Technical Developments Related to Deep Cement Mixing Method in Hong Kong

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ABSTRACT

In recent years, deep cement mixing (DCM) method, a non-dredged ground improvement technique, has been adopted in several local large-scale reclamation works. It is also a robust ground improvement solution and can expedite land formation. Currently, design and construction methods adopted in Hong Kong are mostly referred to the practice or guidelines developed in other countries. With more local experience gained and in view of the potential application in possible coming mega development projects which involve reclamation and ground treatment works, it is considered worthwhile and timely to conduct more detailed studies to understand the engineering properties of the materials improved by this technique and to harness the design and construction practice, with a view to enhancing the cost effectiveness of DCM works. This paper briefly introduces some on-going research related to DCM method covering several design and construction aspects including engineering properties, ground investigation and laboratory testing using laboratory mixed and field mixed cores. The objectives, potential application and preliminary results of the studies are presented and discussed in the paper.

Keywords: Deep Cement Mixing, Ground Improvement, Reclamation

1 Introduction

In recent years, deep cement mixing (DCM) method, a non-dredged ground improvement technique, has been adopted in several local large-scale reclamation works including the Three-Runway System project, the Tung Chung East reclamation project, and the Integrated Waste Management Facilities Phase 1 near Shek Kwu Chau. Soft deposit beneath the reclamation area is left in place and treated in-situ by DCM. The principle of DCM is to mix a cementitious agent with soft soils to produce either a column, a panel, or a mass block of improved materials with higher strength and enhanced stiffness characteristics within a short period of time. DCM is a robust ground improvement solution and can expedite land formation. Ground settlement can also be effectively controlled and the quantity of fill material for replenishing the settlement can be greatly reduced comparing with conventional drained ground improvement method using prefabricated vertical drains (PVD) and surcharging. Lastly, this method realizes the non-dredged reclamation more thoroughly that bulk removal and disposal of dredged materials, particularly for seawall construction, is no longer required. Potential impacts to surrounding water quality and marine ecology can be substantially reduced.

Currently, design and construction methods adopted in Hong Kong are mostly referred to the practice or guidelines developed in other countries such as Japan, Korea and United States. With more local experience gained and in view of the potential application of DCM in possible coming mega development projects which involve reclamation and ground treatment works like Lantau Tomorrow Vision and Northern Metropolis, it is considered worthwhile and timely to conduct more detailed studies

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to understand the engineering properties of the materials improved by DCM and to harness the design and construction practice, with a view to enhancing the cost effectiveness of DCM works.

This paper briefly introduces some on-going research related to DCM covering a number of design and construction aspects including engineering properties, ground investigation and laboratory testing using laboratory mixed and field mixed cores. The research includes reviewing the strength and stiffness characteristics of the treated soils under confining condition, evaluating tensile properties and compressibility of treated soils, evaluating the use of smaller diameter of cores for unconfined compression strength (UCS) test, developing correction factors for low aspect ratio specimens in UCS test, exploring alternative and supplementary test methods for DCM works, and proposing a standardized laboratory mixing test procedure. The objectives, potential application and preliminary results of the studies are presented and discussed in the paper.

2 On-Going Research

2.1 Strength and stiffness characteristics of DCM materials

The state of practice in Japan and United States is to use total stress friction angle of $\phi = 0$ and cohesion intercept of $c = 0.5*UCS$ for stability analyses (Bruce et al. 2013). Design parameters derived from UCS results without consideration of the effect of confinement of surrounding soils may be on the conservative side. In order to simulate the actual site conditions, to enable more rigorous analyses, and to review whether there are rooms to optimize the design of DCM works, consolidated undrained triaxial tests on field mixed cores were conducted. For each triaxial test, a corresponding UCS test was conducted on a sample selected along the same metre of the core. As such, all selected samples had the same diameter (approximately 100mm) and length (approximately 200mm).

Based on 21 triaxial test results, it was revealed that there was no significant difference between UCS and peak strength from triaxial test under the normal range of confining pressure (e.g., 50 to 400kPa). As presented in Figure 1, the peak shear strength from triaxial tests with respect to the corresponding UCS mainly ranged between 0.8 and 1.5. Comparing UCS test of which there is no residual strength in theory, residual strength with the presence of confining pressure, even under a low pressure of 45kPa, became evident (Figure 2). In triaxial tests, residual strengths were about 0.3 to 0.7 of the UCS.

As shown in Figure 3, the residual strength to UCS ratio appeared to decrease with increasing UCS. In other words, the drop of strength in the post peak stage under confining condition increased when DCM material possessed higher UCS. Figure 4 presents the relationship between the axial strain at failure (ε_f) and peak strength in triaxial test and UCS test. Overall, the magnitude of ε_f of DCM material determined from both tests was small (within 2%). However, in the case of confining conditions, the magnitude of ε_f, ranged between 0.4% to 1.8%, was about 1 to 4 times larger than those without confinement (about 0.4%). In addition, ε_f increased with the peak strength in triaxial test but relatively insensitive in UCS test. In view of this, the serviceability limit with reference to the strain from UCS tests can be considered as more robust.

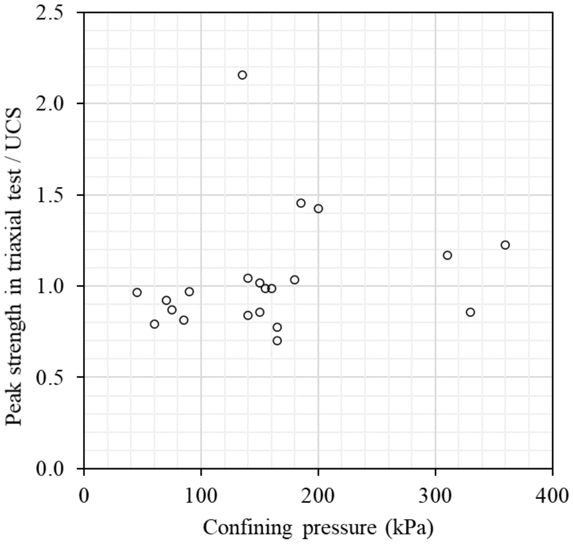

Figure 1: Relationship between peak strength in triaxial test to UCS of field mixed DCM material and confining pressure

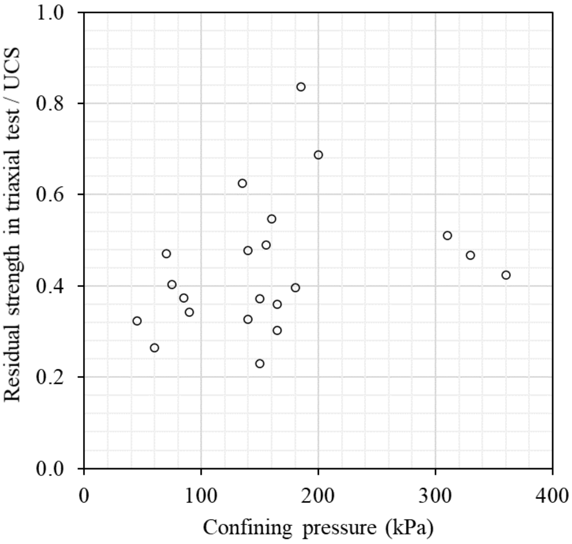

Figure 2: Relationship between residual strength in triaxial test to UCS of field mixed DCM material and confining pressure

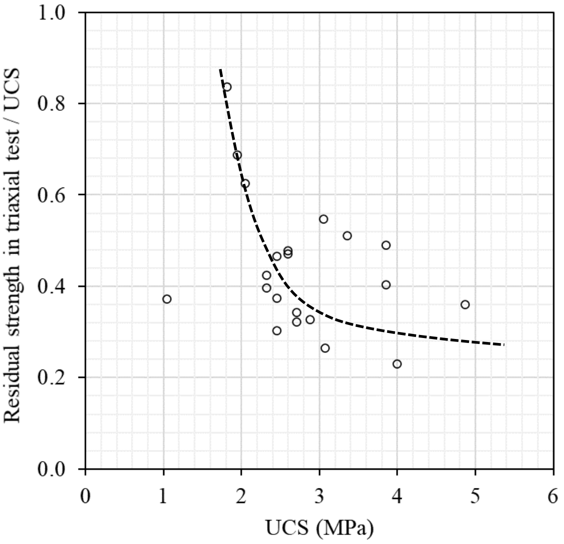

Figure 3: Relationship between residual strength in triaxial test and UCS of field mixed DCM material

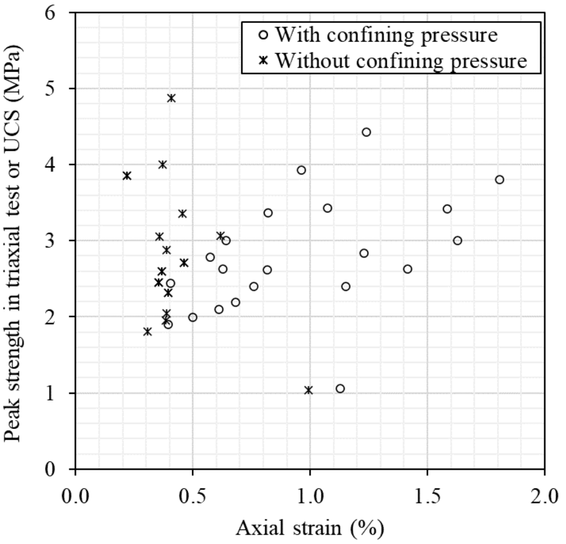

Figure 4: Strain at failure of field mixed DCM material with and without confining pressure

2.2 Tensile Properties of DCM Materials

Typical configuration of DCM materials includes column-pattern, wall-pattern, grid-pattern and block-pattern. Design in each pattern involves evaluation of external stability and internal stability under a variety of potential failure modes to ensure that the stress induced within and adjacent the treated soil do not exceed the material capacities like compressive strength, shear strength and tensile strength. Limited research has been conducted on the tensile properties of DCM material in Hong Kong (Cheung et al. 2021). This has limited the application of some configurations like column-pattern DCM material to support structures or control settlement. There is a lack of internationally testing standard for determining tensile strength of DCM material. Tensile strength of DCM material was evaluated by indirect tensile test (Brazilian test), simple tension test and bending test in previous studies (Bofinger 1970, Koseki et al. 2008, Consoli et al. 2010, Azneb et al 2021). However, the testing procedures were either inconsistent or not reported in detail.

A study aiming to review different testing methods and investigate tensile properties of DCM materials was carried out. Based on the results of laboratory mixed specimen, it was found that tensile strength determined by direct tensile test and Brazilian test are similar provided that the crack initiation process is cautiously monitored in the Brazilian test. For example, the crack should initiate from the centre of the specimen (Yanagidani et al. 1978). We found that the use of flat platen with plywood strip can prevent effectively premature failure in DCM specimens. The typical set up of a Brazilian test is presented in Figure 5. In the study, only test results from specimens with crack initiated from centre of the specimen were considered. Figure 6 shows an example of the crack development process in the specimen. Our results reveal that the tensile strength was about 17% to 21% of the UCS for laboratory mixed specimen with average UCS of 1.2 MPa; while for field mixed specimens with UCS ranged between 2.9 to 4.6 MPa, the tensile strength was about 9 to 18% of the UCS. The stress ratios (tensile strength / UCS) are generally consistent with the data in the literature (Bruce et al. 2013). The current design approach without considering tensile strength is on the conservative side. With improved knowledge on the tensile properties, potential beneficial effect in stability analysis for the application like DCM in column-type or DCM material as a retaining structure can be further studied.

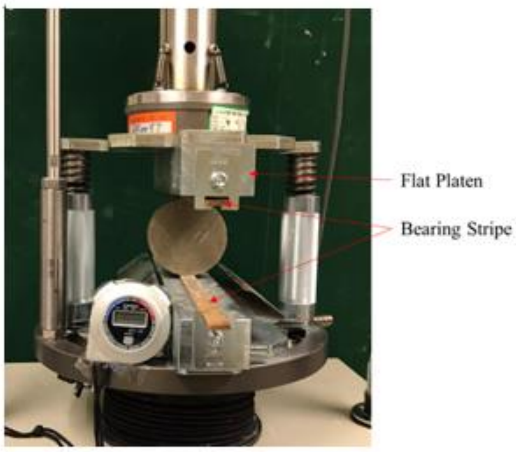

Figure 5: Set up of Brazilian test with the use of flat platen and plywood strip

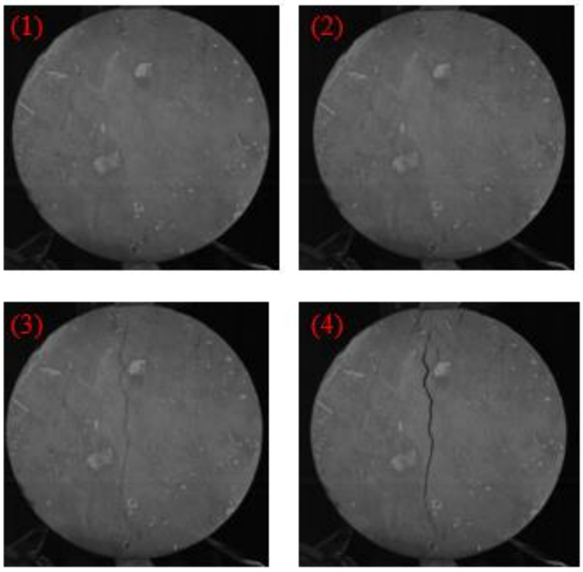

Figure 6: Crack development process of field mixed DCM materials (crack initiated from the centre of the specimen)

2.3 Compressibility of DCM materials

It has been documented in many literatures that the strength of DCM material continuously increases with time (Kawasaki et al. 1981, Saitoh 1988, Cement Deep Mixing Association 1999, Hwang et al 2004). However, there is not much information on its long-term creeping behavior. Although creeping is expected to be small, the intent of the study is to determine compressibility properties of DCM material for supplementing current design practice.

A series of oedometer tests were conducted on specimens trimmed from field DCM cores and cores of untreated marine deposit. The tests were carried out according to GEOSPEC 3 (2017). Coefficient of secondary compression (C_{sec}) of treated and untreated soil were determined at different applied pressures. C_{sec} is defined as $C_\alpha/(1+e_0)$ where C_α is the secondary compression index and e_0 is the initial void ratio. Figure 7 reveals that the magnitude of C_{sec} of DCM materials was about one order less than that of the untreated soil. After stabilized by DCM, C_{sec} of the treated material was not sensitive to the applied pressures (100 – 800kPa). It can be concluded that the treated material is unlikely a key player of the long-term deformation.

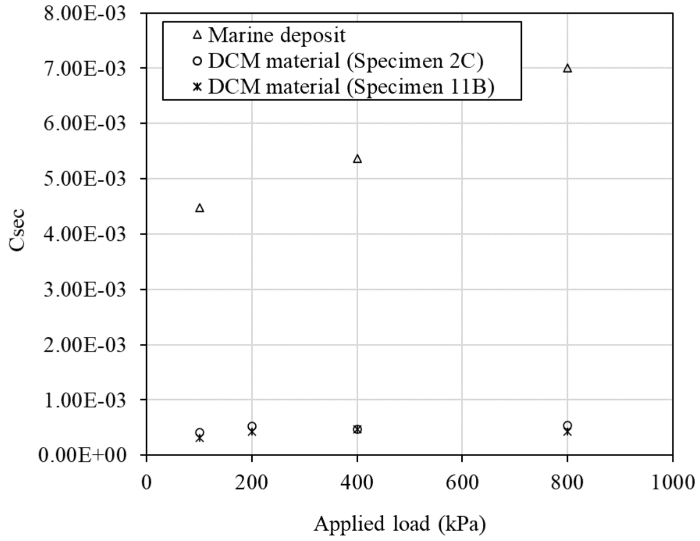

Figure 7: Coefficient of secondary compression of untreated and treated marine deposit by DCM

2.4 Use of smaller diameter of cores for unconfined compression test

In the current practice for UCS testing of DCM specimens, 50mm or 75mm diameter cores are used for laboratory mixed samples while 100mm diameter cores are adopted for field mixed samples. It is believed that specimens prepared under a laboratory-controlled environment possess far less potential variation as a consistent mixing method is applied. On the other hand, 100mm diameter specimens are considered less susceptible to localized ground variations and uncertainties during field mixing process. However, larger diameter specimens imply higher cost in coring and subsequent laboratory testing. A study is therefore conducted to investigate the credibility of adopting smaller diameter field mixed cores.

It is recommended in Federal Highway Administration Design Manual that the core diameter should be at least 64mm (Bruce et al. 2013). In this study, 100mm cores and 76mm or 64mm cores at adjacent locations were taken from field mixed DCM columns. Specimens were then selected along every metre from both the 100mm and 76mm or 64mm cores for UCS testing. As shown in Figure 8, a good correlation was observed between UCS of the 100mm diameter cores and the smaller 76mm or 64mm diameter cores, given the inherent variation of UCS results from field DCM cores. It was also noticed that smaller diameter cores were more susceptible to disturbance during core boring and fractures were found more frequently, resulting in less suitable specimens selected for test. The average success rate of specimen selection was 85% for smaller diameter cores (76mm or 64mm) and 95% for 100mm diameter cores. Based on available information, it is considered that both smaller core diameters are suitable for UCS test.

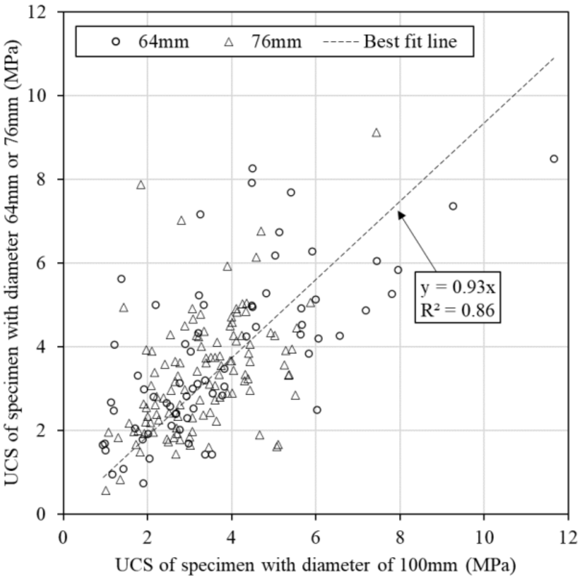

Figure 8: Relationship between UCS of 64mm/76mm diameter cores and UCS of 100mm diameter cores

2.5 Correction factor for shorter specimens in UCS test

Length to diameter (L/D) ratio affects the stress and strain distribution within the specimen during compression. The confinement effect due to the frictional force at the end surfaces would be insignificant if length to diameter ratio is sufficient. Specimen with smaller L/D ratio is typically able to resist higher loads. Currently, UCS test is carried out in accordance with HKIE Interim Guidelines on Testing of Unconfined Compressive Strength of Cement Stabilized Soil Cores in Hong Kong (HKIE, 2017). According to the Interim Guidelines, cylindrical specimen with L/D ratio of 2 is recommended for the test and specimen with L/D ratio between 1.5 (inclusive) and 2.0 can also be tested with lubricated ends and with the application of correction factor on the measured UCS. It is not uncommon to retrieve cores from DCM column with insufficient length (L/D < 1.5). To allow more flexibility in specimen selection for quality control, pilot tests were arranged on laboratory mixed specimens with different L/D ratios, ranging from 1.0 to 2.0, with an aim of determining a set of correction factors for shorter specimens.

Under the collaboration with the University of Hong Kong, laboratory mixed cores with target UCS ranged between 1MPa and 3MPa were prepared using kaolin or marine deposits as natural soil mixed with binder which included Portland cement or Portland blast-furnace cement. 250 specimens were then cut from these cores with different L/D ratios (1.0, 1.25, 1.50, 1.75 and 2). UCS was measured on the specimens cured for 21, 28 and 90 days. The data reported by Lin (2018) and Liu (2021) were consolidated and the correction factor under various L/D ratios were calculated using the following equation:

$$Correction\ factor = \frac{Average\ UCS\ of\ specimen\ with\ \frac{L}{D}\ of\ 2}{UCS\ of\ specimen\ with\ specific\ L/D} \tag{1}$$

Figure 9 presents the correction factors for specimens with different L/D ratios. As noted from the Figure, the mean and median of the correction factors for L/D ratio between 1 and 2 were both close to one. Although it is generally accepted that higher UCS will be resulted from shorter specimen, the result in this study indicated that the effect of L/D ratio on UCS was not significant. However, it should be noted that the data at various L/D ratios were scattered. The shaded area (bounded by a pair of black dash lines) covered about 80% of the data. The variation of correction factor was about ±0.1, ranged between 0.9 and 1.1. Based on the available test results, the correction factor recommended in Federal

Highway Administration Design Manual (Bruce et al. 2013) for specimens with L/D ratio less than 1.5 can be considered as conservative.

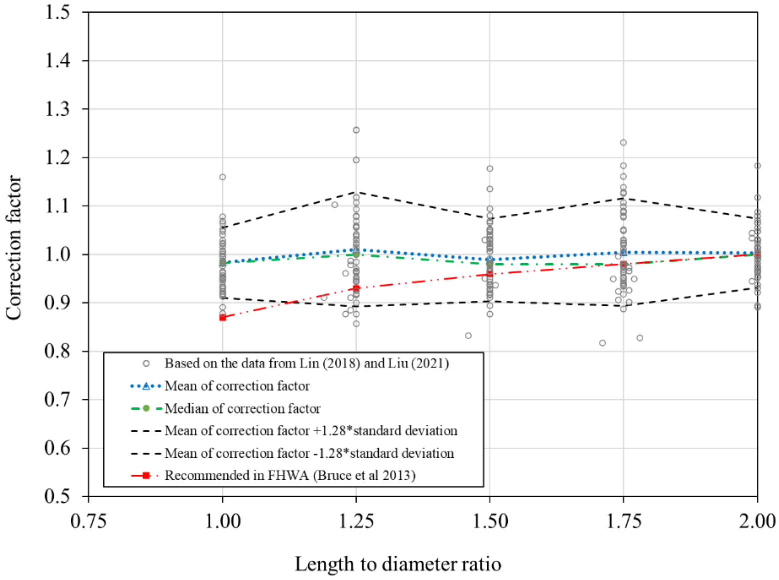

Figure 9: Relationship between correction factor and length to diameter ratio

2.6 Alternative and Supplementary Test Methods for DCM Works

The most commonly used engineering property for quality control is UCS. However, the requirement on the quality of field cores for UCS test is relatively high and the testing duration including the specimen preparation time is long. The study aimed to develop quick test methods, as alternative or supplementary tests, with less requirements on the specimens to facilitate early and fast testing on site. The applicability of two index test methods on DCM materials were studied.

2.6.1 Point Load Test

Point load test (PLT) is an index test for strength classification of rock materials. It is a form of "indirect tensile" test which is performed by loading the specimen between two steel conical platens to induce horizontal tensile stress until splitting failure occurs. The specimen can be loaded either diametrally or axially. Although ASTM D5731-16 suggests that PLT is applicable for medium strength rocks with UCS not less than 15MPa, some researchers suggested that this test method is applicable to brittle materials (Robins 1980, Levent & Gokce 2015). Considering the brittleness of DCM specimens and the advantages of PLT (such as simple testing procedures and less specimen preparation works), laboratory tests were arranged on laboratory and field mixed specimens to investigate the feasibility of using PLT to determine the UCS of DCM materials. According to ASTM D5731-16, point load strength index ($I_{s(50)}$) is calculated by following equation:

$$I_{s(50)} = (\frac{D}{50})^{0.45}\frac{P_f}{D^2} \tag{2}$$

where D is the diameter for diametrally loaded core specimen, or the equivalent core diameter ($D_e = \sqrt{\frac{4WD}{\pi}}$) for axially tested core specimen, W is the distance between loading points, and P_f is the failure load. Typically, a constant correlation (k) between UCS and $I_{s(50)}$ is proposed (UCS = $kI_{s(50)}$) for estimating UCS from PLT for rock testing. Laboratory mixed cement stabilized soil specimens with target UCS ranging from 1MPa to 30MPa were prepared to evaluate applicability of PLT to cement mixed material. As shown in Table 1, the coefficient of variation (CoV) of $I_{s(50)}$ for specimens with UCS less than 15MPa is slightly higher than that for specimens with higher strength. Overall, the CoV was less than 10% across specimens of all strengths. This magnitude of variation is comparable with the results from point load tests on rocks conducted by Bieniawski (1974). It seems that PLT can also be applied to cement mixed material with UCS below 15MPa without significant variation.

Table 1: Statistics of point load strength index for laboratory mixed specimens

Mix ID	Average UCS (MPa)	Diametral PLT				Axial PLT			
		No. of Test	Ave. $I_{s(50)}$ (MPa)	Std. dev. $I_{s(50)}$ (MPa)	CoV	No. of Test	Ave. $I_{s(50)}$ (MPa)	Std. dev. $I_{s(50)}$ (MPa)	CoV
PBFC-MD-1	0.9	8	0.08	0.006	7.9%	8	0.09	0.006	6.2%
PBFC-MD-2	3.8	5	0.19	0.014	7.4%	8	0.26	0.017	6.5%
PBFC-MD-3	4.9	5	0.27	0.029	10.7%	7	0.27	0.023	8.8%
PBFC-S-1-10	12.4	8	1.18	0.084	7.1%	8	1.22	0.099	8.2%
PBFC-S-2-20	22.5	8	1.73	0.095	5.5%	8	1.82	0.088	4.8%
PBFC-S-3-20	24.1	8	1.82	0.094	5.2%	8	1.93	0.090	4.6%
PBFC-S-4-30	36.3	7	2.02	0.122	6.0%	8	1.68	0.118	7.0%

Both diametral and axial PLT were carried out on field mixed DCM cores collected from a local project. However, correlation between UCS and $I_{s(50)}$ were scattered (Figure 10). This might be partly attributed to the heterogeneity of test specimens due to variability in soil conditions and mixing condition. In general, test results of axial PLT were more consistent than that of diametral PLT. Similar observation was noticed in the results of laboratory mixed specimen. For specimens which had similar UCS of field mixed cores (average UCS from 0.9MPa to 4.9MPa), axial PLT gave lower CoV of $I_{s(50)}$. Nevertheless, the lower bound values of k for two types of PLT were in similar order. Failure modes of specimen after PLT were briefly reviewed. It appeared that there is no significant relationship between $I_{s(50)}$ and the failure patterns. Potential use of the axial PLT to provide supplementary information to estimate UCS roughly will be carefully examined with the consideration of the distribution of data comparing with that in rocks from literatures.

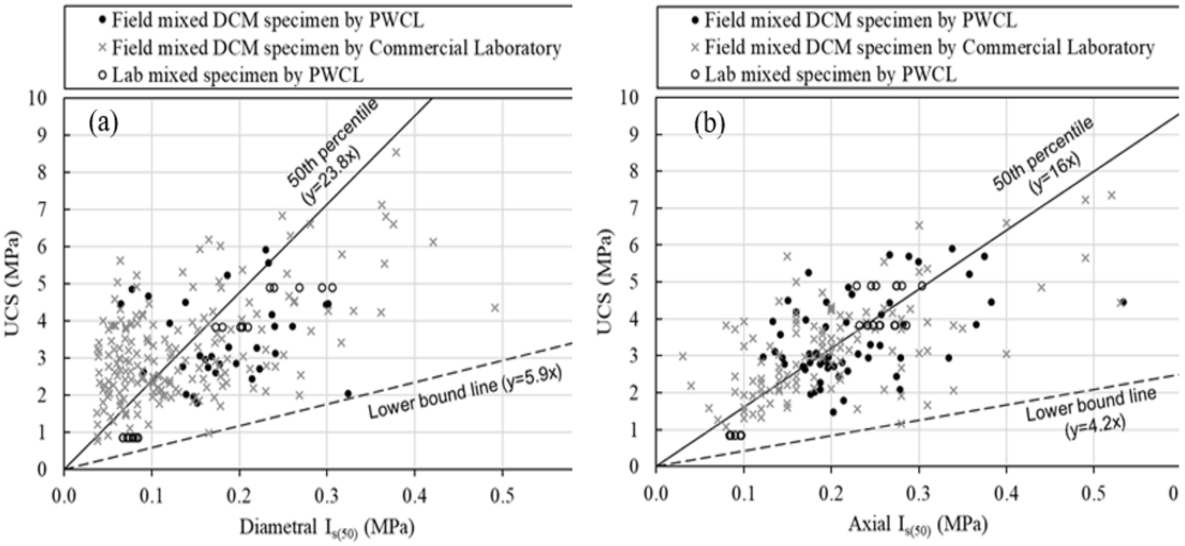

Figure 10: Correlation between UCS and $I_{s(50)}$ for field mixed DCM specimens and lab mixed specimen; (a) diametrally loaded; (b) axially loaded

2.6.2 Needle Penetration Test

Needle penetration test (NPT) is an index test for determining UCS of soft rock or stabilized soil through a correlation between needle penetration index (NPI) and UCS. Needle penetrometer, as shown in Figure 11, is a lightweight and portable device which utilizes a needle to penetrate the surface of the material to be tested. NPI is determined by following equation based on the measured load and the penetration of the needle:

$$NPI = F/D \qquad \textbf{(3)}$$

where F is the measured load (N) and D is the measured depth of penetration (mm). The test is applicable to materials having UCS lower than 20 MPa (Ulusay et al. 2014). According to the ISRM Suggested Method for the NPT (Ulusay et al, 2014), the specimen is suggested to be greater than 15mm in thickness for cylindrical samples with diameter of 40 – 50mm. There are no special preparation requirements on the surface of the specimen.

Predicted UCS of DCM specimen can be determined based on a correlation between NPI and UCS proposed by Martuo Co. Ltd (2006) for artificial cement-based samples. Figure 12 presents the relationship between the measured UCS and the predicted UCS determined from NPI of DCM specimens. About 77% of the data had the difference between the measured and the predicted UCS within 1MPa. The analysis shows that UCS can be estimated from NPI based on the empirical relationships proposed by Maruto Co. Ltd. (2006):

$$\log(UCS) = 0.978\log(NPI) + 2.621 \qquad \textbf{(4)}$$

where unit of UCS is kN/m^2 and NPI in N/mm. Considering that NPT has less requirements on the dimension and size of the specimen and can be carried out in laboratory or on site quickly, it may be used as a supplementary test method to estimate UCS when samples with sufficient length is limited or early knowledge of UCS of DCM specimens is required. Application of this test as a step of preliminary screening for determination of full coring and refining the testing programme can be explored. To further substantiate the correlation between the NPI and UCS and to develop the corresponding strength criteria, more test data can be collected from specimens with different soil types, binder dosages and binder types. However, when applying this test, practitioners should be aware of the uniformity of specimen in order to obtain a representative result from NPI.

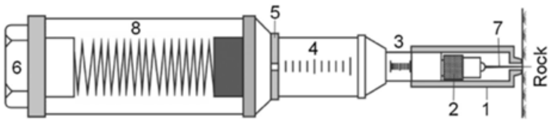

Figure 11: Needle penetrometer and its parts: 1 – presser, 2 – chuck, 3 – penetration scale, 4 – load scale, 5 – load indicating ring, 6 – cap, 7 – penetration needle and 8 – spring (Ulusay et al. 2014)

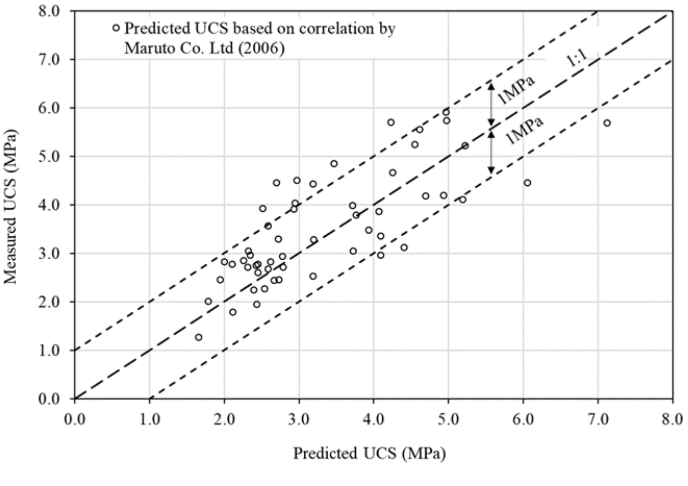

Figure 12: Relationship between measured UCS and predicted UCS based on NPI

2.7 Standardized laboratory mixing procedure

Laboratory mixing procedure is important for the mix design of DCM works as it greatly affects the strength and stiffness of the stabilized soils. Laboratory test results are used to establish design parameters for designers, and to determine operational parameters for construction. Jabban et al. (2020) reviewed various laboratory mixing procedures including ways to homogenize natural soil, blending time, mold types, molding techniques and curing conditions. They noted that molding techniques and curing conditions considerably influence more the properties of the stabilized soil. Tapping, rodding, static compaction and dynamic compaction are common molding techniques adopted in preparation of specimens in other counties. Previous research showed that molding techniques can greatly affect the magnitude and variation of UCS regardless of the soil type, type and amount of binder used (Kitazume et al. 2015).

In Hong Kong, a clear guideline for the selection of mixing and molding methods has not yet been established. Besides, there are no specified methods for evaluating the uniformity of the laboratory mixed specimens. In this context, several mixing methods from international testing standards and reported in literatures (e.g. BSI 1990a & 1990b, Bruce et al. 2013, Kitazume & Terashi 2013, Kitazume et al. 2015) were reviewed. Series of UCS tests on laboratory mixed specimens were conducted to study the applicability of two molding techniques available in local laboratories (the use of vibrating table and impact-type compactor). The variation of wet density and UCS of specimens were examined. Based on the review and laboratory test results, a mixing procedure with recommendations covering the preparation works on natural soil, soil and binder mixing, molding and curing are being prepared.

3 Conclusion

In view of the potential application of DCM in major reclamation projects, a series of studies related to material engineering properties of DCM material, ground investigation and laboratory testing were carried out using both laboratory prepared cores and field mixed cores collected from a local project. The objectives and preliminary results of the studies were presented in this paper. More works are in progress and all findings and recommendations will be consolidated later for further deliberation of the practitioners with the view to improve the practice and enhance the cost effectiveness of infrastructure works constructed by DCM method.

4 Declarations

4.1 Acknowledgements

This paper is published with the permission of the Director of Civil Engineering and Development and the Head of the Geotechnical Engineering Office, the Government of the Hong Kong Special Administrative Region.

4.2 Publisher’s Note

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