Test Method for Unconfined Compressive Strength of Cement Stabilised Soil Cores

GEO Report No. 365

F.L.F. Chu & P.W.K. Chung

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

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This report was originally produced in February 2023 as GEO Technical Note No. TN 2/2023

First published, August 2023

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Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

Raymond WM Cheung
Head, Geotechnical Engineering Office
August 2023

Foreword

Since the publication of the "Interim Guidelines on Testing of Unconfined Compressive Strength (UCS) of Cement Stabilised Soil Cores in Hong Kong" by the Geotechnical Division of The Hong Kong Institution of Engineers (HKIE-GD) in 2017, much experience has been gained in respect of testing UCS of stabilised soil. The present study, initiated by the Geotechnical Engineering Office (GEO) and collaborated with local practitioners and academia, aims to consolidate the experience accrued and explore possible improvements in the testing procedure for the determination of UCS of stabilised soil. This report presents the findings of the study, together with recommendations to enhance the guidelines on testing of UCS of stabilised soil cores. An updated test method is promulgated accordingly. A procedure is also proposed to standardize the practice of preparing laboratory mixed stabilised specimens.

This study was carried out by Ms F.L.F. Chu under the supervision of Mr P.W.K. Chung. Laboratory mixing works and subsequent tests were carried out in the Public Works Central Laboratory. Sustainable Lantau Office provided valuable field stabilised soil cores and soil samples to support the study. The draft version of the report was circulated to local commercial laboratories and professional bodies for comment. The contributions of all parties are gratefully acknowledged.

M. N. K. Chan
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Abstract

Since the publication of the "Interim Guidelines on Testing of Unconfined Compressive Strength (UCS) of Cement Stabilised Soil Cores in Hong Kong" in 2017, much experience has been gained in respect of testing cement stabilised soil. Several studies have been carried out by the Geotechnical Engineering Office in collaboration with local practitioners and academia. This report presents the review of several updated international/national and local testing standards related to the UCS test, experience accrued in testing, findings of the studies and recommendations to enhance the test method. An updated test method is promulgated accordingly. To standardize the practice of preparing laboratory mixed specimens, a procedure including the mixing and the curing process for stabilised soil specimens is also proposed.

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1 Introduction

The unconfined compressive strength (UCS) test of stabilised soil cores is commonly adopted as a test to verify the quality of deep cement mixing (DCM) works. In 2017, a Task Force on Testing UCS of Cement Stabilised Soil in Hong Kong was established under the auspices of the Geotechnical Division of The Hong Kong Institution of Engineers (HKIE-GD). The Task Force published a report, "Interim Guidelines on Testing of UCS of Cement Stabilised Soil Cores in Hong Kong" (Interim Guidelines), to recommend a test method for determining UCS of cement-soil cores.

Since 2017, experience has accrued in testing cement stabilised soil cores. About 54,000 UCS tests have been carried out through Public Works Laboratories (PWL). Some studies on the test method have also been carried out in collaboration with practitioners and academia. It is considered timely to conduct a review of the current test method with the consideration of the knowledge gained and experience accumulated in recent years.

This report presents a review of several updated international/national testing standards related to the UCS test, observations on the results of the UCS tests carried out in Hong Kong in recent years, and findings of studies related to the UCS tests. Following the review of the UCS test, a procedure for preparing stabilised soil specimens in the laboratory is suggested. Explanatory notes on salient items of the method of the preparation of the specimens are documented. The recommendations on the specimen preparation in the laboratory are applicable to the soil to be stabilised using cement, granulated blast furnace slag (GBS), ground granulated blast furnace slag (GGBS) or a combination of cement with GBS/GGBS through wet mixing. Should the designers consider it appropriate, the recommendations on the preparation procedure can be applied to soil stabilised using fly ash or lime.

2 Review of Relevant Testing Standards and Available UCS Test Results

2.1 Review of Relevant Testing Standards

Several international/national and local testing standards for the determination of UCS of cylindrical specimens of cohesive soil, laboratory mixed stabilised soil specimens, concrete and rock were reviewed during the development of the Interim Guidelines (HKIE, 2017). Table 2.1 summarises the status of the testing standards and the corresponding current testing standards.

Although most of the previously reviewed testing standards have been replaced, there is not much change in the requirements on the loading rate and the specimen surface in the current testing standards. The required loading rates used to determine the UCS of various materials as required in the selected testing standards are summarised in Table 2.2. Similar to the review in Interim Guidelines (HKIE, 2017), strain rate is used to control the rate of loading for testing relatively weak materials (e.g. soil); while stress rate is more commonly adopted in testing strong materials (e.g. concrete and rock).

It is known from previous studies that specimens with deviations from flatness, perpendicularity and parallelism would have a lower value of UCS (e.g. Hoskins and Horino, 1968; Richardson, 1991). Table 2.3 presents the surface requirements of various

construction materials in the selected testing standards. It is noted that more relaxed tolerance is allowed on flatness, perpendicularity and parallelism of the specimen surface for the material with lower strength. For example, BS EN 17892-7 only specifies that the end surfaces of the soil specimen shall be planar and perpendicular to the longitudinal axis. However, the tolerance value is not explicitly described. Whereas for materials with high strength (e.g. concrete, rock), tolerance values are clearly stated, and the surface requirements are more stringent when UCS of the material is getting higher.

Table 2.1 Status of International/National and Local Testing Standards Reviewed in the Interim Guidelines (HKIE, 2017)

Testing Standard Reviewed in the Interim Guidelines		Current Testing Standard
Title	Status	
BS 1377-7:1990 Method of test for soils for civil engineering purposes – Part 7: Shear strength tests (total stress)	Replaced	BS EN ISO 17892-7:2018 Geotechnical investigation and testing – laboratory testing of soil, Part 7: Unconfined compression test
ASTM D2166/D2166M-16 Standard test method for unconfined compressive strength of cohesive soil	Current	-
BS 1924-2:1990 Stabilised materials for civil engineering purposes – Part 2: Methods of test for cement-stabilized and lime-stabilized materials	Replaced	BS1924-2:2018 Hydraulically bound and stabilized materials for civil engineering purposes – Part 2: Sample preparation and testing of materials during and after treatment
BS EN 12390-3:2009 Testing hardened concrete – Part 3: Compressive strength of test specimens	Replaced	BS EN 12390-3:2019 Testing hardened concrete – compressive strength of test specimens
ASTM C39/C39M-17a Standard test method for compressive strength of cylindrical concrete specimen	Replaced	ASTM C39/C39M-21 Standard test method for compressive strength of cylindrical concrete specimens
CS1:2010 Construction Standard Testing concrete	Current	-
ASTM D2938-95 Standard test method for unconfined compressive strength of intact rock core specimen	Replaced	ASTM D7012-14 Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures
ASTM D7012-14 Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures	Current	-

Table 2.2 Loading Rates for Determination of Unconfined Compressive Strength of Selected Construction Materials as Specified in Several Current International/National and Local Testing Standards

Testing Standard	Material	Loading Rate	Remarks
BS EN ISO 17892-7:2018	Soil	1% to 2% of specimen height per minute	Strain rate control
ASTM D2166/D2166M-16	Cohesive soil	● 0.5% to 2% of specimen height per minute ● Time to failure shall not exceed about 15 minutes	Strain rate control
JGS 0511-2009 (JIS A1216) (1)	Soil	1% per minute	Strain rate control
BS 1924-2:2018	Hydraulically bound and stabilized materials	Failure occurs within 0.5 to 2 minutes (2)	-
ASTM D1633-17(3)	Soil-cement	● 1.3mm per minute ● 70 to 210 kPa per second	Strain rate or stress rate control
BS EN 12390-3:2019	Concrete	0.6 ± 0.2 MPa per second	Stress rate control
ASTM C39/C39M-21	Concrete	0.25 ± 0.05 MPa per second	Stress rate control
CS1:2010	Concrete	0.2 to 1.0 MPa per second	Stress rate control
ASTM D7012-14	Rock	● 0.5 to 1.0 MPa per second or a constant strain rate ● Selected rate shall produce failure of specimen in a test time between 2 and 15 minutes	Stress rate or strain rate control

Notes:
(1) JGS 0511-2009, which was not covered in the review in the Interim Guidelines (HKIE, 2017), is commonly adopted to determine the UCS of cement stabilised soil in Japan (Lanh et al, 2017; Takahashi et al, 2018). This testing standard is included in Table 2.2 for comparison.
(2) BS1924-2:2018 refers to BS EN 13286-41 for testing the compressive strength of cylindrical specimens. The loading rate is extracted from the current testing standard BS EN 13286-41:2021.
(3) ASTM D1633-17, which was not covered in the review in the Interim Guidelines (HKIE, 2017), is a test method for compressive strength of molded soil-cement cylinders. This testing standard is included in Table 2.2 for comparison.

Table 2.3 Requirements on Preparation of Specimen for Determination of Unconfined Compressive Strength of Selected Construction Materials as Specified in Several Current International/National and Local Testing Standards

Testing Standard	Material	Requirements		
		Flatness Tolerance for the Load-bearing Surface	Perpendicularity Tolerance for Load-bearing Surface with Respect to the Axis	Parallelism Tolerance for the Load-bearing Surface
BS EN ISO 17892-7:2018	Soil	See Note (1)	See Note (1)	Nil
ASTM D2166/D2166M-16	Cohesive soil	Nil	Nil	Nil
JGS 0511-2009 (JIS A1216) (2)	Soil	Nil	Nil	Nil
BS 13286-41:2021	Unbound and hydraulically bound mixtures	Nil	Nil	Not exceeding 2 mm in 100 mm
ASTM D1633-17 (3)	Soil-cement	Nil	Nil	Nil
BS EN 12390-3:2019	Concrete	< 0.06% of specimen diameter	< 0.7% of specimen diameter	Nil
ASTM C39/C39M-21	Concrete	< 0.05 mm	< 1 mm in 100 mm	Nil
CS1:2010 (4)	Concrete	< 0.06% of specimen diameter	< ± 1.0 mm	< ± 2.0 mm
ASTM D7012-14 (5)	Rock	< 0.025 mm	< 0.43% of specimen diameter	< 0.13° (6)

Notes:
(1) It is specified that the soil specimen end surfaces shall be plane and perpendicular to the longitudinal axis. However, the tolerance level is not specified.
(2) JGS 0511-2009, which was not covered in the review in the Interim Guidelines (HKIE, 2017), is commonly adopted to determine the UCS of cement stabilised soil in Japan (Lanh et al, 2017; Takahashi et al, 2018). This testing standard is included in Table 2.3 for comparison.
(3) ASTM D1633-17, which was not covered in the review in the Interim Guidelines (HKIE, 2017), is a test method for compressive strength of molded soil-cement cylinders. This testing standard is included in Table 2.3 for comparison.
(4) Test specimen shall be preferably of 100 mm diameter and in no case shall it be less than 75 mm diameter.
(5) ASTM D7012-14 refers to ASTM D4543 for the requirements of the specimen preparation. The requirements on the specimen are extracted from the current testing standard ASTM D4543-19.
(6) The tolerance is applied to the angular difference between the opposing best-fit straight line on each specimen end.

2.2 Review of Available UCS Test Results

A total of 53,987 test results of UCS tests carried out through PWL between 2019 and mid-2022 were collected to review the applicability of the test method in the Interim Guidelines (HKIE, 2017) in local projects. About 96% of the test results had UCS measured in accordance with the test method recommended in the Interim Guidelines (HKIE, 2017). No UCS was reported in the remaining test results, and the reasons are summarised in Table 2.4. As shown in the Table, only about 0.3% and 0.26% of the tests did not proceed because the specimens did not meet the surface requirement and the compression force exceeded the capacity of the compression machine, respectively. Such low percentages implied that the apparatus available in the local laboratories were in general capable of preparing the specimen with surface flatness, perpendicularity and parallelism according to the Interim Guidelines (HKIE, 2017) and had sufficient loading capacity in most of the UCS tests. It is also noted that about 2% of the tests could not be carried out due to insufficient length of the specimen (i.e. length to diameter (L/D) ratio of the specimen less than 1.5).

Table 2.4 Distribution of Test Results of UCS Tests

	Reason of Not Measuring UCS	Number of Test Results	Percentage in Total
Test results with UCS measured	-	51,788	95.93%
Test results without UCS measured	Sample broken before specimen preparation	828	1.53%
	Specimen with L/D ratio less than 1.5	1,069	1.98%
	Specimen not meeting the surface requirement (i.e. flatness, perpendicularity or parallelism)	162	0.30%
	Compressive load exceeded the capacity of the compression machine	140	0.26%

Among the 51,788 test results with UCS measured, most specimens (≈ 97%) had UCS less than 7 MPa. As shown in Figure 2.1, about 80% of the UCS ranged between 1 MPa and 5 MPa. Moreover, 5.5% of the UCS results were less than 1 MPa. The ages of the specimens varied widely, from less than 30 days to more than one year (Figure 2.2). Although the reason for testing specimens at different ages was not known in this review, specimens tested with various ages might help designers understand the development of UCS of the stabilised soil. Regarding the concern about whether the capacity of the compression machine specified in the Interim Guidelines (HKIE, 2017) is sufficient for specimens with higher ages, Figures 2.1 and 2.2 reflected that the UCS of specimens encountered in local projects were well within 10 MPa with ages as high as 360 days. Regarding the dimension of the specimens, the

diameter of the specimens was mainly between 100 mm and 105 mm (Table 2.5) and most specimens with L/D ratio between 1.7 and 2.0 (Figure 2.3). Among these tests, 99.8% of the specimens were not capped. Based on the test results, it is considered that both the capacity of the compression machine and the preferable diameter range of cores specified in the Interim Guidelines (HKIE, 2017) are in general sufficient and appropriate for the application in local projects. A minor modification is suggested on the preferable diameter range to cover 63 mm to 105 mm (previously 100 mm) core specimens.

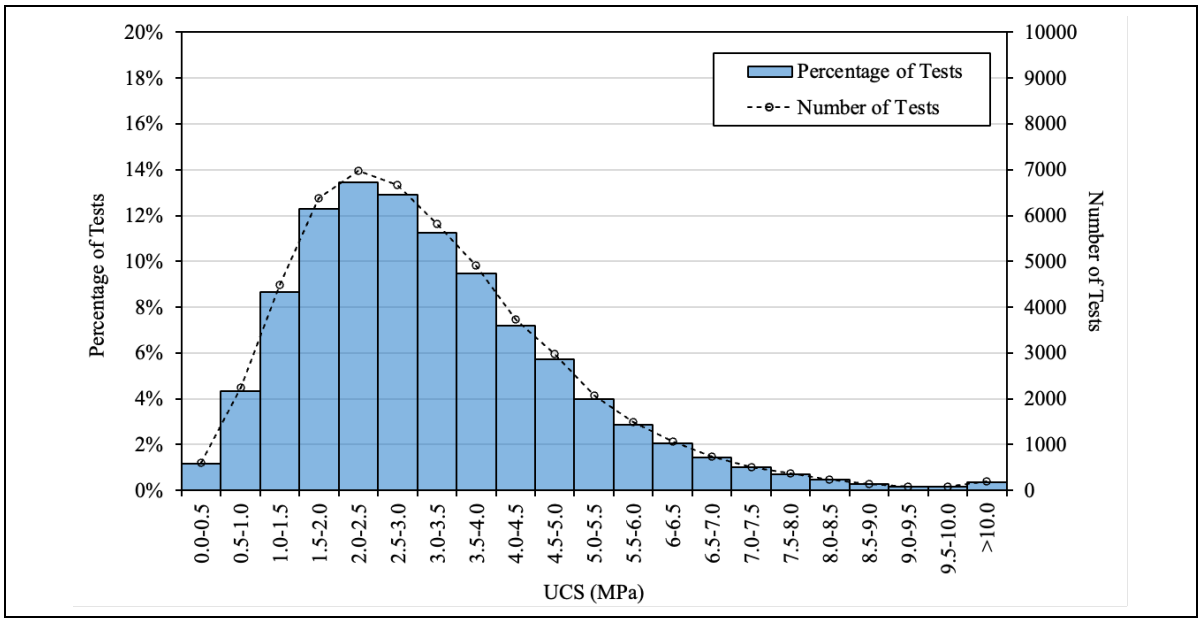


Figure 2.1 Distribution of UCS Value of Specimens

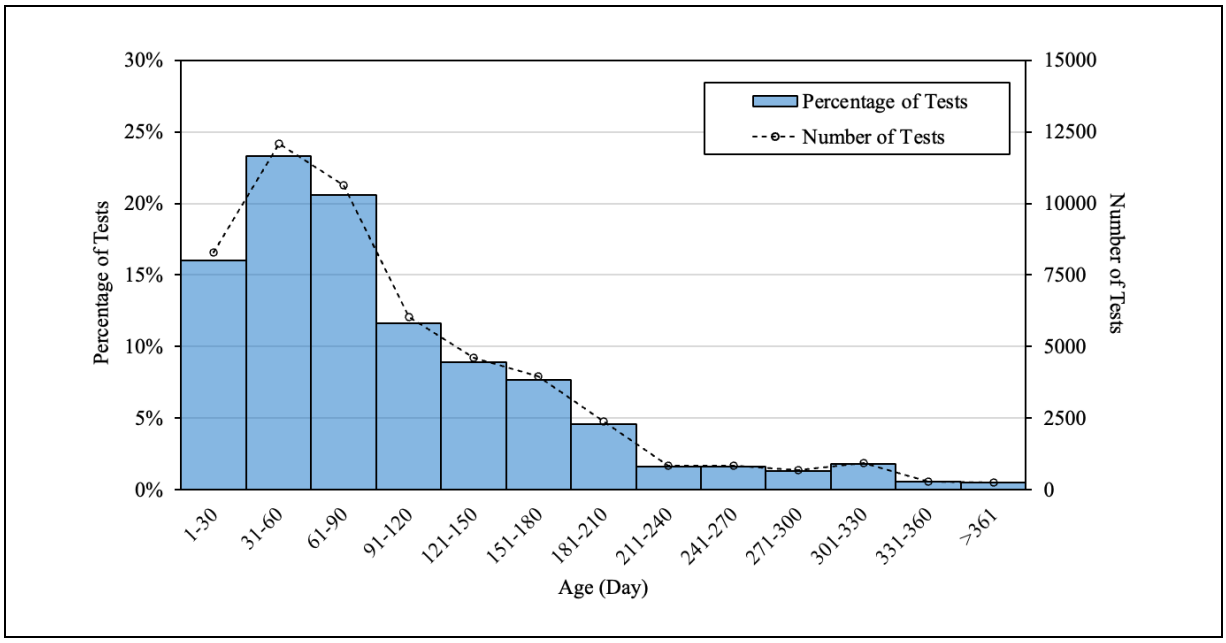


Figure 2.2 Distribution of Age of Specimens

Table 2.5 Distribution of Diameter of Specimens

Range of Diameter (mm)	Percentage of the Specimen (%)
65 – 80	1.91
80 – 95	0.42
95 – 100	11.04
100 – 105	86.61
105 – 130	0.02

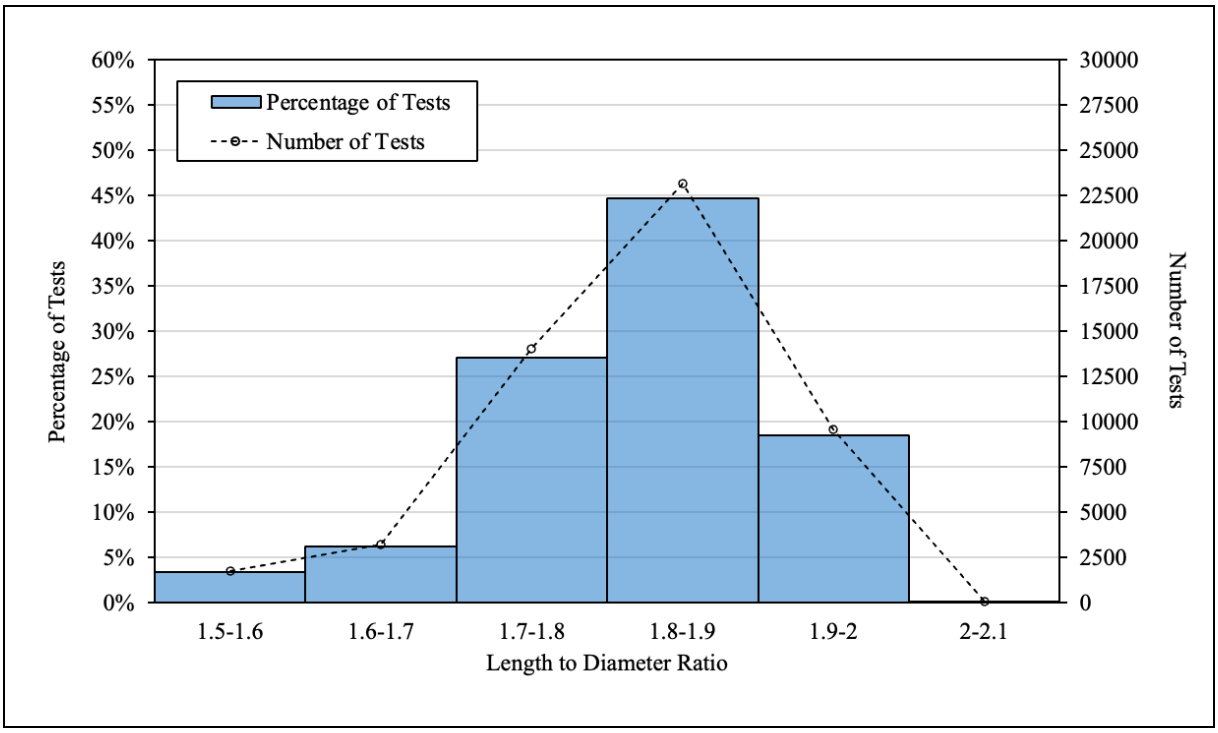


Figure 2.3 Distribution of Length to Diameter Ratio of Specimens

3 Recommendations on the Test Method

3.1 Diameter of Core

In the current practice for UCS testing of DCM specimens, the diameter of laboratory mixed specimens is usually 50 mm or 75 mm. In contrast, the usual diameter of field mixed specimens is 98 mm to 104 mm. Specimens prepared under a laboratory-controlled environment are expected to possess less potential variation if a consistent mixing method is used. On the other hand, specimens with a larger diameter are considered less susceptible to

localized ground variations and uncertainties during the field mixing and coring process. However, testing specimen with larger diameters implies higher costs in coring and subsequent laboratory testing. A study in a local project was conducted to investigate the credibility of adopting smaller-diameter field mixed cores in UCS tests (Chung et al, 2022).

It is recommended in Federal Highway Administration Design Manual that the core diameter should be at least 64 mm (Bruce et al, 2013). In the study by Chung et al (2022), cores in 100 mm diameter and in 76 mm or 64 mm diameter were taken from the same field mixed DCM cluster which had a cross sectional area of about 4.6 m^2. It was noticed that smaller diameter cores were more susceptible to disturbance during core boring, and fractures were found more frequently, resulting in a smaller number of suitable specimens to be selected for UCS test (e.g. L/D ratio less than 1.5). The average success rate of specimen selection was 85% for smaller diameter cores (76 mm or 64 mm) and 95% for 100 mm diameter cores.

Specimens along every meter from the 100 mm and 76 mm or 64 mm cores were selected for UCS test at the same age per the Interim Guidelines (HKIE, 2017). As shown in Figure 3.1, a reasonable correlation was observed between the UCS of the cores in 100 mm diameter and the cores with smaller diameters, given the inherent variability of the UCS results from the field DCM cores. Based on the available test results, cores with smaller diameters are also applicable for the UCS test.

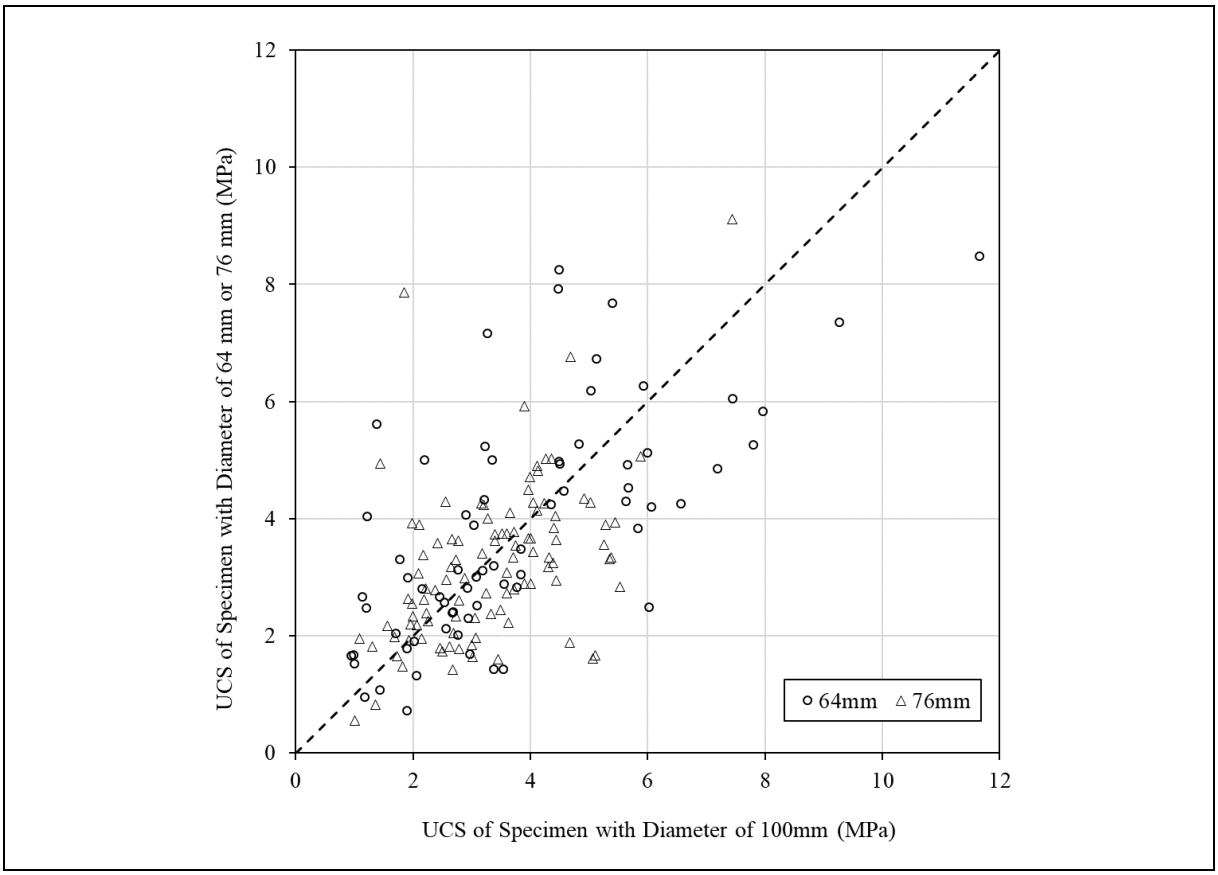


Figure 3.1 Relationship between UCS of 64 mm / 76 mm Diameter Core and UCS of 100 mm Diameter Core (Chung et al, 2022)

3.2 Length to Diameter Ratio of Specimen

It is commonly believed that the 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 will be insignificant if the L/D ratio is sufficient. Specimen with a smaller L/D ratio is expected to resist higher loads. As specified in the Interim Guidelines (HKIE, 2017), a cylindrical specimen with an L/D ratio of 2 is recommended for the test, and a specimen with an L/D ratio between 1.5 (inclusive) and 2.0 can also be tested with lubricated ends and with the application of a strength correction factor on the measured UCS. It is not uncommon to retrieve cores from field mixed DCM columns with insufficient length (L/D ratio < 1.5). To allow more flexibility in specimen selection, studies were conducted on laboratory mixed specimens with L/D ratios ranging from 1.0 to 2.0 to evaluate appropriate strength correction factors for shorter specimens.

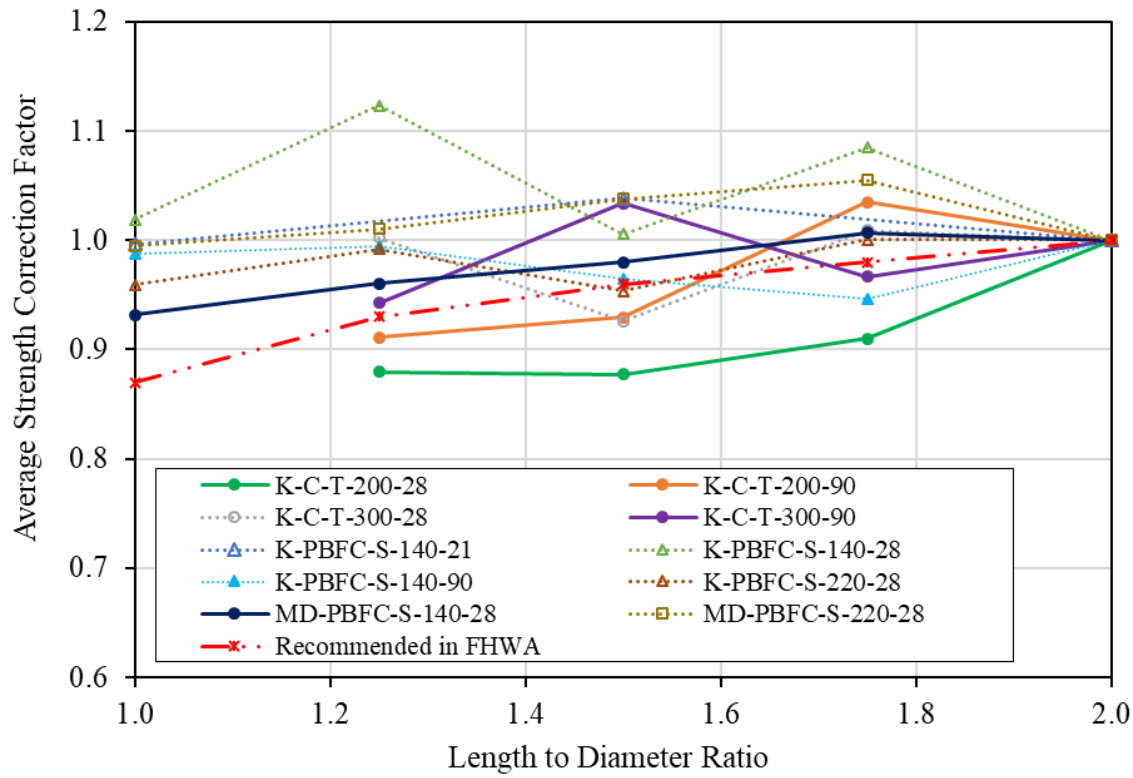
In collaboration with the Department of Earth Sciences of the University of Hong Kong, laboratory mixed cores were prepared by mixing kaolin or marine deposit with binder slurry with binder dosage similar to that of a local reclamation project. Either Portland cement or Portland blast-furnace cement (PBFC) was used to prepare the slurry. In the study, ten different mixing formulas were used to prepare stabilised cores, and 250 specimens were cut from these cores with different L/D ratios (1.00, 1.25, 1.50, 1.75, 2.00). The average UCS of specimens with L/D ratio of 2 ranged between 0.9 MPa and 2.99 MPa. The data reported by Lin (2018) and Liu (2021) were consolidated, and the strength correction factor under various L/D ratios was calculated using the following equation:

$$\text{Strength correction factor} = \frac{\text{Average UCS of specimen with } \frac{L}{D} \text{ ratio of 2}}{\text{UCS of specimen with specific } \frac{L}{D} \text{ ratio}}$$

Among the test results of specimens from ten different mixing formulas, only results from four mixing formulas showed a trend of decreasing strength correction factors with shorter specimens (shown as solid lines in Figure 3.2). Such trend aligned with that suggested in Federal Highway Administration Design Manual (Bruce et al, 2013).

To further review the data in detail, the individual strength correction factor of specimens (from ten various mixing formulas) was plotted against the L/D ratio in Figure 3.3. As noted in the Figure, the mean and median strength correction factors for the L/D ratio between 1.0 and 2.0 were close to one. The results of this study indicated that the influence of the L/D ratio on UCS was not evident. The necessity of applying the strength correction factor on UCS may not be conclusive based on the local data. However, the data at various L/D ratios were scattered. The shaded area (bounded by black dashed lines) covered about 80% of the data. The variation of the strength correction factor was about ±0.1, ranging between 0.9 and 1.1. From the perspective of the engineering properties, higher UCS is usually observed in soil/concrete/rock specimen with an L/D ratio less than 2.0, and the increase in UCS become more obvious when the L/D ratio gets closer to one (Güneyli & Rüşen, 2016; Suzuki et al, 2011; Tuncay & Hasancebi, 2009). Given these and the variability of the correction factors in Figure 3.3, overestimated UCS may be obtained from the specimen with a lower L/D ratio if strength correction factor is not applied. As shown in Figures 3.2 and 3.3, the strength correction factors in Table 3.1 as recommended in Federal Highway Administration

Design Manual (Bruce et al, 2013) provide a decreasing trend with respect to decreasing L/D ratio. It matches with some local samples and in general, this correction curve conservatively covers the potential variability of the strength correction factors for specimens with L/D ratio less than 1.5. Hence, it is considered that the strength correction factors as shown in Table 3.1 for specimens with an L/D ratio between 1.0 (inclusive) and 1.5 may also be applied in Hong Kong. Adopting a wider range of strength correction factors extends the applicability of the test method and allows more flexibility in the selection of the specimen for testing.



Notes:

(1) In the legend, K means kaolin; C means Portland cement; T means tap water; MD means marine deposit; PBFC means Portland blast-furnace cement and S means seawater.

(2) In the legend, Figures "140", "200", "220" and "300" stand for the binder dosage (kg/m^3) used in preparing the laboratory mixed specimens.

(3) In the legend, Figures "21", "28" and "90" stand for the age of the laboratory mixed specimens (day) subject to UCS tests.

Figure 3.2 Average Strength Correction Factors for Specimen (from Ten Different Mixing Formulas) with Different Length to Diameter Ratios

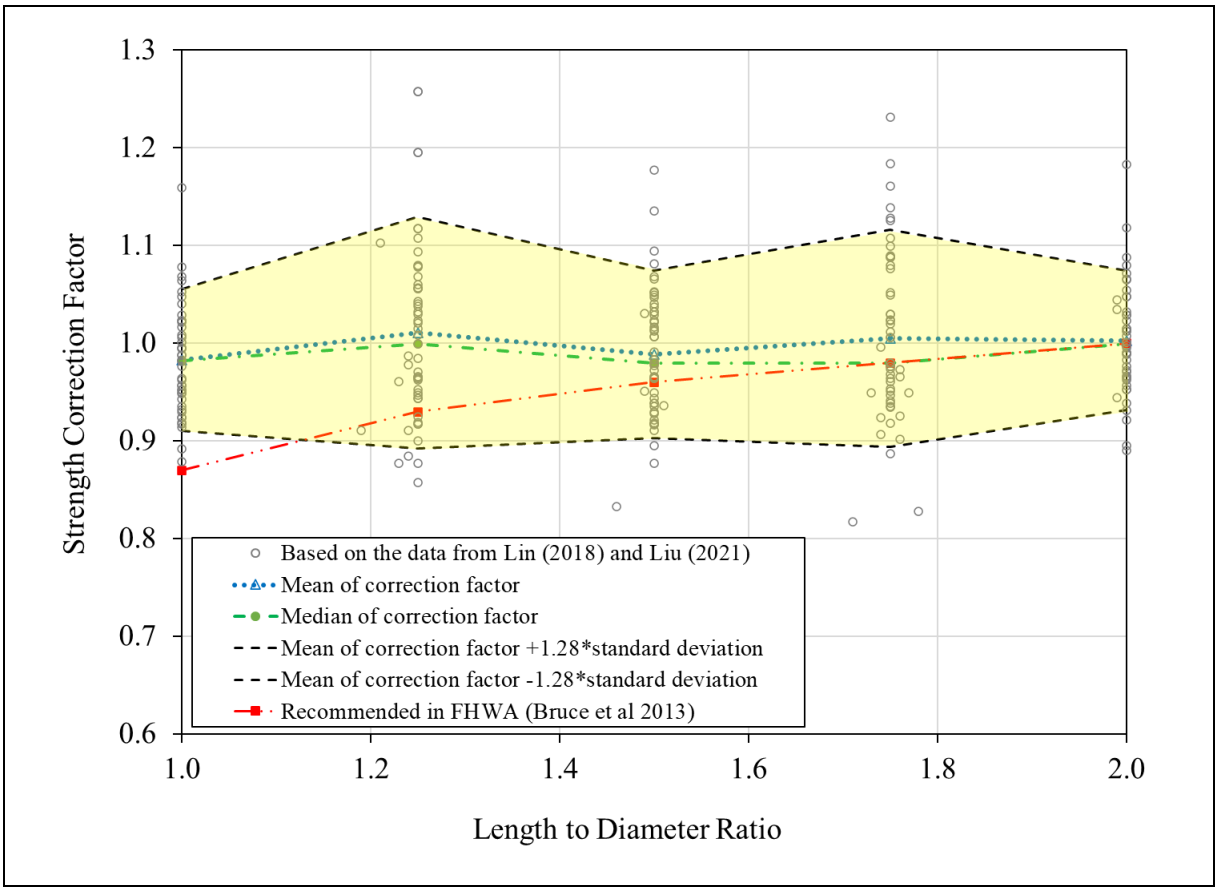


Figure 3.3 Strength Correction Factors for Specimen with Different Length to Diameter Ratios

Table 3.1 Strength Correction Factors Given in Federal Highway Administration Design Manual (Bruce et al, 2013)

L/D Ratio	2.00	1.75	1.50	1.25	1.00
Strength Correction Factor	1.00	0.98	0.96	0.93	0.87

Note: Values not specified in the table can be determined by linear interpolation.

3.3 Determination of Elastic Modulus of Specimen

There are various interpretation methods to determine elastic modulus from the stress-strain curve, for example, measuring tangent modulus at a fixed percentage of the maximum strength, calculating the average gradient of the linear portion of the stress-strain curve, determining the secant modulus at a fixed percentage of the maximum strength etc. Among these methods, secant modulus at 50% of the UCS ($E_{50,secant}$) is more popular to be used in the settlement analysis (Bruce et al, 2013; Alipour et al, 2016) and establishing a correlation with UCS (e.g. Asano et al, 1996; Saitoh et al, 1996; Lee et al, 2005; Kitazumi & Terashi, 2013, etc.).

Stress-strain curves from about 100 UCS tests on field mixed or laboratory mixed specimens were reviewed. The UCS of the specimens ranged between 0.5 MPa and 5.5 MPa. In these specimens, kaolin or marine deposits in Hong Kong were mixed with binder slurry in different dosages. Portland cement or PBFC was used in the preparation of the binder slurry. $E_{50,secant}$ of the specimens is plotted against the UCS in Figure 3.4. Irrespective of the types of soils, the types of binders or the mixing methods, the magnitude of $E_{50,secant}$ increased with UCS generally. The value of the ratio of $E_{50,secant}$ to UCS was in the range of 150 to 650. The ratio was in similar order compared with those reported in previous studies (e.g. Asano et al, 1996; Tan et al, 2002; Kitazumi & Terashi, 2013).

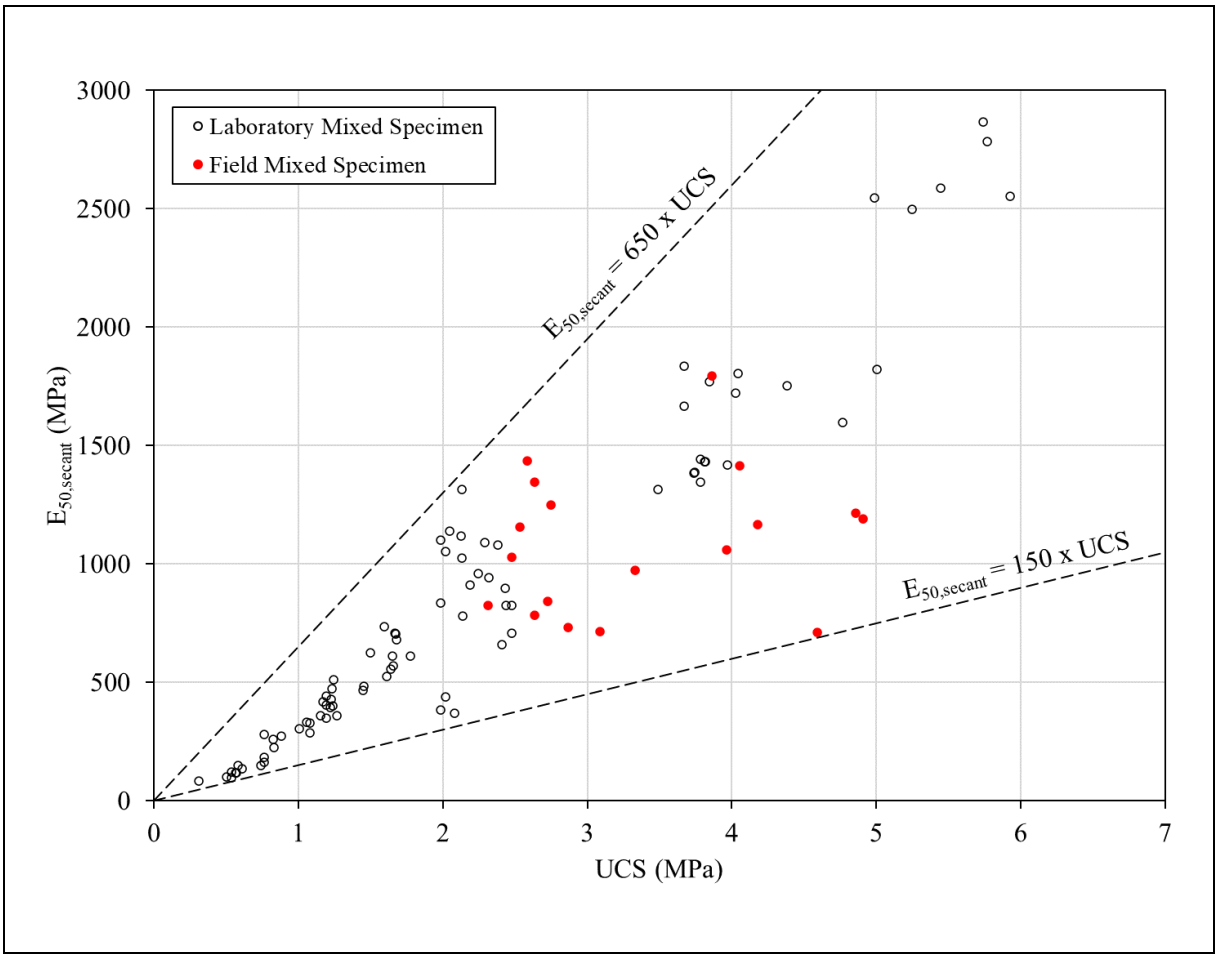


Figure 3.4 Secant Modulus of Elasticity ($E_{50,secant}$) of Field Mixed or Laboratory Mixed Stabilised Soil Specimens

Figures 3.5(a) to 3.5(d) show four typical stress-strain curves. It is noted that the stress-strain relationship of the stabilised soil was usually non-linear irrespective of the UCS or preparation method of the specimen. It is also noted that the shape of the stress-strain curve was usually affected by seating and/or bedding at the start of compression. Where appropriate, the curve can be corrected to minimise the effect due to seating and bedding errors in the determination of elastic modulus. The method of determination of elastic modulus, $E_{50,secant}$, from the stress-strain curves is presented in the Figure 3.5 for reference.

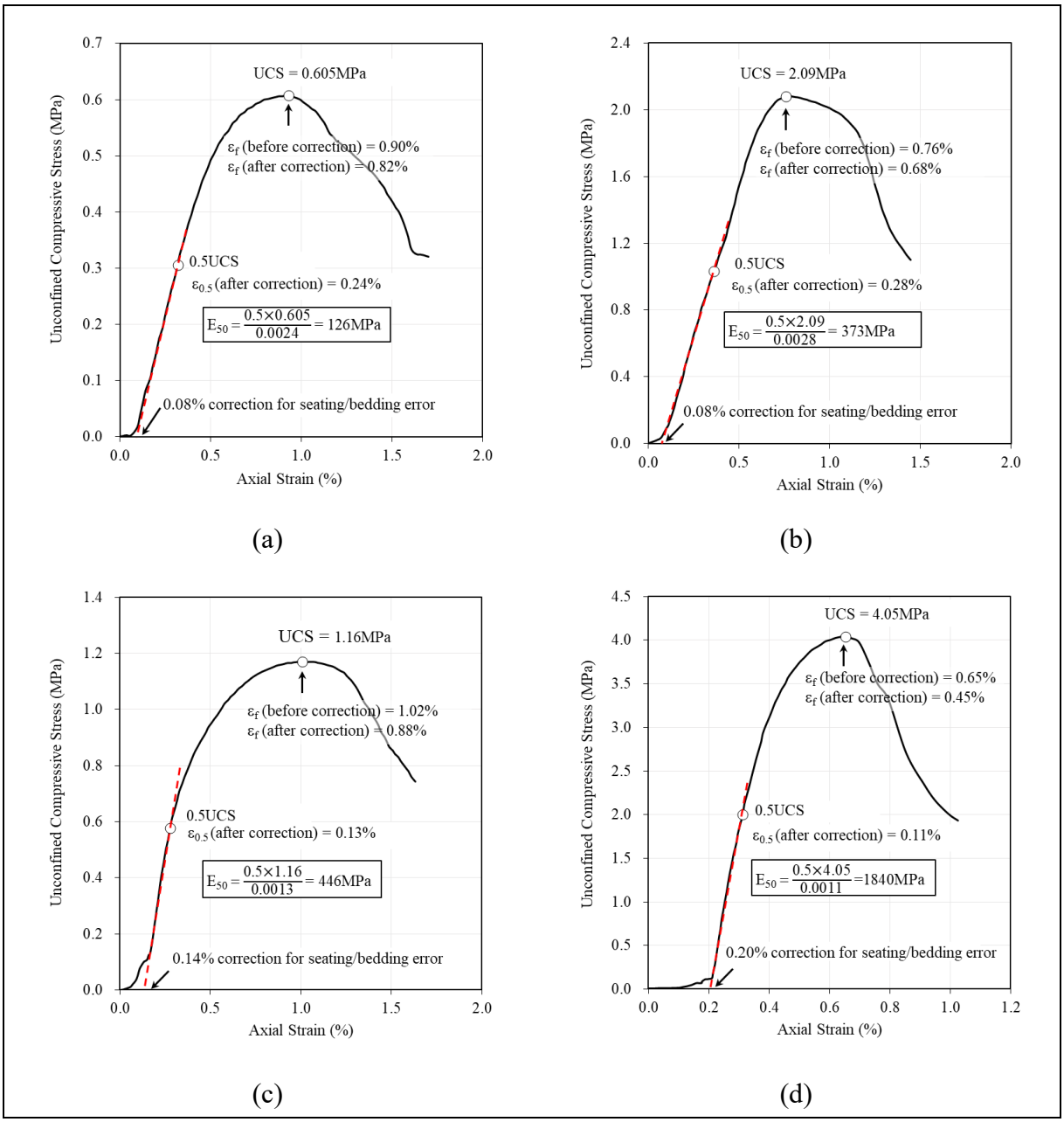


Figure 3.5 Stress-strain Curves of Stabilised Soil Specimens

Indeed, higher elastic modulus may be observed at lower strain levels in some cases, and the elastic modulus determined from local strain measurement may be larger in magnitude as the contribution of the deformation from apparatus in the UCS test could be excluded. However, as highlighted in Federal Highway Administration Design Manual (Bruce et al, 2013), the measurement of the elastic modulus from UCS test of the specimen has not considered the effect of creeping, which may cause a certain reduction in the elastic modulus in the long run. The effect of higher stiffness at a low strain level or higher modulus resulting from local strain measurement could counteract the creeping effect. Thus, $E_{50,secant}$ from the stress-strain curve of UCS test is suggested to be used to estimate the compression of the treated zone. However, if the designers consider it appropriate, other interpretation methods can be used to determine the elastic modulus to suit the analysis.

Based on the above review, it is considered that the test method of testing UCS of cement stabilised soil cores in Hong Kong recommended in the Interim Guidelines (HKIE, 2017) is generally appropriate. The test method is considered applicable to the specimen with length to diameter ratio between 1.00 (inclusive) and 2.00 with the adoption of the correction factors stated in Table 3.1. To provide additional information to the designer, it is also suggested to include the determination of the elastic modulus of the specimen in the test method. The updated test method is documented in Appendix A.

4 Laboratory Mixing Procedure

The design of the mix proportions for DCM works relies heavily on the results of the UCS test on laboratory mixed stabilised soil specimens. Factors such as type and dosage of binder, curing time and water-to-binder ratio etc. will be adjusted to determine an optimal mix proportion for a specific soil. However, even all these factors are fixed, the strength of the laboratory mixed stabilised soil specimen can be influenced by the mixing and the curing process. Improper mixing techniques render lower measured UCS and higher variability of the UCS of the specimen. This may lead to using a higher binder dosage to achieve the required target strength. Al-Jabban et al (2020) present the common laboratory procedures used to prepare and cure stabilised soil specimens in various countries. Differences are observed in the procedures, such as the ways to homogenise natural soil, the mixing time, the mould type, the moulding techniques and the curing conditions. With the growing popularity of the DCM method in Hong Kong, establishing a clear local laboratory mixing procedure would help to achieve a higher consistency of the laboratory mixed specimens and could make the test results of the laboratory mixed specimens from different laboratories comparable without the need to review the mixing, moulding and curing condition.

4.1 Review of Several International/National Mixing Procedures

A review was conducted to compare several international/national mixing procedures for stabilised soil (BRE, 2002; JGS, 2009a; Bruce et al, 2013; ASTM, 1992; BSI 1990b and 1990c). Table B.1 in Appendix B summarizes the requirements of the mixing works in these procedures. In general, the mixing procedure involves several key steps. Natural soil is first homogenised, and cementitious binder is added in either dry or slurry form. The soil-binder mixture is blended thoroughly for a certain period either using an electric mixer or by hand mixing. Although various moulding methods are noted, they all aim to fill the mould with minimal air voids. The specimen is then cured under a controlled environment until the further test is carried out.

4.2 Recommended Procedure

Appendix C presents a laboratory mixing procedure recommended for mixing, moulding and curing binder stabilised soil specimens. The procedure had made reference to the aforesaid mixing procedures in Section 4.1. Modifications, where appropriate, as discussed in the following sections, are recommended to suit the local practice.

4.2.1 Scope

The recommended laboratory mixing procedure is applicable to workable soils to be stabilised using cement, granulated blast furnace slag (GBS), ground granulated blast furnace slag (GGBS) or a combination of cement with GBS/GGBS through the wet mixing method. Should the designers consider it appropriate, the procedure can be applied on soils stabilised by fly ash or lime.

4.2.2 Apparatus

An electric mixer consisting of a motor, a stirring blade and a mixing bowl with sufficient capacity should be used. It should be capable of mixing soil and binder uniformly. The mixer shall be able to operate at low speed (e.g. 60 to 150 revolutions per minute) and high speed (e.g. larger than 240 revolutions per minute) to facilitate the mixing process of the natural soil with the binder slurry. It is preferable that the mixing blades can revolve with planetary motion. In other words, the mixing blade can have both rotation and revolution. Figure 4.1 shows examples of the electric mixers with two capacities. The one with a capacity of about 5 litres is adequate for preparing two cylindrical specimens with a diameter of 75 mm and a height of 200 mm. In comparison, the other one with a capacity of 20 litres, is sufficient to prepare about nine cylindrical specimens of the same size. Two types of stirring blades for mixing soil are shown in Figure 4.2. The appropriate blades to result in even mixing depends on the soil type, the initial water content of soil, the type and the amount of the binder used. Based on our experience, a flat type blade can provide uniform mixing on the stabilised Hong Kong marine deposit in its natural moisture content. However, other types of stirring blades may be used if a consistent mixture can be made.

Binder mixing equipment shall be capable of evenly mixing the binder with water to form a uniform slurry. It is considered that the mixer used to prepare cement mortar is applicable to this mixing procedure. The mixer for the binder mixing shall comply with the requirements of BS EN 196-1:2016 (BSI, 2016).

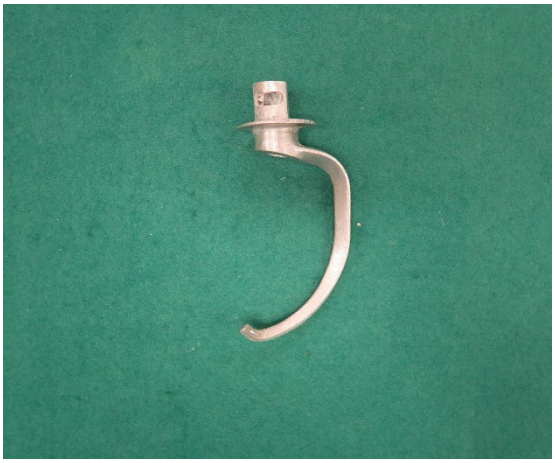
The size of the mould is common, with an inner diameter of 50 mm and a height of 100 mm (BRE, 2002; JGS, 2009a; Bruce et al, 2013 and BSI, 1990b). However, it is not uncommon to have large obstacles such as shell fragment in Hong Kong marine deposit as shown in Figure 4.3. Kitazumi & Terashi (2013) pointed out that the internal dimensions of the mould can be changed to suit the actual soil characteristics, but with the height to diameter ratio of the mould maintained between 2.0 to 2.5. To select an appropriate mould size, the capacity of the loading machine and the dimension requirements of the specimen for the subsequent test (e.g. UCS test) should also be considered. The proposed height of the mould should be adequate for producing a specimen to have sufficient length for cutting to the required dimension for the subsequent test. Generally, the dimensions of the mould with an inner diameter of about 75 mm and a height of 200 mm could form a specimen applicable for soft soil in Hong Kong, taking into account the common size of the particles that may be encountered in local marine deposit (as highlighted in the red dotted box in Figure 4.3) and the dimension requirements on the specimen of the subsequent test (e.g. UCS test, triaxial test).

(a) Electric mixer with capacity of 5 litres

(b) Electric mixer with capacity of 20 litres

Figure 4.1 Examples of Mixers

(a) Flat type

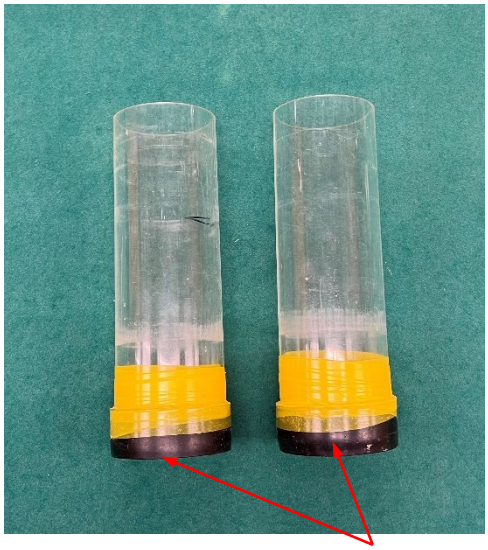


(b) Hook type

Figure 4.2 Examples of Mixing Blades

The material of the mould suggested in the reviewed international/national mixing procedures includes steel, plastic and plastic-coated cardboard. Figure 4.4 shows examples of the moulds with materials that are preferable for preparing specimens due to their less susceptibility of rusting. Irrespective of the size or material of the mould, it shall be with sufficient rigidity and be rigidly held together and fixed to the baseplate. During the moulding process, the assembly shall be such that there is no distortion or leakage.

Figure 4.3 Large Particles Found in Hong Kong Marine Deposit



(a) Plastic mould

(b) Plastic-coated cardboard mould

Figure 4.4 Examples of Moulds

4.2.3 Receipt of Soil and Binder and Homogenisation of Soil

The reaction between the natural soil and the binder can be affected by the moisture content of the soil, the quantity of water added to the soil and the binder, and the curing environment. Precautions shall be taken to prevent moisture loss after soil sampling, during transportation to laboratories, mixing and testing. For example, the soil shall be kept in a sealed container after sampling and storing in the laboratories. The binder shall be kept in a sealed container. Any lumps of the binders shall be removed.

The soil shall be sieved through a test sieve with an appropriate aperture size. Kitazume & Terashi (2013) suggested that the maximum grain size of the sieved sample should be less than one-fifth of the inner diameter of the mould. Besides, disaggregation of natural soil prior to the stabilization can help homogenise the natural soil and reduce the variation of the water content (Al-Jabban, 2019). Figure 4.5 shows the sieving process and the appearance of the sieved soil. A sufficient quantity of the soil to prepare the required number of the stabilised specimen shall be estimated and prepared before mixing. Remixing the soil is the common way to homogenise the soil, as recommended in the reviewed international/national mixing procedures. However, most of them do not specify the required mixing time. Noting that the time to achieve a homogenised soil can be affected by various factors (e.g. soil type, particle size distribution and water content of soil etc.), it is suggested that the soil shall be mixed until the soil is visually homogeneous. If necessary, spatula can be used to check if lumps of soil still exist.

(a) Sieving natural soil

(b) Sieved and disaggregated natural soil

Figure 4.5 Treatment on Natural Soil

4.2.4 Binder Slurry Preparation

The required amount of binder shall be determined before mixing. If the binder consists of two or more components, the components shall be first mixed in the required proportions before adding water. Pakbaz and Farzi (2015) showed that the dry and the wet mixing method resulted different engineering properties of the stabilised soil. For example, 28-day UCS of the specimens treated with cement and prepared by wet mixing was higher than

that of dry mixing. The wet mixing method is the proposed procedure, as detailed in Appendix C. The binder shall be mixed with water as per the required water-to-binder ratio to form a slurry for subsequent mixing works with soil to be stabilised. Should the dry mixing method be adopted in the field, the procedure for preparing the laboratory mixed specimen in Appendix C shall be adjusted accordingly. The binder shall be first mixed with the soil to be stabilised thoroughly before the addition of water.

4.2.5 Soil-binder Mixing

Once the binder slurry is prepared, it shall be added to the soil immediately. Hand tools (e.g. plastic spatula) could be used to aid in transferring the binder slurry to the soil mixing bowl. The quantity of the binder slurry added to the soil as designed shall be controlled, for example by measuring the weight of the binder mixing bowl before and after transferring the binder slurry to the soil. Excess binder slurry could be prepared so that the required quantity of the binder slurry is added to the soil. To avoid splashing of the binder slurry, it is suggested to mix the soil and the binder slurry by hand briefly before starting the mixing using the electric mixer.

Soil and binder slurry shall be mixed thoroughly to form a uniform mixture (Figure 4.6). A duration of 10 minutes is commonly adopted for mixing (Bruce et al, 2013; BSI, 1990b and JGS, 2009a). Some studies showed that the UCS of the stabilised specimens reduced noticeably when the mixing time was less than 10 minutes but only increased slightly when the mixing time was more than 10 minutes (Kitazume & Terashi, 2013). During the mixing process, it was commonly found that certain soil-binder mixture adhered to the blade or the side of the bowl. It is therefore suggested to stop the electric mixer after 5 minutes of mixing. A plastic spatula is then used to push the mixture attached to the blade and the side of the bowl back towards the centre for further mixing. The time for manual scraping is not included in the mixing time using the electric mixer.

Figure 4.6 Soil-binder Mixture with Thoroughly Mixing

4.2.6 Specimen Preparation

Various moulding methods are specified in the reviewed international/national mixing procedures (BRE, 2002; JGS, 2009a; Bruce et al, 2013; ASTM, 1992 and BSI, 1990b). Tapping, rodding, dynamic compaction and static compaction are some examples. Kitazume et al (2015) found that moulding methods could bring noticeable differences on the magnitude and variation of the UCS and the wet unit weight of the laboratory mixed stabilised soil specimens. They also found that the applicability of the method depended on the consistency of the soil-binder mixture. The tapping method was applicable to a more fluid soil-binder mixture with undrained shear strength (S_u) smaller than 10 kPa. The coefficient of variation (COV) of the UCS of the laboratory mixed specimens moulded by tapping ranged between 3% and 18%. Dynamic compaction method was applicable on stiffer soil-binder mixture with S_u larger than 20 kPa. The corresponding COV of the UCS of the specimen fell within a range of 5% to 10%. The rodding method was found to be suitable for mixture in different consistencies, and the COV of the UCS of the specimen varied between 1% and 15%.

The suggested moulding method in Appendix C is considered applicable to soil-binder mixtures in various consistency but with low sand content. The mixture was placed in the mould in 3 layers, and each layer was subject to 60 shocks in about one minute. Figure 4.7 shows how the moulds were securely mounted on the working platform of the apparatus for compaction. To evaluate the effectiveness of the moulding method to remove air voids, a total of 137 stabilised soil specimens with diameter of about 75 mm were prepared. Two soil types, including kaolin and a marine deposit collected in Hong Kong, were used to prepare a soil-binder mixture in different consistencies. The initial water content of the soil, the binder type, the binder content, and the water-to-binder ratio were summarised in Table 4.1. The specimens were inspected after demoulding, and no significant air voids were observed on the surface of the specimen (see Figure 4.8). After 28 days of curing, the specimens were subjected to UCS tests according to the Interim Guidelines (HKIE, 2017). The failed specimens were inspected after test. No significant air voids were found inside the specimens. As presented in Table 4.1, the average UCS of the specimens varied between 0.77 MPa and 5.52 MPa. The COV of the UCS of different types of specimens fell within a narrowly low range of 3.5% to 10%, compared with that in the study by Kitazume et al (2015). The observation on the specimens and the UCS test results suggested that the air voids inside the specimen can be effectively removed, and homogenous specimens could be prepared with variations consistently lower than that prepared using the typical moulding method in the reviewed mixing procedures. The proposed method is generally applicable to soil-binder mixtures with UCS ranging between 0.5 MPa and 6.0 MPa. However, should segregation be observed in the specimen or soil to be mixed have high sand content, the compaction energy applied to the specimen (e.g. through a number of shocks per layer) shall be reviewed, or alternative moulding methods (e.g. tapping, rodding) shall be used.

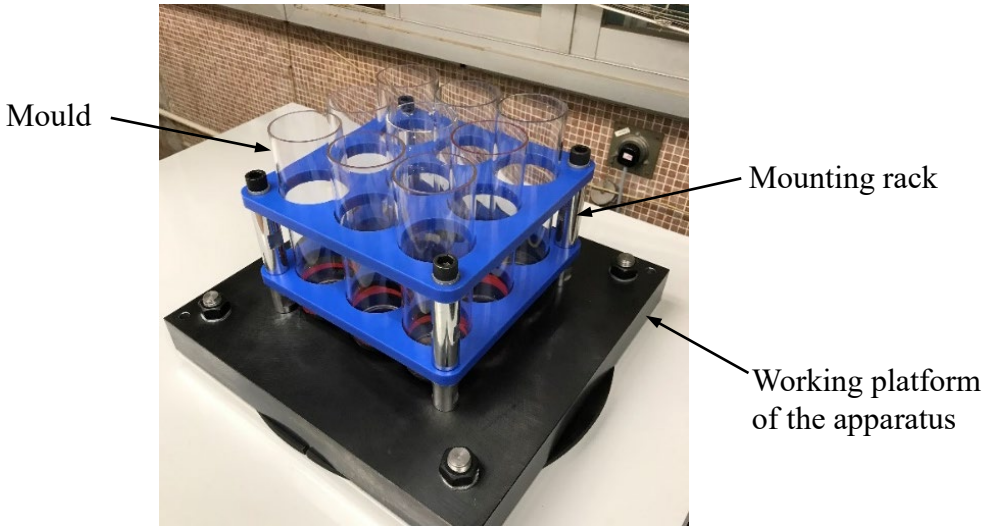
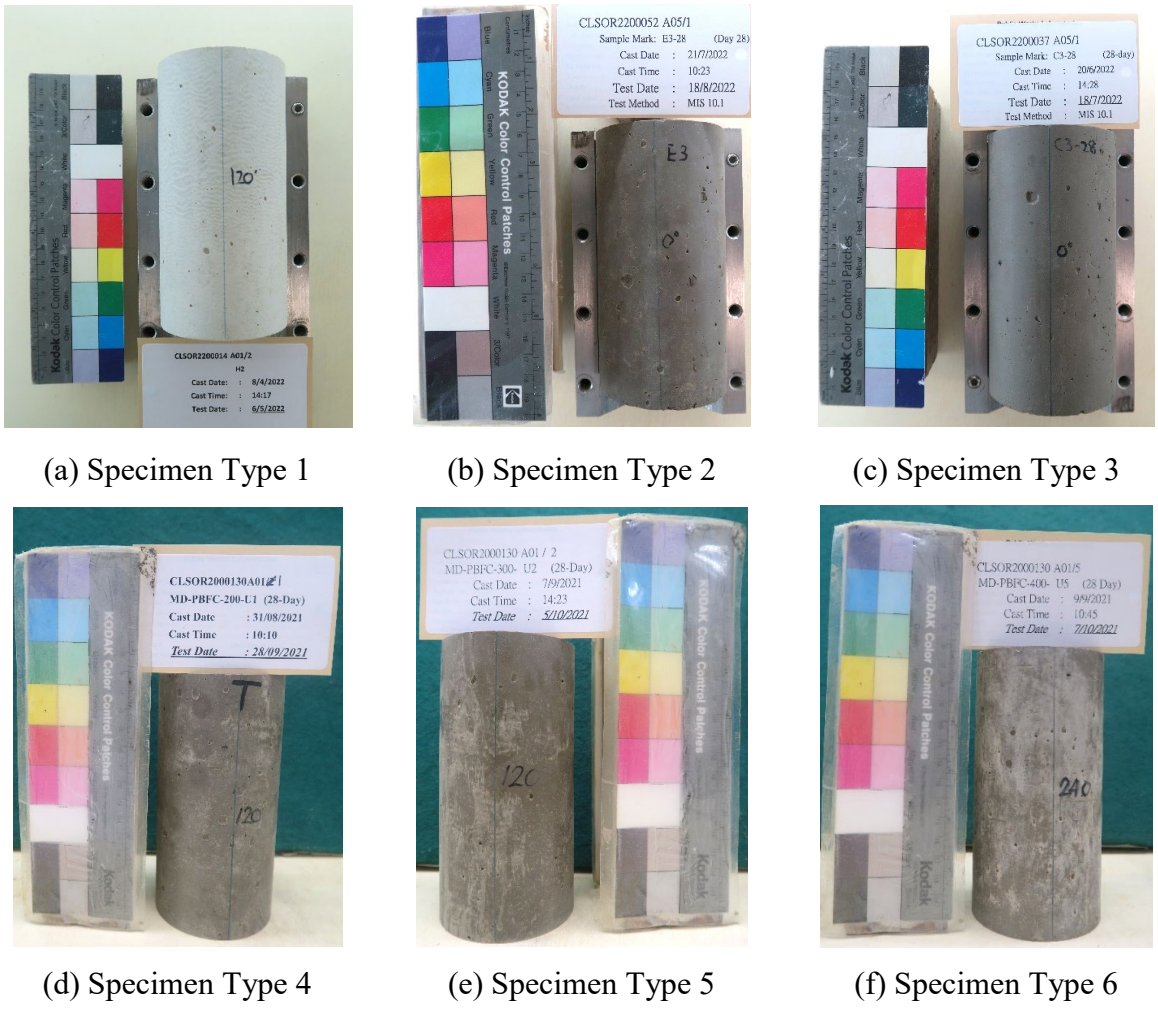


Figure 4.7 Moulds Securely Mounted on the Apparatus for Compaction

Table 4.1 Mix Proportions in Trial Tests and the Average and Coefficient of Variation of UCS of Specimen after 28 Days of Curing

Specimen Type	Soil	Initial Moisture Content of Soil (%)	Binder Type	Binder Content (kg/m^3)	Water to Binder Ratio	No. of Specimen	Average UCS (MPa)	COV of UCS (%)
1	Kaolin	65	OPC	300	0.8	107	2.15	4.36
2	Marine deposit	95	OPC	150	0.8	5	0.77	4.50
3	Marine deposit	95	PBFC	150	0.8	6	1.67	3.48
4	Marine deposit	95	PBFC	200	0.8	6	2.21	5.33
5	Marine deposit	95	PBFC	300	0.8	6	3.93	6.95
6	Marine deposit	95	PBFC	400	0.8	7	5.36	9.84

Notes: (1) OPC means Ordinary Portland Cement.
(2) PBFC stands for Portland Blast Furnace Cement which comprised 40% OPC and 60% Ground Granulated Blast Furnace Slag (GGBS).
(3) Marine deposit was first sieved through a 5 mm test sieve before preparing the laboratory mixed specimen.



(a) Specimen Type 1 (b) Specimen Type 2 (c) Specimen Type 3

(d) Specimen Type 4 (e) Specimen Type 5 (f) Specimen Type 6

Note: (1) Please refer to Table 4.1 for the details of the specimen types.

Figure 4.8 Appearance of Stabilised Soil Specimens with Different Mix Proportions

To early identify potential non-homogenous specimen, Bruce et al (2013) proposed that specimens made of a thick soil-binder mixture should be discarded if it weighs less than 95% of the weight of the heaviest specimen; while for fluid mixture prone to segregation, specimens which vary by more than 3% from the average weight of all specimens should be discarded.

To facilitate demoulding, a thin layer of grease can be applied on the inner surface of the mould (Kitazumi & Terashi, 2013). As the chemical reaction between binder and water starts immediately after the binder slurry is prepared, the soil-binder mixture would become hard and air bubbles in the mixture would become difficult to be removed with time. It is suggested that the moulding shall be completed within 1 hour after the addition of water into the binder. No significant influence on the 28-day strength of the stabilised specimen was observed when the duration of the mixing and moulding works was up to 1 hour (Terashi & Kitazume, 2011). Based on our experience, this duration is considered adequate for preparing nine specimens with a diameter of 75 mm according to the suggested method in Appendix C. Mixture that cannot be satisfactorily placed in the mould within 1 hour shall be discarded.

4.2.7 Curing of Specimen

Curing conditions such as temperature, humidity, surcharge etc. can affect the strength development of the stabilised soil (Terashi & Kitazume, 2011; Bruce et al, 2013; Ju, 2018). Lanh et al (2017) also pointed out that carbonation and suction effect could contribute to certain proportion of the developed strength when stabilised soil is exposed to the carbon dioxide and cured in dry condition. To minimize the variation of the strength development of the laboratory mixed specimens, the soil-binder mixture in the mould shall be covered by sealant after moulding to prevent the change of the moisture content and to minimise the exposure to the carbon dioxide. To achieve this, the mould can be covered by plastic wrap and sealed with electrical tape (Figure 4.9). As the suggested mixing procedure is mainly for preparing specimen for UCS test, the curing condition of the prepared specimens is suggested to be same as that for UCS test. The specimen shall be cured at 20°C to 25°C and with relative humidity above 95%. When the specimen gains sufficient strength, it is considered acceptable to remove the specimen from the mould for continuing curing. However, the specimen shall be re-sealed to minimise exchange of the moisture content.

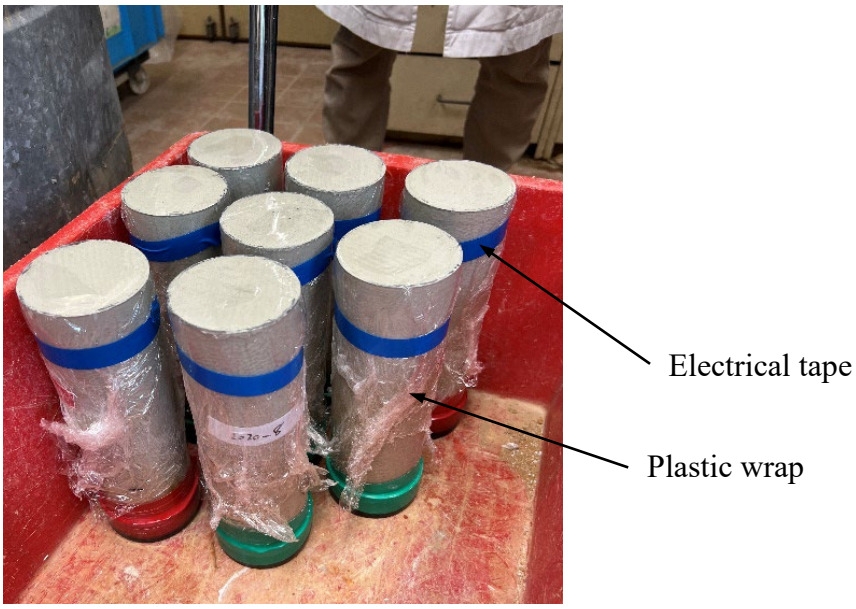


Figure 4.9 Specimens Covered by Sealant for Curing

5 Conclusion

This report has reviewed the test method recommended in the Interim Guidelines (HKIE, 2017) with reference to the several updated international/national and local testing standards for soil, treated soils, concrete and rock, and the testing experience accumulated in the past few years. Based on the review of the UCS test results in the past few years and recent studies, it is considered that the test method recommended in the Interim Guidelines (HKIE, 2017) is in general appropriate. Some recommendations related to the diameter of the specimen and the length to diameter ratio of the specimen are also documented

based on the studies carried out recently. An updated test method based on the review is documented. A procedure is also proposed to standardize the practice of preparing laboratory mixed stabilised specimen and to make the test results of the laboratory mixed specimens from different laboratories comparable without the need to review the mixing, moulding and curing condition.

6 References

Al-Jabban, W. J. (2019). *Soil Modification by Adding Small Amounts of Binders – a Laboratory Study*, Doctoral thesis, Luleå University of Technology, 2019.

Al-Jabban, W., Laue, J., Knutsson, S. & Al-Ansari, N. (2020). Briefing: common laboratory procedures to prepare and cure stabilised soil specimens: a short review. *Geotechnical Research,* 7(1):3-10.

Alipour, R., Khazaei, J., Pakbaz, M. S. & Ghalandarzadeh, A. (2016). Settlement control by deep and mass soil mixing in clayey soil. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, Volume 170 Issue 1, pp. 27-37.

Asano, J., Ban, K., Azuma, K., & Takahashi, K. (1996). Deep mixing method of soil stabilization using coal ash. *Grouting and Deep Mixing: Proc. IS Tokyo '96*, 2nd Int. Conf. on Ground Improvement Geosystems, 393-398.

ASTM. (1992). Standard practice for making and curing soil-cement compression and flexure test specimens in the laboratory (ASTM D1632-87). *ASTM Standards on Soil Stabilization with Admixtures (2nd edition)*, *Publication code number: 03-418292-38*, ASTM International.

ASTM. (1995). *Standard Test Method for Unconfined Compressive Strength of Intack Rock Core Specimen (ASTM D2938-95).* ASTM International, West Conshohocken, PA.

ASTM. (2014). S*tandard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures (ASTM D7012-14).* ASTM International, West Conshohocken, PA.

ASTM. (2016). *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil (ASTM D2166/D2166M-16)*. ASTM International, West Conshohocken, PA.

ASTM. (2017a). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen (ASTM C39/C39M-17a)*. ASTM International, West Conshohocken, PA.

ASTM. (2017b). *Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633-17)*. ASTM International, West Conshohocken, PA.

ASTM. (2019). *Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerance (ASTM D4543-19)*. ASTM International, West Conshohocken, PA.

ASTM. (2021). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C39/C39M-21)*. ASTM International, West Conshohocken, PA.

BRE (Building Research Establishment). (2002). *EuroSoilStab – Development of Design and Construction Methods to Stabilise Soft Organic Soils, Design Guide Soft Soil Stabilisation*, *CT97-0351*, Project No. BE 96-3177, HIS, BRE Press, London, UK.

Bruce, M.E.C., Breg, R.R., Collin, J.G., Filz, G.M., Terashi, M. & Yang, D.S. (2013). *Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support*, *Publication No. FHWA-HRT-13-046*. Offices of Research and Development, Federal Highway Administration, Washington, DC, USA.

BSI. (1990a). *Methods of Test for Soils for Civil Engineering Purposes (BS 1377: 1990, Part 7)*. British Standards Institute, London, 1990.

BSI. (1990b). *Stabilized Materials for Civil Engineering Purposes, Part 1: General Requirements, Sampling, Sample Preparation and Tests on Materials before Stabilization (BS1924-1:1990).* British Standards Institution, 1990.

BSI. (1990c). *Stabilized Materials for Civil Engineering Purposes, Part 2: Methods for Test for Cement-stabilized and Lime-stabilized Materials (BS1924-2:1990)*. British Standards Institution, 1990.

BSI. (2009a). *Testing Hardened Concrete – Part 3: Compressive Strength of Test Specimens (BS EN 12390-3:2009)*. British Standards Institute, London, 2009.

BSI. (2016). *Method of Testing Cement, Part 1: Determination of Strength (BS NE 196-1:2016)*. British Standards Institute, London, 2016.

BSI. (2018a). *Geotechnical Investigation and Testing – Laboratory Testing of Soil, Part 7: Unconfined Compression Test (ISO 17892-7:2018)*. British Standards Institute, London, 2018.

BSI. (2018b). *Hydraulically Bound and Stabilized Materials for Civil Engineering Purposes, Part 2: Sample Preparation and Testing of Materials During and After Treatment (BS 1924-2:2018)*. British Standards Institute, London, 2018.

BSI. (2019). *Testing Hardened Concrete, Part 3: Compressive Strength of Test Specimens (BS EN 12390-3:2019)*. British Standards Institute, London, 2019.

BSI. (2021). *Unbound and Hydraulically Bound Mixtures, Part 41: Test Method for the Determinations of the Compressive Strength of Hydraulically Bound Mixtures (BS EN 13286-41:2021)*. British Standards Institute, London, 2021.

Chung, P.W.K., Chu, F.L.F, Cheung, H.K.T., Yan, C.H., Cheung, C.K.W. & Wong, A.H.K. (2022). Technical development related to deep cement mixing method in Hong Kong. *Proceeding of The HKIE Geotechnical Division 42th Annual Seminar 2022*. The Hong Kong Institution of Engineers.

Güneyli, H. & Rüşen, T. (2016). Effect of length-to-diameter ratio on the unconfined compressive strength of cohesive soil specimens. *Bulletin of Engineering Geology and the Environment*, 75, 793-806 (2016).

HKIE (Hong Kong Institution of Engineers). (2017*). Interim Guidelines on Testing of Unconfined Compressive Strength of Cement Stabilised Soil Cores in Hong Kong*. Geotechnical Division, the Hong Kong Institution of Engineers.

HKSAR. (2010). *Construction Standard CS1:2010, Volumes 1 & 2.* Hong Kong Special Administration Region, Hong Kong.

Hoskins J.R. & Horino F.G. (1968). Effects of end conditions on determining compressive strength of rock samples. *Rep Investig Stand Bur Mines*, 1968:7171.

JGS. (2009a). *Practice for Making and Curing Stabilized Soil Specimens without Compaction*, JGS 0821-2009. Japanese Geotechnical Society.

JGS. (2009b). *Method for Unconfined Compression Test of Soils*, JGS 0511-2009 (JIS A1216). Japanese Geotechnical Society.

Ju, H. (2018). *Influence of Curing Temperature on Strength of Cement-treated Soil and Investigation of Optimum Mix Design for the Wet Method of Deep Mixing,* Master of Science dissertation, Virginia Polytechnic Institute, 2018.

Kitazume, M., Grisolia, M., Leder, E., Marzano, I.P., Correia, A.A.S., Oliveria, P.J.V., Åhnberg, H. & Andersson, M. (2015). Applicability of molding procedures in laboratory mix tests for quality control and assurance of the deep mixing method. *Soils and Foundations*, 2015, 55(4):761-777.

Kitazume, M. & Terashi, M. (2013). *The Deep Mixing Method*. CRC Press, Boca Raton, FL, USA.

Lanh, S.H., Nakarai, K., Ogawa, Y., Sasaki, T. & Morioka, M. (2017). Strength development of cement-treated soils: effects of water content, carbonation, and pozzolanic reaction under drying curing condition. *Construction and Building Materials*, 134 (2017) 703 – 712.

Lee, F.H., Lee, Y., Chew, S.H. & Yong, K.Y. (2005). Strength and modulus of marine clay-cement mixes. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 131(2):178 – 186.

Lin, M.H. (2018). *Laboratory Testing of Unconfined Compressive Strength of Cement Stabilized Soil Cores*, Master of Science dissertation, The University of Hong Kong, 2018.

Liu, Y.X. (2021). *Laboratory Testing of Unconfined Compressive Strength of Cement Stabilized Soil Cores*, Master of Science dissertation, The University of Hong Kong, 2021.

Pakbaz, M.S. & Mohsen, F. (2015). Comparison of the effect of mixing methods (dry vs. wet) on mechanical and hydraulic properties of treated soil with cement or lime. *Applied Clay Science,* 105-106 (2015) 156-169.

Richardson, D.N. (1991). Review of variables that influence measured concrete compressive strength. *Journal of Materials in Civil Engineering*, 1991, Vol. 3, p. 95-112.

Saitoh, S., Suzuki, Y., Nishioka, S. & Okumura, R. (1996). Required strength of improved ground. *Grouting and Deep Mixing: Proc. IS Tokyo '96*, 2nd Int. Conf. on Ground Improvement Geosystems, 353-356.

Suzuki, S., Kage, T. & Seko, S. (2011). Influence that ratio of length to diameter of high-strength concrete core to compressive strength of concrete. *Proceeding of International Conference on Durability of Building Materials and Components*, Porto-Portugal, April 12th-15th, 2011.

Takahashi, H., Morikawa, Y., Fujii, N. & Kitazume, M. (2018). Thirty-seven-year investigation of quicklime-treated soil produced by deep mixing method. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, 171(3): 135-147.

Tan, T.S., Goh, T.L. & Yong, K.Y. (2002). Properties of Singapore marine clays improved by cement mixing. *Geotechnical Testing Journal*, Dec. 2002, Vol. 25, No. 4.

Terashi, M. & Kitazume, M. (2011). QA/QC for deep-mixed ground: current practice and future research needs. *Ground Improvement*, 164 Issue GI3.

Tuncay, E. & Hasancebi, N. (2009). The effect of length to diameter ratio of test specimens on the uniaxial compressive strength of rock. *Bulletin of Engineering Geology and the Environment*, 68, 491-497 (2009).

Appendix A

Test Method for Unconfined Compressive Strength of Cement Stabilised Soil Cores

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1 Scope

1.1 This method sets out the procedure for the determination of unconfined compressive strength of cement stabilised soil cores preferable with diameter between 63 mm and 105 mm and with unconfined compressive strength below 10.0 MPa. Should the customer consider it necessary and applicable, the method can be applied on cores with diameter outside the preferable range provided that the apparatus should be checked to ensure that the measured force is within the calibrated range. The method is written in accordance with "Interim Guidelines on Testing for Unconfined Compressive Strength of Cement Stabilised Soil Cores in Hong Kong (October 2017)" prepared by the Task Force on Testing Unconfined Compressive Strength of Cement Stabilised Soil in Hong Kong established under the Geotechnical Division of The Hong Kong Institution of Engineers and "GEO Report No. 365 – Test Method for Unconfined Compressive Strength of Cement Stabilised Soil Cores (August 2023)" prepared by the Standards and Testing Division of Geotechnical Engineering Office.

2 Terminology

2.1 Definitions

2.1.1 Age of specimen – the period between the completion time of mixing cementitious agent to soil and the time of carrying out the test.

2.1.2 Core – a cylindrical sample of cement stabilised soil, usually obtained by means of a core drill. It can also be prepared in a laboratory.

2.1.3 Specimen – portion of a core sample prepared for testing.

2.1.4 Unconfined compressive strength (q_u) – the compressive stress at which an unconfined cylindrical specimen of cement stabilised soil will fail in a simple compression test; in this test method, unconfined compressive strength is taken as the maximum load attained per unit area.

3 Apparatus

3.1 Universal testing machine shall be at least Class I accurate to 1% and readable to 0.01 kN. The testing machine shall be of sufficient capacity to apply load at a suitable rate of displacement. The actual rate of platen displacement shall not vary by more than ± 20% of the rate specified in Clause 4.4.6. The axial deformation measuring device of the testing machine shall be readable to 0.01 mm and accurate to 0.02 mm, and capable of providing an axial compression equivalent to axial strain of at least 15% of the specimen tested. Simultaneous readings of the force and the axial displacement at a minimum of 15 load levels that are evenly spaced over the load range of compression shall be recorded.

3.2 If a universal testing machine specified in 3.1 is not available, a compression

machine with the following ancillary apparatus can be used for the test:

(a) a calibrated machine shall be of sufficient capacity to apply load at a suitable rate of displacement. The actual rate of platen displacement shall not vary by more than ± 20% of the rate specified in Clause 4.4.6. The compression machine shall be capable of providing an axial compression equivalent to axial strain of at least 15% of the specimen tested;

(b) a calibrated axial deformation measuring device which shall be readable to 0.01 mm and accurate to 0.02 mm and with a range of not less than about one-third of the length of the specimen. It may consist of a calibrated digimatic indicator or displacement transducer; and

(c) a calibrated force-measuring device which shall be of suitable capacity, at least accurate to 1% of the measured value and readable to 0.01 kN. The device can be a proving ring coupled with a digimatic indicator or load cell coupled with a digital readout. The device shall be supported by the crosshead of the compression machine so as to prevent its own weight being transferred to the specimen.

3.3 Two flat highly polished steel platens of the same diameter of the specimen or larger, through which the axial force is transmitted.

3.4 Apparatus for measuring dimensions of the specimen, to an accuracy of 0.1 mm.

3.5 Balance of suitable capacity to weigh the specimen to determine the mass of the specimen to within 0.1% of its total mass.

3.6 Saw capable of cutting rock cores with water as the cooling fluid.

3.7 Apparatus for measuring the perpendicularity of the specimen (an example is shown in Figure 1).

3.8 Apparatus for measuring the straightness and the flatness of the specimen.

3.9 Steel ruler graduated in millimetres.

3.10 Apparatus for providing an environment with relative humidity of at least 95% and with temperature ranged between 20 °C and 25 °C.

3.11 Maximum/minimum thermometer accurate to 0.5 °C (continuous recording thermometer is equivalent).

3.12 Jig and baseplate for setting core caps.

3.13 Thermostatically controlled sulphur melting pot and ladle.

3.14 Sulphur capping compound complying with Clause 15.5.2 of CS1:2010.

3.15 Engineer square.

3.16 Paint brush.

3.17 Light oil.

3.18 Centre scriber and protractor for cores.

3.19 Thermometer capable of measuring 100 °C to 200 °C and accurate to 0.5 °C.

4 Procedure

4.1 Receipt of Cores

4.1.1 The diameter of the core shall preferably be within 63 mm to 105 mm.

4.1.2 The prepared specimen shall normally have a length to diameter ratio of 2.0. Any specimen with a length to diameter ratio smaller than 1.0 (exclusive) is not suitable for testing.

4.1.3 Each core shall be examined for the presence of voids and cracks. If there is variation in the quality along the core, the customer should advise which portion of the core to be tested.

4.1.4 Check whether the customer has marked or provided the identification number and depth on the core.

4.1.5 Core which is sealed as received shall be stored within a controlled environment with relative humidity of at least 95% and with temperature between 20 °C and 25 °C.

4.2 Preparation of Specimen

4.2.1 Cutting and Measurement of Specimen

4.2.1.1 Measure the maximum and the minimum lengths (L_{max} and L_{min}) of the core as received, and record the readings (Note 7.1). Determine whether the length of the core is sufficient for preparing specimen(s) as requested.

4.2.1.2 Mark or by other reliable means indicating the laboratory specimen number on the core, prior to cutting.

4.2.1.3 Ensure the angle between the saw blade and the sample fixture is in right angle.

4.2.1.4 Inspect the condition of the saw blade visually and determine whether it is suitable for cutting.

4.2.1.5 Cut the core so that the ends are approximately flat and perpendicular to the longitudinal axis of the core. Wipe off surface moisture after cutting.

4.2.1.6 Mark lines that parallel to the longitudinal axis and around circumference of the specimen at 0°, 120°, and 240° respectively. The orientation can be slightly adjusted to avoid soft and weak spots or surface irregularities.

4.2.1.7 Take a set of three photos at 120° intervals showing all the markings and two photos on each end of the specimen.

4.2.1.8 Measure the length of the specimen after cutting (L_s) at points around the circumference of the specimen at 120° intervals, and record the readings. Calculate and record the mean of the three measurements to the nearest 0.1 mm.

4.2.1.9 Measure the diameter (D) of the specimen by taking two pairs of readings at right angles to each other at each one-third point along the length, and record the readings. The location of measurement can be slightly adjusted to avoid soft and weak spots or surface irregularities. Calculate and record the mean of the four measurements to the nearest 0.1 mm.

4.2.2 Flatness Checking of Specimen

4.2.2.1 Mark the end surface with two perpendicular axes intersecting at the longitudinal axis of the specimen. Soft and weak spots or surface irregularities can be neglected.

4.2.2.2 Clean the end surface of the specimen.

4.2.2.3 Check the flatness tolerance, which shall be 0.06% of the core diameter (in millimetres), for the prepared end surface. If the specimen does not meet the tolerance, proceed to Clause 4.2.5 for capping the specimen; or return to Clause 4.2.1.5 for re-cutting the specimen.

4.2.2.4 Repeat Clauses 4.2.2.3 for the other axis.

4.2.2.5 Repeat Clauses 4.2.2.1 to 4.2.2.4 for the other end surface of the specimen.

Note: A method for checking flatness of the specimen is given in Appendix 1 for reference.

4.2.3 Perpendicularity Checking of Specimen

4.2.3.1 Check the perpendicularity for the prepared end at 0º, 120º and 240º with respect to the longitudinal axis of the specimen. The orientation can be slightly adjusted to avoid soft and weak spots or surface irregularities. The perpendicularity tolerance for the prepared end with respect to the longitudinal axis of the specimen as datum axis shall be ± 1 mm.

4.2.3.2 If the specimen does not meet the perpendicularity tolerance, proceed to Clauses 4.2.5 for capping the specimen; or return to Clause 4.2.1.5 for re-cutting the specimen.

Note: A method for checking perpendicularity of the specimen is given in Appendix 1 for reference.

4.2.4 Parallelism Checking of Specimen

4.2.4.1 Check the parallelism for the prepared top surface at 0º, 120º and 240º with respect to the bottom surface of the specimen. The orientation can be slightly adjusted to avoid soft and weak spots or surface irregularities. The parallelism tolerance for the prepared top surface with respect to the bottom surface of the specimen as datum face shall be ± 2 mm.

4.2.4.2 If the specimen does not meet the parallelism tolerance, proceed to Clause 4.2.5 for capping the specimen; or return to Clause 4.2.1.5 for re-cutting the specimen.

Note: A method for checking parallelism of the specimen is given in Appendix 1 for reference.

4.2.5 Capping of Specimen (if necessary or as requested by the customer; otherwise proceed to Clause 4.3)

4.2.5.1 Wipe off surface moisture and extraneous matter on the specimen. Weigh the specimen and record the mass (M_1).

4.2.5.2 Dry one end of the specimen sufficiently to allow adhesion of the capping compound.

4.2.5.3 Cap the specimen according to the requirements in CS1:2010.

4.2.5.4 Repeat Clauses 4.2.5.2 to 4.2.5.3 for the other end of the specimen.

4.2.5.5 Repeat the test procedures stated in Clauses 4.2.2 to 4.2.4 for checking the flatness, perpendicularity and parallelism of the capped specimen.

4.2.5.6 If the capped specimen does not comply with the tolerances given in Clauses 4.2.2 to 4.2.4, the cap shall be removed and repeat the test procedures stated in Clauses 4.2.5.1 to 4.2.5.5.

4.2.5.7 Measure the length of the specimen after capping (L_u) at points around the circumference of the specimen at 120° intervals, and record the readings. Calculate and record the mean of the three measurements to the nearest 0.1 mm. Weigh the specimen and record the mass (M_2). Calculate the mass of the cap ($M_3 = M_2 – M_1$).

4.2.5.8 Proceed to Clause 4.3.

Note: A method for preparing a capped specimen is given in Appendix 1 for reference.

4.3 Curing of Specimen

4.3.1 Store the sealed specimen within a controlled environment with a relative humidity of at least 95% and with temperature between 20 °C and 25 °C until test is carried out.

4.4 Determination of the Axial Compressive Stress

4.4.1 Remove the specimen from the controlled environment; wipe off surface moisture and extraneous matter on the specimen (Note 7.2). Weigh the specimen and record the mass (M_4).

4.4.2 Clean the loading surfaces of the testing machine (both top and base platen).

4.4.3 Provide lubricated ends at two ends of the specimen (if the length to diameter ratio is less than 2).

4.4.4 Place the specimen on the base platen centrally and check that the specimen axis is vertical.

4.4.5 Set the readings of axial force and axial displacement to zero.

4.4.6 Select a rate of axial deformation such that the rate of axial strain is within 0.5 - 2%/min.

4.4.7 Apply compression to the specimen without shock and continuously increase the load at the selected rate and record simultaneous readings of the force and the axial displacement at a minimum 15 load levels that are evenly spaced over the load range.

4.4.8 Continue the test until the compressive stress (calculated as in Clause 5.2.2) drops to two-thirds of the maximum value, or the axial strain reaches 15% or otherwise at a stress level specified by the customer.

4.4.9 Remove the load from the specimen.

4.4.10 Remove the specimen from the base platen.

4.4.11 Take photos of the specimen to show the mode of failure.

5 Calculation and Plotting

5.1 Notations

L_s	:	Length of specimen after cutting	(mm)	(Clause 4.2.1.8)
L_u	:	Length of specimen after capping	(mm)	(Clause 4.2.5.7)
D	:	Diameter of specimen	(mm)	(Clause 4.2.1.9)
M_1	:	Mass of specimen without capping	(Mg)	(Clause 4.2.5.1)
M_2	:	Mass of specimen after capping	(Mg)	(Clause 4.2.5.7)
M_3	:	Mass of cap (a) $M_3 = M_2 - M_1$; (b) $M_3 = 0$ if specimen is not capped.	(Mg)	
M_4	:	Mass of specimen before test	(Mg)	(Clause 4.4.1)
A	:	Cross sectional area of specimen	(mm^2)	
V	:	Volume of specimen	(m^3)	
α	:	Length to diameter ratio		
ρ	:	Density of specimen	(Mg/m^3)	

5.2 Calculation and Plotting

5.2.1 Calculate the axial strain, ε of the specimen for each set of readings from the equation

$$\varepsilon_f = \frac{\Delta L}{L_s} \quad \text{if capping is not used; or}$$

$$\varepsilon_f = \frac{\Delta L}{L_u} \quad \text{if capping is used.}$$

where ΔL is the change in length of the specimen (in mm);

5.2.2 Calculate the axial compressive stress, σ_1 (in kPa), in the specimen for each set of readings, on the assumption that the specimen deforms as a right cylinder, from the equation

$$\sigma_1 = \frac{P(1-\varepsilon)}{A_0} \text{ x } 1000 \text{ x } F$$

where P is the force, applied to the specimen for each set of readings (in N);
ε is axial strain of the specimen for each set of readings;
A_0 is initial cross-sectional area of the specimen (mm^2);
F is the strength correction factor for the specimen with a length to diameter (L/D) ratio between 1.00 and 2.00. If the specimen is tested with capping, the length of the specimen after capping should be used to compute the L/D ratio. The strength correction factor is shown in the following table:

Length to Diameter (L/D) Ratio	2.00	1.75	1.50	1.25	1.00
Strength Correction Factor (F)	1.00	0.98	0.96	0.93	0.87

Note: Values not specified in the table can be determined by linear interpolation.

5.2.3 Plot calculated values of compressive stress as ordinates against corresponding values of strain (expressed as a percentage) as abscissae, and draw the stress-strain curve through the points. The initial mobilised strain to fully contact the specimen and the apparatus, if any, should be eliminated by offsetting this initial strain value when plotting the stress-strain curve.

5.2.4 Ascertain the point on the graph representing the failure condition, which is the point at which the maximum compressive stress sustained by the specimen occurs.

5.2.5 Use that point, determine the compressive stress in the specimen at failure, and report as the unconfined compressive strength, q_u (in kPa).

5.2.6 Determine the secant value of the elastic modulus of the specimen at 50% of the unconfined compressive strength from the equation:

$$E_{50,\text{secant}} = \frac{0.5q_u}{\varepsilon_{0.5q_u}}$$

5.2.7 Calculate the axial strain, $\boldsymbol{\varepsilon_f}$, of the specimen at failure from the equation

$$\varepsilon_f = \frac{\Delta L_f}{L_s} \qquad \text{if capping is not used; or}$$

$$\varepsilon_f = \frac{\Delta L_f}{L_u} \qquad \text{if capping is used.}$$

where ΔL_f is the change in length of the specimen at failure (in mm).

5.2.8 Calculate the bulk density of the specimen from the equation

$$A = \frac{\pi D^2}{4} \qquad (\text{mm}^2)$$

$$V = L_s A \times 10^{-9} \qquad (\text{m}^3)$$

$$\rho = \frac{(M_4 - M_3)}{V} \qquad (\text{Mg/m}^3)$$

6 Reporting of Results

6.1 Report the following:

(a) Identification number of the core.

(b) Date of receipt of the core.

(c) Condition of the specimen after cutting such as presence of soft spots, surface irregularities and cracks.

(d) Average diameter of the specimen to the nearest 0.1 mm.

(e) Length of the specimen to the nearest 1 mm. If capping is applied on the specimen, length of the specimen before and after capping should be reported.

(f) Measurement of flatness, perpendicularity and parallelism of the specimen. If capping is applied on the specimen, measurement after capping should be reported.

(g) A set of three photos taken at 120° intervals and two photos on each end of the specimen after cutting.

(h) Date of test.

(i) Rate of strain (in %/min) applied.

(j) Age of the specimen at date of test, if known.

(k) Unconfined compressive strength of the specimen to the nearest 0.01 MPa.

(l) Strain at failure (in %), to two significant figures.

(m) Secant value of elastic modulus at 50% of unconfined compressive strength of the specimen to the nearest 1MPa.

(n) Bulk density of the specimen to nearest 10 kg/m^3.

(o) Photos of the specimen after test.

(p) The stress-strain curve.

7 Notes

7.1 The length recorded as ‘maximum’ shall be the distance between the ‘peaks’ of two ends of the core, measured parallel to the longitudinal axis. The length recorded

as ‘minimum’ shall be the distance between the ‘troughs’ of the two ends of the core, measured parallel to the longitudinal axis.

7.2 Specimen with cracked or loose caps shall not be tested. The specimen shall be tested as soon as practicable after it is removed from the controlled environment and the test shall be carried out within the following tolerances of ages for testing:

(a) ± 30 minutes for ages up to and including 30 hours.

(b) ± 2 hours for ages above 30 hours and up to and including 4 days.

(c) ± 8 hours for ages above 4 days and up to and including 60 days.

(d) ± 1 day for ages above 60 days.

Appendix 1

A Method of Checking Flatness, Perpendicularity and Parallelism of Specimen and Capping Specimen (for reference only)

A. Flatness Checking of Specimen

A.1 Use the centre scriber, protractor and a sharp pencil to mark the cut face with two perpendicular axes intersecting at the longitudinal axis of the specimen. Soft and weak spots or surface irregularities can be neglected.

A.2 Clean the cut face of the specimen.

A.3 Determine the maximum allowable thickness of feeler gauge (0.06% of the specimen diameter) and select a suitable thickness of feeler gauge which shall be smaller than the maximum allowable thickness.

A.4 Press gently the straight edge on the cut face of the specimen along one of the perpendicular axes.

A.5 Slide the feeler gauge between the cut face of the specimen and the straight edge along the whole line. Record 'Yes' if the feeler gauge blade cannot pass through the gap between the cut face and the straight edge, otherwise record 'No' and proceed to Clause D for capping the specimen; or return to Clause 4.2.1.5 for re-cutting the specimen.

A.6 Repeat Clauses A.4. to A.5. for the other axis.

A.7 Repeat Clauses A.1. to A.6. for the other cut face of the specimen.

B. Perpendicularity Checking of Specimen

B.1 Use the release cable, lift off the spindle of the dial gauge. Put the specimen approximately in the middle of the turn table of the apparatus as shown in Figure 1.

B.2 Place the dial gauge against the point at near top of the specimen. Care shall be taken to avoid loosening or disturbing the dial gauge mounting.

B.3 Use the release cable to lift the spindle of the dial gauge off the specimen surface, and align the turntable to the zero degree mark. Release the dial gauge and record the reading.

B.4 Repeat Clause B.3 with the turn table aligned at 120º, 240º and 360º. The reading recorded at 360º would serve as a check and it shall not differ from the reading at zero degree by more than 0.05 mm. The orientation can be slightly adjusted to avoid soft and weak spots or surface irregularities.

B.5 Repeat Clauses B.2 to B.4 but with the dial gauge set against the point near the bottom of the specimen.

B.6 Calculate the maximum difference between the top and bottom measurements at 0º, 120º and 240º as the perpendicularity of the specimen.

B.7 If the perpendicularity exceeds 1 mm, proceed to Clause D for capping of the specimen; or return to Clause 4.2.1.5 for re-cutting the specimen.

C. Parallelism Checking of Specimen

C.1 Use the caliper to measure the length of the specimen between cut faces, at 0º, 120º and 240º around the circumference as indicated by the axes marked in Clause 4.2.1.6, and record the results to the nearest 0.1 mm.

C.2 If the difference of the three cut length measurements within 2 mm then the specimen shall be considered parallel. Otherwise, proceed to Clause D for capping of the specimen; or return to Clause 4.2.1.5 for re-cutting the specimen.

D. Capping of Specimen (if necessary or as requested by the customer)

D.1 Wipe off surface moisture and extraneous matter on the specimen. Weigh the specimen and record the mass (M_1).

D.2 Dry one end of the specimen sufficiently to allow adhesion of the capping compound.

D.3 Heat the capping compound to a suitable viscosity for capping (Note 1). Use a suitable thermometer to check the temperature of the compound after stirring. The temperature shall be within the range of 130 °C to 150 °C.

D.4 Coat the capping former with a thin film of warm oil. Excess oil may affect the flatness of the cap.

D.5 Pour the capping compound into the capping former in such a manner to ensure that the finished cap will be as thin as possible.

D.6 Place the specimen into the capping compound immediately using the former to maintain the axis perpendicular to the cap.

D.7 Allow the compound to harden, remove any surplus and then remove the specimen from the former. Check the cap for air bubbles or lack of adhesion by tapping.

D.8 Repeat Clauses D.2 to D.7 for the other end of the specimen.

D.9 Repeat the test procedures stated in Clauses A to C for checking the flatness, perpendicularity and parallelism of the capped specimen.

D.10 If the capped specimen does not comply with the tolerances given in Clauses A to C, the cap shall be removed. Repeat test procedures stated in Clauses D.1 to D.9.

D.11 Use calliper to measure the length of the specimen after capping (L_u) at points around the circumference of the specimen at 120° intervals, and record the readings. Calculate and record the mean of the three measurements to the nearest 0.1 mm. Weigh the

specimen and record the mass (M_2). Calculate and record the mass of the cap ($M_3 = M_2 – M_1$).

D.12 Proceed to Clause 4.3 for curing the specimen.

Note 1: The strength of each new stock of capping compound shall be checked by preparing a cap on a rock core specimen stronger than the compound and then testing it in compression. The capped specimen shall be loaded to at least 20 N/mm^2 and after the load is released, the capping compound shall be inspected. The stock shall be accepted only if there is no sign of damage on the capping compound.

Figure 1

An Apparatus for Measuring the Perpendicularity of Specimen
(for reference only)

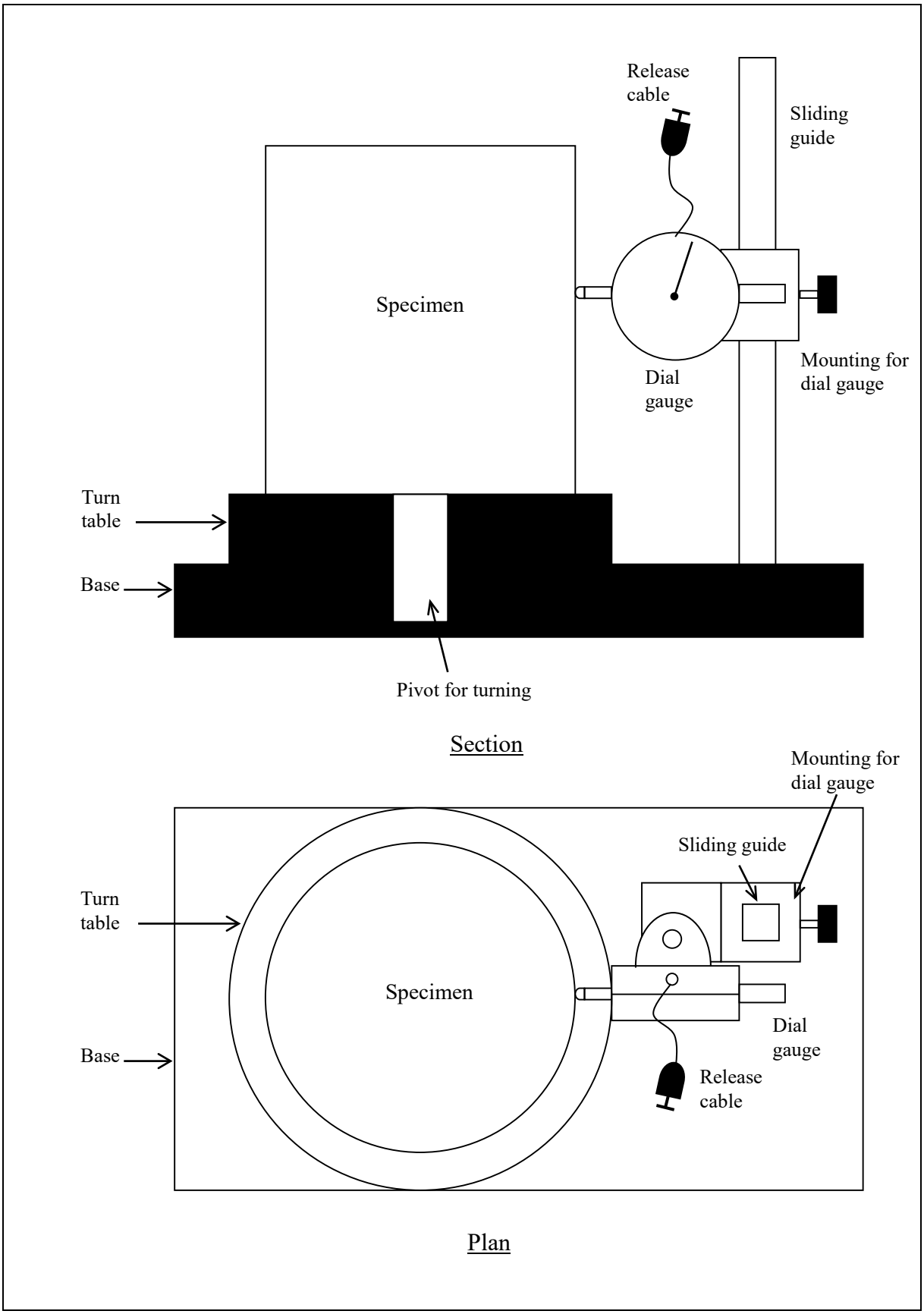

Figure 1 An Apparatus for Measuring the Perpendicularity of Specimen (for reference only)

Appendix B

Summary of Several International/National Mixing Procedures for Preparing Laboratory Mixed Stabilised Soil Specimens

Table B.1 Summary of Several International/National Mixing Procedures for Prepared Laboratory Mixed Stabilised Soil Specimens (Sheet 1 of 2)

Standards	Method to Prepare Soil before Mixing with Binders	Mixing Tool	Mixing Duration of Soil-binder Mixture	Specimen Mould	Number of Layers in the Mould	Moulding Methods	Curing Conditions Measures to Check the Correctness of Specimens
BRE (2002)	The soil is mixed until it is visually homogeneous.	Mixing machine with sufficient capacity	5 minutes	Plastic tubes or plastic-coated cardboard, 50 mm diameter and length at least 100 mm	4 layers with each thickness about 0.5 of the specimen diameter	Static compaction[(a)] The mixed soil must be formed into samples within 30 minutes of mixing.	The specimen is cured and stored in sealed tubes at 18 – 22 °C.
JGS (2009a)	The soil is sieved through a sieve with appropriate size so that the maximum grain size of sieved soil is less than one-fifth of the inner diameter of the mold. The soil is then homogenized using mixer.	Mixer capable of evenly mixing soil and binder	Approximately in 10 minutes	Mold is in 50 mm diameter and 100 mm in height. Specimen diameter can be varied depending on soil characteristics. Height of specimen is set to be 2.0 – 2.5 of diameter.	3 layers	Method remove the air bubbles from each layer is not specified.	The specimen in the mold is covered by sealant to prevent the change of water content and cured at 20 ± 3 °C.
Federal Highway Administration Design Manual (Bruce et al, 2013)	The soil is mixed for approximately 3 minutes using mixer at lowest setting (approximate rotation of the mixing tool of 100 to 175 cycles/minute and revolution of mixing tool around the bowl of not less than 100 cycles/minute in planetary mixing action).	Mixer should produce the most thorough mixing considering the plasticity of soil being mixed. Dough hook works well for mixing cohesive soils; a flat beater may work well for some non-plastic soils.	About 10 minutes	50 mm by 100 mm plastic mold with lids	3 layers	The molding aims to completely fill the plastic mold without air voids while simultaneously minimizing segregation. Two molding methods are suggested: (1) Rodding (for thicker lower water content mixtures) (2) Light tapping (for fluid mixtures with high water content) Discard any mix that is not satisfactorily placed in a mold within 30 minutes of completing initial mixing.	The specimen is completely sealed and stored under controlled condition with temperature at 20 to 25°C and relative humidity of 95 to 100%.

Table B.1 Summary of Several International/National Mixing Procedures for Prepared Laboratory Mixed Stabilised Soil Specimens (Sheet 2 of 2)

Standards	Method to Prepare Soil before Mixing with Binders	Mixing Tool	Mixing Duration of Soil-binder Mixture	Specimen Mould	Number of Layers in the Mould	Moulding Methods	Curing Conditions Measures to Check the Correctness of Specimens
ASTM (1992)	The soil is dried below 60°C and aggregations are broken down. Particles retained on 50 mm sieve should be removed while particles passing through 50 mm sieve and retained on 19 mm sieve should be replaced by particle passing through 19 mm sieve and retained on 4.75 mm sieve.	Hand mixing or suitable laboratory mixer	The soil and binder should be mixed thoroughly. Time is not specified.	Cylindrical steel mold with internal diameter of 71 mm and height of 229 mm for producing specimen with diameter of 71 mm and height of 142 mm	One layer	Rodding [(b)]	The specimen is cured in mold or protect from dripping water in the moist room.
BSI (1990a, 1990b)	The soil is dried at 105 ± 5°C and aggregations are broken down.	Hand mixing or mechanical mixer with suitable capacity	10 minutes	Tapered mold with two steel plugs for preparing specimen with following dimensions: • 50 mm diameter and 100 mm high (for fine-grained soil) • 100 mm diameter and 200 mm high (for medium-grained soil)	One layer for fine-grained soil Six layers for medium-grained soil	Two suggested molding methods: (1) Static compression force to a pre-determined density [(c)] (2) Constant compactive effort [(d)] On completion of mixing, specimen manufacture shall proceed immediately and shall be completed within 2 hours following cement addition.	The specimen is either coated with wax and stored at a constant temperature of 20 ± 2°C. The specimen can be wrapped in plastic sheeting and store in a sealed airtight plastic bag to prevent loss of water.

Notes:

(a) Each layer with thickness of about 25 mm is statically compressed with a pressure of 100 kPa three times approximately 2 seconds, each time with the stamp against the wall of the mold and the compaction rod inclined towards at approximate 10-15°, and rotate 120° along the circumference of the mold each time. The layer will be compacted with three more strokes but with the rod held vertically and rotate these strokes 60° relative to the first series.

(b) The mixture is compacted initially from the bottom up by steadily and firmly forcing (with little impact) a square-end cut in 12.7 mm diameter smooth steel rock repeatedly through the mixture from the top down to the point of refusal, distributing the rodding uniformly over the cross section of the mold. The rodding is continued until the mixture is packed out to a height of approximately 150 mm. The specimen is then compressed by either a static load or dynamic load until its height is reduced to 142 mm.

(c) The compression force is not specified but should be sufficient to produce the required height of specimen.

(d) For fine-grained soil, the soil is compacted by 15 blows of rammer dropped from a height of 300 mm. The mold is inverted, the soil is further compacted by 15 blows from the rammer. For medium-grained soil, each layer of soil is compacted by 25 blows of the rammer dropped from a height of 300 mm.

Appendix C

Laboratory Procedure for Mixing and Curing of Stabilised Soil Specimen through Wet Mixing Method

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1 Scope

1.1 This procedure is developed for relatively easily mixed soils to be stabilised using cement, granulated blast furnace slag (GBS), ground granulated blast furnace slag (GGBS) or a combination of cement with GBS/GGBS through wet mixing method. It does not apply to stabilised soil which will be segregated easily by continuous compaction. Should the designer consider it appropriate, the procedure can be applied on soils stabilised by fly ash or lime. This procedure is written in accordance with "GEO Report No. 365 – Test Method for Unconfined Compressive Strength of Cement Stabilised Soil Cores (August 2023)" prepared by the Standards and Testing Division of Geotechnical Engineering Office.

2 Terminology

2.1 Definitions

2.1.1 Additive – chemical material to be added to binder for improving properties of stabilised soil

2.1.2 Binder – chemically reactive material that can be used for mixing with soils to improve the engineering properties of soils

2.1.3 Binder factor – ratio of dry weight of binder to dry weight of soil to be stabilised (%)

2.1.4 Binder content – ratio of dry weight of binder to volume of soil to be stabilised (kg/m^3)

2.1.5 Binder slurry – slurry-like mixture of binder and water

2.1.6 Stabilised soil – soil stabilised by mixing with binder

3 Apparatus

3.1 Soil-binder mixer which shall allow planetary mixing action and multiple beater attachments including a dough hook and a flat beater.

3.2 Binder mixer which shall comply with the requirements of BS EN 196-1:2016 with the following speeds of the mixer blade:

	Rotation per Minute	Planetary Movement per Minute
Low Speed	140 ± 5	62 ± 5
High Speed	285 ± 10	125 ± 10

3.3 Mixing bowl with sufficient capacity for soil-binder mixture

3.4 Mixing container with sufficient capacity for binder slurry

3.5 Apparatus for compacting the soil-binder mixture ("compactor") (an example of the specification of the apparatus is provided in Annex 1)

3.6 Plastic Spatula

3.7 Ladle

3.8 Test sieve conforming to BS 410 and with an aperture size of 14mm

3.9 Balance of suitable capacity to weigh the soil, binder and soil-binder mixture, accuracy of 0.1% of the mass or better.

3.10 Apparatus for measuring dimensions of the specimen, accuracy of 0.1 mm or better.

3.11 Mould with a diameter of 75 ± 1 mm and a length of 200 ± 1 mm for making the specimen. The mould shall be rigid enough to prevent distortion and have sufficient rigidity to maintain its shape after placing the mixture and without leakage of the mixture.

3.12 Straight edge

3.13 Apparatus for providing an environment with a relative humidity of at least 95% and with temperature ranging between 20 °C and 25 °C.

3.14 Plastic wrap or plastic bag

3.15 Air-tight container

3.16 An extruder to suit the mould, and to which it can be securely attached during extrusion

3.17 Stop-watch shall be accurate to 0.5 second

4 Procedure

4.1 On Receipt of Soil and Binder

4.1.1 Before processing, place the natural soil in an air-tight container or equivalent as soon as possible to prevent loss or gain of moisture.

4.1.2 Determine the required amount of binder for the entire mixing programme. Sift the binder to remove any lumps and store it in an airtight container before mixing.

4.2 Soil Preparation

4.2.1 The natural soil shall be sieved through a test sieve with an appropriate aperture size so that the maximum grain size of the sieved soil should be less than one-fifth of the inner diameter of the mould.

4.2.2 Mix the sieved soil with mixer or equivalent to produce thorough mixing and measure the moisture content of the representative sample of the mixed soil. Preserve the moisture content of the mixed soil by placing it in an airtight container.

4.2.3 Determine the weight of soil required for preparing the soil-binder mixture.

4.2.4 Choose an appropriate attachment for the mixer (e.g. dough hook, flat beater or other style) that will produce the most thorough mixing considering the plasticity of the soil being mixed and the total amount of water in soil and binder slurry.

4.2.5 Measure the required weight of soil to the nearest 0.1 g and place it in the mixing bowl. Record the weight of soil.

4.2.6 If the laboratory testing programme requires that the moisture content of soil to be increased above its initial moisture content, the required additional water can be mixed into soil. Record the weight of water added to the nearest 0.1 g.

4.2.7 Place the mixing bowl onto the mixer and begin mixing until the soil is visually homogenous. When necessary, use a spatula to remove soil from the blades and the sides of bowl and push the soil back towards the centre of the bowl for further mixing.

4.2.8 Reseal the soil sample if soil-binder mixing is not carried out immediately.

4.3 Binder Slurry Preparation

4.3.1 Determine the dry weight of binder and the weight of water to be added to the binder for producing one batch of the soil-binder mixtures based on the binder content and water-to-binder ratio.

4.3.2 Measure the required weight of binder and water to the nearest 0.1 g. Record the dry weight of binder and weight of water added to binder. Place the dry binder and water in the mixing container. Record the time that water is added to the dry binder to the nearest minute, as “zero time”.

4.3.3 Start the mixer at low speed whilst starting the timing of the mixing stages. After 60 seconds of mixing, switch the mixer to the high speed and continue the mixing for an additional 30 seconds.

4.3.4 Stop the mixer for 90 seconds. During the first 30 seconds, use a spatula to remove binder adhering to the wall and bottom part of the bowl and place in the middle of the bowl.

4.3.5 Continue the mixing at high speed for 60 seconds.

4.4 Soil-binder Mixing

4.4.1 Pour binder slurry into the soil mixing bowl. Use the spatula to aid in transferring as much of the binder slurry as possible into the soil mixing bowl. Weigh the binder-slurry container before and after transferring the slurry into the mixing bowl to determine the actual weight of the binder slurry added into the soil. The exact amount of binder slurry required for the mix design should be added to the soil so that the design water-to-binder ratio is maintained. Record the weight of binder slurry added to soil. Excess binder slurry could be prepared to ensure an adequate amount of binder slurry is added to the soil.

4.4.2 Mix the soil-binder mixture using the mixer at a low speed (e.g. 60 to 150 revolutions per minute) for 2 minutes and then at a high speed (e.g. more than 240 revolutions per minute) for 3 minutes.

4.4.3 Stop the mixer for 60 seconds. Remove the soil-binder mixture adhering to the sides of the mixing bowl and attachment for the mixer using spatula and push the soil-binder mixture back towards the centre of the mixing bowl.

4.4.4 Continue mixing the soil using mixer at high speed (e.g. more than 240 revolutions per minute) for another 5 minutes or until the mixture is thoroughly mixed. Record the total mixing time to the nearest minute.

4.5 Specimen Preparation

4.5.1 Apply a thin layer of grease on the inner surface of the mould.

4.5.2 Record the weight of the mould with base cap to the nearest 0.1 g.

4.5.3 Clamp the mould firmly to the compactor.

4.5.4 Place the soil-binder mixture in the moulds as soon as possible following the soil-binder mixing. Fill each mould in three lifts with approximately the same thickness. Spread the layer uniformly using the spatula. Remove air voids by compacting the soil-binder mixture using the compactor with 60 shocks in 60 ± 3 seconds per lift. Adjust the number of shocks per lift or the method to remove air pockets inside the specimen if segregation is found in the specimen.

4.5.5 Finish by screeding the top of the specimen flush with the top of the mould, using a straight edge to produce a flat surface. Specimens that have leakage at the base cape should be discarded.

4.5.6 After all moulds have been filled, clean the mould. Weigh each specimen individually in its mould and seal the specimen immediately to prevent moisture loss. No specimen should weigh less than 95% of the weight of the heaviest

specimen in one batch. Specimens that do not satisfy the tolerance should be discarded.

4.5.7 Discard any mixture that is not satisfactorily placed in a mould within 1 hour after water is added to the binder.

4.6 Curing of Specimen

4.6.1 Store the specimen in an upright position for the specified curing period under controlled conditions at 95 to 100 per cent relative humidity and between 20°C to 25°C unless a different curing temperature is specified. The specimens should not be stacked.

4.7 Removal of Specimen from Mould

4.7.1 Specimen can be removed from the mould after the strength of the specimen reaches a sufficient level but should be at the same age for the whole batch of the specimens. Record the date of demoulding.

4.7.2 If bleed water has formed at the top of the specimen, record the weight of the bleed water.

4.7.3 Re-seal the specimen as soon as possible to minimize the moisture loss and store the re-sealed specimen in an upright position under the controlled conditions (as specified in Section 4.6) to complete the curing process.

5 Reporting

5.1 The report shall affirm that the specimen was prepared in accordance with this test method and shall contain the following information:

(a) Identification number of the soil

(b) Soil type

(c) Binder type

(d) Binder factor (%)

(e) Binder content (kg/m^3)

(f) Water type used in the mixing

(g) Water to binder ratio (%)

(h) Additive type (if used)

(i) Additive amount (%) (if used)

(j) Size of sieve used to sieve the soil before mixing with binder (mm)

(k) Percentage by mass of particles of sizes larger than that acceptable if found within the soil and a photograph of them taken alongside a suitable scale and a colour chart (%)

(l) Average moisture content of soil to two significant for values up to 10% or to the nearest whole number for values above 10% (%)

(m) Target moisture content of soil before mixing (%)

(n) Completion date and time of moulding of specimen (for one batch of specimens)

(o) Laboratory sample no. of the specimen

(p) Weight of bleed water to the nearest 0.1 g (g) (if any)

(q) Any deviation from the test method and any incidents that could have effect on the result.

Annex 1

A Specification of Apparatus for Compacting Soil-Binder Mixture to Form a Cylindrical Specimen

A Specification of Apparatus for Compacting Soil-Binder Mixture to Form a Cylindrical Specimen

1. The apparatus should include a movable standing body with a built-in motor and a shock working platform.

2. The working platform of the apparatus should be rigid. It should be stood with four movable rams and could be moved upward and downward mechanically (move upward automatically and fall downward by self-weight).

3. The dimension of the working platform should not exceed 500 mm (W) × 500 mm (L) × 150 mm (H).

4. The weight of the working platform should be 150 ± 1.5 kg.

5. The travel distance of the working platform should be 100 ± 2 mm.

6. The working platform of the apparatus should have a repetition rate of up to 60 shocks in 60 ± 3 seconds.

7. A mounting rack should be provided and mounted on the working platform tightly for holding moulds.

8. The dimension of the mounting rack should not exceed 300 mm (W) × 300 mm (L) × 180 mm (H).

9. The mounting rack should hold at least 9 moulds securely and the mould should be within 74 mm to 76 mm.

Annex 2

Calculations for Laboratory Preparation of Soil-binder Mixture

Method to Determine Materials for Preparing Soil-Binder Mixture

1. Determine average moisture content ($\overline{w}$) (%) of soil

2. Determine the required mass of soil (m_T) (g)

$$\text{Wet density } (\rho_T)\ (\text{g/cm}^3) = \frac{1+\frac{\overline{w}}{100}}{\left(\frac{1}{\rho_s}+\frac{\overline{w}}{100}\right)}$$

where ρ_s is the specific gravity of soil.

$$\text{Mass of soil } (m_T) = \text{no. of specimen} \times \text{volume of mould} \times \rho_T \times R$$

where R is redundancy factor, which is usually taken as 1.1 to 1.2.

3. Determine the mass of binder (m_H) (g)

$$\text{Dry mass of soil } (m_D) = \frac{m_T}{\left(1+\frac{\overline{w}}{100}\right)}$$

$$\text{Binder factor (\%)} = \text{ratio of dry mass of binder to dry mass of soil to be stabilised}$$

$$\text{Binder content } (\text{kg/m}^3) = \left(\frac{10\rho_T}{(1+\frac{\overline{w}}{100})}\right) \times \text{Binder factor}$$

$$\text{Mass of binder } (m_H) = m_D \times \text{Binder factor}/100$$

4. Mass of water for mixing with binder (m_w) (g)

$$m_w\ (\text{g}) = m_H \times \text{water to binder ratio (\%)}/100$$

5. Mass of additive (m_A) (g)

$$m_A\ (\text{g}) = m_H \times \text{additive amount (\%)}/100$$

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