphere in the spherical seat coincided with the centre of the loaded end of the specimen. The spherical seat was lubricated to ensure free movement. The movable portion of the platen was held closely in the spherical seat, but the design was such that the bearing face could be rotated and tilted through small angles in any direction.

5.1.8. Strength testing

Upon completion of curing for each target days, the specimens were tested for UCS, elastic modulus and other parameters. The testing procedures and methods were referenced to American Society for Testing of Materials (ASTM) D2938-95 (ASTM, 1995) and ASTM D7012-14 (ASTM, 2014) Method C. However, the specimens were tested at room temperature. A strain rate control method was adopted for the compression testing. A constant loading rate of 1.0 mm per minute, corresponding to a strain rate of 0.5%/min - 1%/min for specimen height of 100 mm - 200 mm, was applied to the test specimens until failure within two minutes - 15 minutes, the unconfined compressive strength thus was obtained and the broken sample was taken to determine the moisture content after the test.

5.2. Relationship between UCS and W:C ratio

The W:C ratio of the cement slurry not only affects the strength of the cement mixing soil, but also has an important impact on the DCM barge's slurry conveying system in the field installation. If the W:C ratio is too high, then the target strength may not be achieved. If the W:C ratio is too low, the cement slurry would have a potential to block the cement slurry convey pipe in field installation. Major maintenance would be required to clean the clogged convey pipe if blocking occurs. This would significantly affect the progress of the construction as well as the quality. To study the effect of W:C ratio on strength, a range of W:C ratio, including 0.8, 0.9 and 1.0, was used respectively for the cement slurry preparation. Different dosages with these W:C ratios were applied to mix with different soils recovered from the project site (i.e. MF in CMP, native MC and AC) to form the cement-soil mixture for determination of the UCS and other properties.

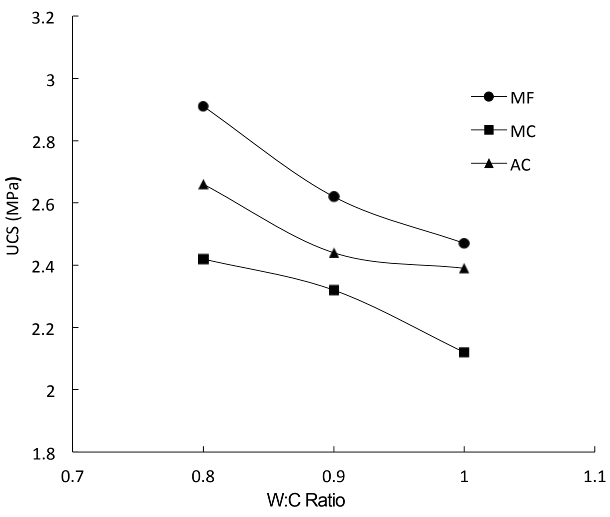

Figure 6. UCS vs W:C ratio (dosage = 260 kg/m^3).

Figure 6 shows the relationship between UCS at 90 days and W:C ratio of slurry for different cement-soil mixtures for cement dosage of 260 kg/m^3. It shows that the UCS generally decreases with increasing W:C ratio as expected, but the rate of reduction for MF in the CMP is faster than that for MC and AC. This indicates that the MF is more sensitive to W:C ratio. The tests show the UCS values for all three types of cement mixed soils which are greater than 2 MPa.

The test results further demonstrate that the strength of the cement mixture with MF is generally greater than those mixtures with MC and AC, whereas the strength of the mixture with MC is the lowest. It shows that when W:C = 0.8, the cement-soil mixture for all three types of soils achieves the greatest strength, of all W:C, which is 2.91 MPa, 2.42 MPa and 2.66 MPa for MF, MC and AC, respectively. These strengths exceed the contract requirements of 1.4 MPa maximum in the seawall area and 1.2 MPa in the platform area. When W:C = 0.9, the strengths of cement-soil mixture for MF, MC and AC are 2.62 MPa, 2.32 MPa and 2.44 MPa, respectively, which also exceed the contract required 1.4 MPa and 1.2 MPa.

5.3. Relationship between UCS and dosage

In addition to cement quantity, cement dosage is a key influencing factor on the strength of cement-mixed soil and construction costs. For this purpose and in consideration of the soil properties, it is decided to use a total of 10 dosages, i.e. 180 kg/m^3, 200 kg/m^3, 220 kg/m^3, 240 kg/m^3, 260 kg/m^3, 280 kg/m^3, 300 kg/m^3, 320 kg/m^3, 340 kg/m^3 and 350 kg/m^3 for the laboratory test trial. These dosages are tested at various W:C ratio stated above. The measured UCS at 90 days for W:C = 0.9 are presented in Figure 7.

Figure 7 shows that the strength varies from 0.8 MPa - 3.8 MPa for the range of dosages tested. It is observed that the strength of the cement-soil mixture increases with increasing dosage. However, when the cement dosage is greater than 260 kg/m^3, the rate of increase in strength for MF and MC soils becomes lower and much slower than AC soil. The tests indicate that it is unnecessary to add significant amount of cement into the soil in order to achieve the intended target strength, i.e. 1.2 MPa, for the cement-mixed soil.

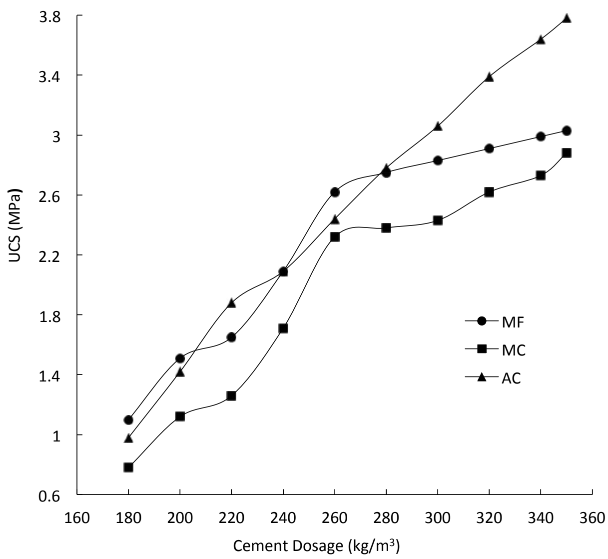

Figure 7. UCS of soil-cement mixture vs cement dosages (W:C = 0.9).

5.4. Age effect on UCS

In order to study the effect of different ages on cement-mixed soil's strength, UCS tests were conducted on different cement-mixed soils with curing ages (days) of 14 days, 28 days, 60 days, 90 days, 120 days and 150 days. The UCS of the cement-mixed soils at each time period was measured and results are shown in Figure 8.

It can be seen from Figure 8 that the strength of cement-mixed soils of the three types increases with time, but the strength gains rapidly for the first 28 days of the curing, and then the rate of increase in strength becomes moderate after 90 days. Among the three types of cement-soil mixtures, the rate of strength gain of the firm to very stiff AC from 30 days - 90 days are lower than the other two soft clays. After 90 days, the strength of cement-soil mixture gains minimal increase, being 1%-3%, where the rate of gain becomes lower and lower with increasing ages and it becomes negligible after 120 days. The results further postulate that the strength at or after 90 days has approximately reached the utmost long-term strength of the mix material.

It is observed from Figure 8 that at 28 days, the strength of mixture with MC reaches 72% of its 90 days strength, whereas 60 days strength is 90% of its 90 days strength. The mixture with MF at 28 days and 60 days has gained 70% and 80% of its 90 days strength, respectively. For the mixture with firm to stiff AC, it gains a higher strength at 28 days, being 83% of its 90 days strength, compared to the soft clay mixtures. However, the AC mixture at 60 days achieves 86% of its 90 days strength. It can be seen that generally, the 28 days and 60 days strengths of cement mixtures for all three separate soils range from 70%-83% and 78%-90% of their 90 days strength, respectively.

It is recommended that the strength of the in-situ DCM clusters should be determined at 60 days - 90 days for the purpose of long-term performance control, depending on the planned loading programme on the treated soils. The strength at 28 days does not appear to be appropriated for long-term applications.

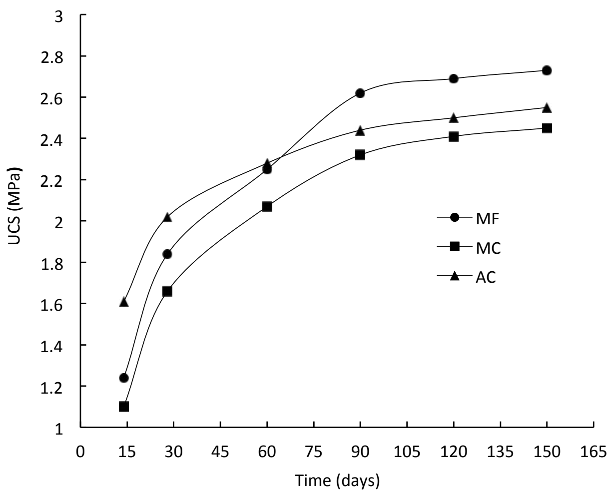

Figure 8. Age effect on UCS of cement-soil mixture.

The strength of the cement mixture with MC is the lowest, of all three types of soils, when other external factors such as dosages (Figure 6), W:C ratio (Figure 7) and age (Figure 8) are unchanged. It is demonstrated that the UCS of the cement-soil mixtures is also influenced by the characteristics of the original soils including sand content or grain size distribution, natural water content, in addition to the external factors mentioned above. Kitazume and Terashi (2013) stated that for a specific treated soil, the UCS decreased with increasing water content of the original soil (clay). Their results also indicated that the UCS increased with increasing sand content contained in the original clayey soil. The test results in the studies showed consistent trends of the UCS. Among the three types of clayey soils being tested, MC had the highest water content and the lowest sand content. Therefore, of all three types of cement mixture (i.e. mixture with MF, mixture with MC and mixture with AC), the tests on the cement mixture with the MC yielded the lowest UCS values (Kitazume and Terashi, 2013).

6. Field DCM cluster installation and strength

6.1. Dosages for field DCM installation

As shown in Section 5.2, theoretically, the cement slurry of any W:C ratio in the range of 0.8 - 1.0 can be used as the designed W:C ratio for the field trial and application, based on laboratory test results. In consideration of workability, applicability and past experience of DCM installation under the marine environment, W:C = 0.9 is the most appropriate condition for the project. The construction would go through two summers during which the air temperatures are high, typically in the range of 30°C - 36°C. The use of W:C ratio of 0.8 for the cement dosage would have a higher potential to cause clog of the binder convey pipes and hoses, as the slurry consistency is high and the fluidity is poor. For cement slurries with higher W:C ratio, they are not deemed to be suitable either as the strength of in-situ mixed soils is expected to be lower, in which the risk of not achieving the target strength might be high.

Laboratory cement-mixed soil typically yields higher UCS than field mixed soil, because better mixing and controlled curing conditions are assured for the former. The ratio of field to laboratory strength (λ) is variable. Past studies indicated that the field cored sample strength (called "field strength") for on-land construction of mixing with clay was 20%-50% of that of laboratory mixed soils, whereas the field strength for marine DCM larger than that of the laboratory mixed soil was measured in some cases (Kamon, 1996; Kawasaki, 1996). Mizutani et al. (1996) reported that the field strength was 60%-80% of that of laboratory mixed soils (called "laboratory strength") (Mizutani et al., 1996). Recently, Kitazume and Terashi (2013) reported that the field strength for on-land mixing ranges primarily from 50% to over 100% of the laboratory strength, whereas the field strength under marine mixing operation is higher than that for on-land mixing strength, being 60% to over 100% of the laboratory strength. In general, the mean value of λ is approximately 2/3 (Kitazume and Terashi, 2013).

When deciding the dosage for the field DCM trial for the project, the mean value of $\lambda = 0.67$ was adopted for relating the field mixed soil strength to laboratory mixed strength to account for the field conditions and potential variation, based on the strength obtained for the laboratory mixed soils. In the proposed dosage for the field application, interpolation was used where a dosage was not directly tried in the laboratory. The dosages for field installation applications are summarised in Table 3.

6.2. Marine DCM clusters installation

Using the decided dosages described in the preceding, a field trial programme was carried out offshore by the rigs mounted on barge. A set of three rigs was mounted on the barge, each rig comprising four auger drills. The

Table 3. Dosages of cement-soil mix vs design strength for field installation.

Design UCS (MPa)	Dosages (kg/m^3)		
	MF	MC	AC
0.8	200	230	210
1.0	210	240	220
1.2	240	250	240
1.4	260	N/A	260

Note: (a) W:C ratio = 0.9 for all dosages; and (b) there was no native MC in the area where UCS = 1.4 MPa is required.

rigs, installation and cement slurry injection system were operated automatically via computer control, which could work round the clock. In addition, the barge was equipped with facilities such as slurry mixer, agitator, grout pumps and convey system. The auger arrangement of a drill rig on the DCM barge is illustrated in Figure 9. A photograph of a barge used for field installation is shown in Figure 10.

Figure 9. Augers of a drill rig on DCM barge.

Figure 10. DCM barge operating offshore.

6.3. Strength of field mixed soils

To verify the construction quality of the field DCM clusters and determine the final dosage, full core through the entire cluster length was carried out after 23 days of installation. The core was typically in 1.0 m section with a diameter of 100 mm. After the cores were transported to the laboratory, specimens were then selected and cut in 200 mm section, which were cured in a control environment of temperature ranging between 17°C - 23°C and humidity of 95% prior to laboratory testing at the specified curing time. The core specimens were tested for UCS at 28 days, 90 days and longer.

The UCS tests were performed according to the "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens" in ASTM D2938-95 (ASTM, 2002) and the elastic modulus tests according to the "Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures" in ASTM D7012-14 (ASTM, 2014). The average values of UCS at 90 days for every 3 m section of depth were presented in Tables 4 - 6.

With respect to the field strength of the cored specimens, the following can be drawn. In general, the upper 2 m - 3 m of DCM clusters have a lower strength than those at depth. For example, this phenomenon is obvious for the MF. The test results are consistent with observations of the field cores that were often highly fractured and poorly mixed. The poor mixing conditions resulted from that the mixing was so close to the seabed with low confining pressure and high sand contents, and as such, pressured grout slurry was likely leaked out or washed out before mixing with the soil. It should be noted that a 2 m thick sand blanket was placed on the existing seabed prior to DCM installation.

The strength of field core specimens increases with depth in the MF and in the MC for certain mix dosages. The field cores show that the core returns below a depth of 2 m, measuring from the seabed which have less fractures with good uniformity of the mixing.

It was found that in the stiffer AC stratum, the strength of the portion near the cluster toe level is typically lower than the upper portion. For example, with the dosage of

Table 4. Comparison of field strength and laboratory strength for MF.

Dosage (kg/m^3)	Specimen type	Design UCS (MPa)	Measured UCS (MPa) at various level (mPD)				
			-3 - -6	-6 - -9	-9 - -12	-12 - -15	-15 - -18
200	Field	0.8	0.05	0.58	1.01	0.79	-
	Laboratory	0.8	1.51	1.53	1.59	1.58	-
210	Field	1.0	-	0.86	1.02	1.06	-
	Laboratory	1.0	1.59	1.63	1.57	1.68	-
240	Field	1.2	1.17	1.23	1.36	1.31	-
	Laboratory	1.2	2.23	2.19	2.09	2.32	-
260	Field	1.4	1.43	1.41	1.74	1.68	1.73
	Laboratory	1.4	2.68	2.62	2.79	2.65	2.73

Table 5. Comparison of field strength and laboratory strength for MC.

Dosage (kg/m^3)	Specimen type	Design UCS (MPa)	Measured UCS (MPa) at various level (mPD)			
			-15 - -18	-18 - -21	-21 - -24	-24 - -27
230	Field	0.8	0.91	0.83	0.96	1.02
	Laboratory	0.8	1.64	1.53	1.76	1.72
240	Field	1.0	1.02	1.13	1.32	1.13
	Laboratory	1.0	1.89	2.02	1.71	1.93
250	Field	1.2	1.31	1.43	1.22	1.36
	Laboratory	1.2	2.04	2.32	2.11	2.54

Table 6. Comparison of field strength and laboratory strength for AC.

Dosage (kg/m^3)	Specimen type	Design UCS (MPa)	Measured UCS (MPa) at various level (mPD)				
			-12 - -15	-15 - -18	-18 - -21	-21 - -24	-24 - -27
210	Field	0.8	0.67	0.98	0.71	-	-
	Laboratory	0.8	1.63	1.55	1.76	-	-
220	Field	1.0	0.96	1.39	0.83	-	-
	Laboratory	1.0	1.88	2.32	2.13	-	-
240	Field	1.2	1.2	1.61	1.34	-	-
	Laboratory	1.2	2.12	2.56	2.09	-	-
260	Field	1.4	-	-	1.41	2.49	1.64
	Laboratory	1.4	-	-	2.44	2.56	2.65

260 kg/m^3, the average strength of the lower portion of 6 m - 9 m is 1.64 MPa, compared to 2.49 MPa in the middle portion of 3 m - 6 m depth. The field cores indicate that there were unmixed clay chunks within the DCM cluster and the mixing was less uniform. The AC has a relatively lower moisture content with a consistency of firm to stiff to very stiff, which is judged to have difficulties in achieving a uniform mixing under an intended rotation number and time duration with a certain quantity of water injection during the penetration (break out and premixing) stage. It was decided at later stage that further installation of field DCM clusters had been injected with more water to reduce the consistency of the clay during the penetration stage with an aim to achieve uniform mixing quality. Details on construction process are beyond the scope of this paper.

For the various cement dosages applied to field installation of DCM, the strength of the field core samples was observed to increase with injection of increasing amount of dosages, similar to the strength of the laboratory mixed samples. It was also observed that the strength of the laboratory mixed soil was constantly greater than that of the field mixed soils.

The field cored samples tended to yield a lower strength in the upper and lower portions of the DCM cluster. Installation procedures were assessed. It was then to increase the amount of dosage in the upper portion of the treated soil and enhancement of mixing process for the lower stiff AC by introducing an additional insertion and mixing cycle. The former aimed to achieve higher strength by the injection of additional cement slurry, whereas the latter intended to improve the uniform mixing quality and thus the strength. The cement dosages were then adjusted for the various soils as shown in Table 7.

Table 7. Field DCM dosages (kg/m^3).

Design Strength (MPa)	MF in CMP	MC	AC
0.8	(240*) 210	230	240
1.0	(240*) 210	240	240
1.2	(250*) 240	250	240
1.4	260	N/A	260

Note: (a) W:C ratio = 0.9 for all dosages; (b) UCS = 1.4 for areas without native MC; and (c) * indicates dosages for the upper 3 m of the treated clusters.

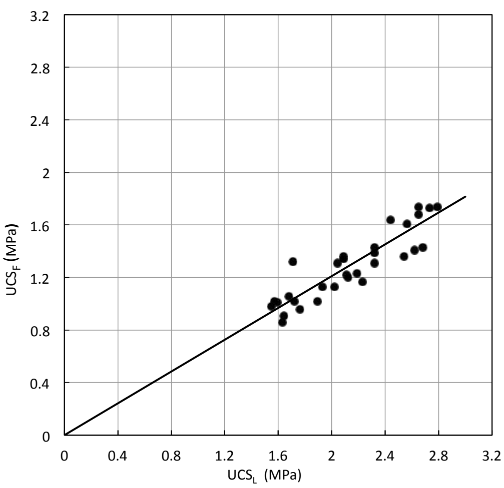

Figure 11. Relationship between field strength and laboratory strength.

6.4. Relationship between field strength and laboratory strength

Based on the results of the test programmes in this study, the relationship between UCS for field mixed soil (UCSF) and laboratory mixed soil (UCSL) is derived. Some data with extreme low and high values have been ignored in this analysis, on the basis of the "three-sigma rule". Figure 11 shows the relationship between UCSF and UCSL collectively for all three types of soils tested. The ratio of field strength to laboratory strength varies appreciably, but generally between 45%-70%, with a mean value of 60%. The UCSF/UCSL under this study are in the similar range to those 40%-100% published by other researchers, e.g. Mizutani et al. (1996) and Kitazume and Karashi (2013), which were discussed in the preceding.

The developed relationship of field strength to laboratory strength can be used to predict the field strength for planning and preliminary design purposes in similar soil and installation conditions based on the strength of the laboratory cement-mixed soils.

7. Conclusion

Based on the ground treatment project in Hong Kong that the authors were involved in, a study was conducted on the improvement of soft MC to stiff AC by using marine DCM method. The effect of W:C ratio, quantity of cement dosage and age on the strength of cement-mixed soils were analysed. The correlation of UCS between field mixed soil and laboratory mixed soil was developed. The following conclusions are drawn from the study:

- The strength of the cement mixed soil increases with decreasing W:C ratio.
- The strength of the cement mixed soil increases with increasing quantity of cement dosage used for the mixing. However, when exceeding 260 kg/m^3, the gain in strength for MF and MC is insignificant.
- The strength of cement mixed soil increases with curing age, but after 90 days the gain in strength is negligible.
- In the field installation of the DCM clusters, it was found that the strength in the upper 2 m - 3 m portion of the treated clusters was typically smaller than those below.
- It was observed that the deep mixing in stiff clay is difficult, particularly in achieving uniform mixing conditions. Thus, the strength of mixed soil in the stiff clay may not achieve as much as that for the soft MC.
- Slurry using W:C = 0.9 was considered the most suited for the environment and soil conditions encountered in this project.
- The cement mixed soil strength at 28 days reaches over 70%-80% of strength at 90 days.
- The strength of the mixed soil almost gains its utmost strength at 90 days with negligible increase thereafter. For acceptance criteria with respect to strength, it is considered that the use of 90 days strength is appropriate.

For initial planning and preliminary design purposes, a ratio of field strength to laboratory strength of 0.6 on average can be used for cement-mixed soft soils in Hong Kong based on the results of this study.

Notes on Contributors

Ir Yanhua Wang is currently a Director and Deputy General Manager of China Road and Bridge Corporation (Hong Kong). He is a registered engineer with strong technical background in civil and geotechnical engineering. Having involved in a wide variety of large-scale infrastructure projects both locally and internationally for over 27 years, he has developed his expertise in construction engineering, contract administration and project management. Ir Wang is a Project Director for a number of renowned projects in Hong Kong such as Liantang/Heung Yuen Wai project, Tuen Mun-Chek Lap Kok Link – Northern Connection Toll Plaza and Associated Works, Three Runway System DCM Project, Tseung Kwan O-Lam Tin Tunnel (Road P2) and Cross Bay Link.

Mr Geng Xie received his master degree in highway and railway engineering from Changsha University of Science & Technology, Changsha, People's Republic of China in 2011. He is currently a Senior Engineer of China Road and Bridge Corporation (Hong Kong). His current research interests include pile foundation, engineering materials and environmental management.

Ir Huaren Dou is a Chief Engineer, Geotechnical of China Road and Bridge Corporation (Hong Kong) with over 30 years of experience in the fields of geotechnical and civil engineering. He obtained his M.A.Sc. degree from the University of British Columbia, Canada. He is a Registered Professional Engineer in Hong Kong. He has been involved in design and construction of a wide spectrum of major civil and infrastructure projects in Hong Kong and internationally, including Hong Kong Disneyland, Hong Kong Express Rail, Shatin to Central Link, Hong Kong International Airport Three Runway System Project, Cross Bay Link and Mass Rapid Transit Circle Line in Singapore. Through the past few decades, he has developed extensive expertise in numerical analysis and design for deep excavation, tunnels, foundation engineering, marine structures, reclamations and seismic engineering.

References

[1] American Society for Testing of Materials (ASTM) (1995). *Standard test method for unconfined compressive strength of intact rock core specimens, 1-3. D2938-95*. ASTM, West Conshohocken, Pennsylvania.

[2] American Society for Testing of Materials (ASTM) (2007). *Standard practice for making and curing soil-cement compression and flexure test specimens in the laboratory, 1-7. D1632-07*. ASTM, West Conshohocken, Pennsylvania.

[3] American Society for Testing of Materials (ASTM) (2014). *Standard test methods for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures, 1-9. D7012-14*. ASTM, West Conshohocken, Pennsylvania.

[4] Federal Highway Administration (FHWA) (2013). *Federal highway administration design manual: Deep mixing for embankment and foundation support. Publication No. FHWA-HRT-13-046*. FHWA, McLean, Virginia.

[5] Jacobson JR, Filz GM and Mitchell JK (2005). *Factors affecting strength of lime-cement columns based on a laboratory study of three organic soils*. In: Proceeding of International conference on deep mixing best practice and recent advances, Deep Mixing'05. Sweden: pp. 87-94.

[6] Japanese Geotechnical Society (JGS) (2009). *Practice for making and curing stabilized soil specimens without compaction. JGS 0821-2009*. (1). JGS, Japan: pp. 426-434.

[7] Kamon M (1996). *Effect of grouting and DMM on big construction projects in Japan and the 1995 Hyogoken-Nambu Earthquake*. In: Grouting and deep Mixing: Proceedings of IS-Tokyo'96, the Second International Conference on Ground Improvement Geosystems. (2). Japan: August Aimé Balkema, pp. 807-823.

[8] Kawasaki K, Kotera H, Nishida K and Murase T (1996). *Deep mixing by spreadable wing method*. In: Grouting and deep mixing: Proceedings of IS-Tokyo'96, the Second International Conference on Ground Improvement Geosystems. (2). Japan: August Aimé Balkema, pp. 631-636.

[9] Kitazume M and Terashi M (2013). *The deep mixing method*. The Netherlands: CRC Press, Taylor & Francis Group.

[10] Mizutani T, Kanai S and Fujii M (1996). *Assessment of the quality of soil-cement columns of square and rectangular shaped formed by a deep mixing method*. In: Grouting and Deep Mixing: Proceedings of IS-Tokyo'96, the Second International Conference on Ground Improvement Geosystems. (2). Japan: August Aimé Balkema, pp. 637-642.

[11] Okumara T (1996). *Deep mixing method of Japan*. In: Grouting and Deep Mixing: Proceedings of IS-Tokyo'96, the Second International Conference on Ground Improvement Geosystems. (2). Japan: August Aimé Balkema, pp. 879-887.