Interim Guidelines on Testing of Unconfined Compressive Strength (UCS) of Cement Stabilised Soil Cores in Hong Kong

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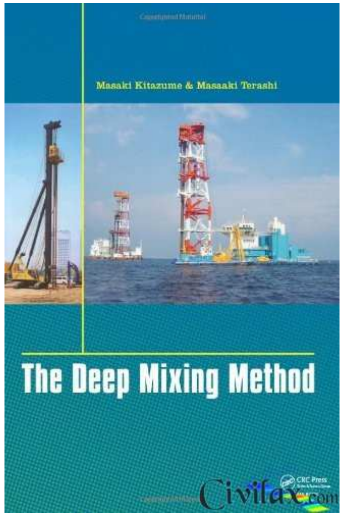
HKIE Geotechnical Division Committee

Contents

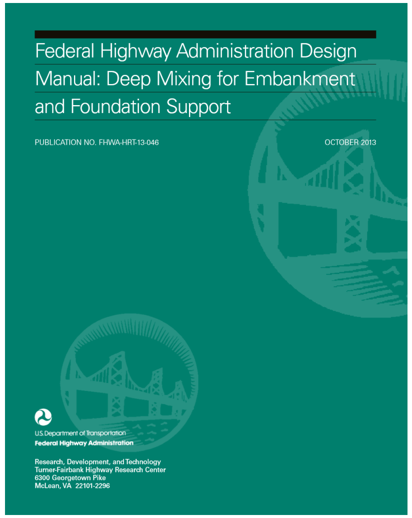
Part A - Introduction

Two major references

Kitazume and Terashi 2013



FHWA Design Manual 2013



Ground Improvement Methods

- Ground improvement is the modification of existing soils to provide better performance under design and/or operational loading conditions.
- The following three slides tabulate some of the ground improvement techniques that have been used in Japan (see *Kitazume and Terashi* "The Deep Mixing Method")

Improvement principle		*Engineering method*	*Work examples*
Replacement		Excavation replacement	Dredging replacement method
		Forced replacement	Sand compaction pile method
Densification	Dewatering/ compaction	Compaction by displacement and vibration	Sand compaction pile method
			Gravel compaction pile method
	Compaction	Vibration compaction	Vibro-flotation method
		Impact compaction	Dynamic consolidation method

Ref: Kitazume and Terashi "The Deep Mixing Method"

Consolidation/ dewatering	Preloading	Preloading method
	Preloading with vertical drains	Sand drain method
		Packed sand drain method
		Board drain method
	Dewatering	Deep well method
		Well point method
		Vacuum consolidation method
	Chemical dewatering	Quick lime pile method

Ref: Kitazume and Terashi "The Deep Mixing Method"

Grouting	Grouting	Chemical grouting method
		High pressure injection method
Solidification (Admixture stabilization)	In-situ mixing	Shallow mixing method
		Deep mixing method
	Plant mixing	Pre-mix mixing method
		Light weight soil method
	Pipe mixing	Pneumatic flow mixing method
Thermal stabilization	Heating	
	Freezing	

Ref: Kitazume and Terashi "The Deep Mixing Method"

Two Remarks on the various soil improvement methods:

1. A combination of the methods is commonly adopted and is a more effective strategy in some projects
2. Each method has its own merits and drawbacks

Deep Mixing is a technique of mixing chemical binder (cement/lime) with soil to improve the engineering properties of the soil.

- Consistency
- Strength
- Deformation

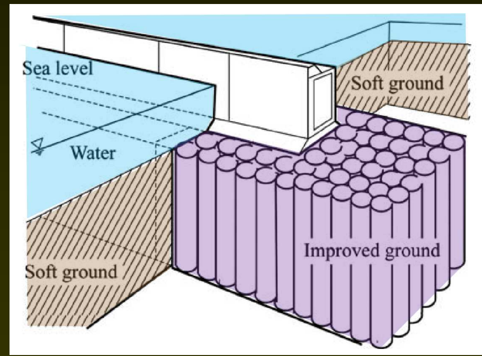
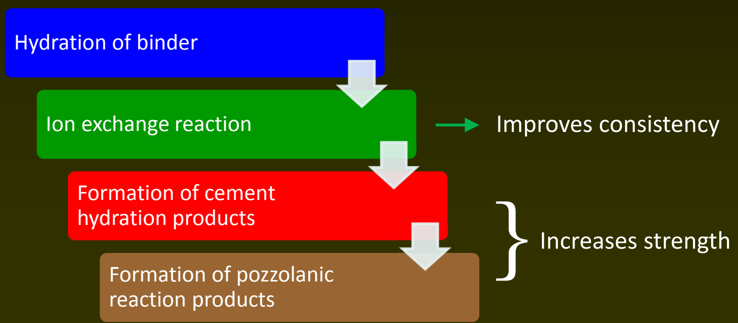


Figure ref: Kitazume and Terashi "The Deep Mixing Method"

Mechanism of deep cement mixing:

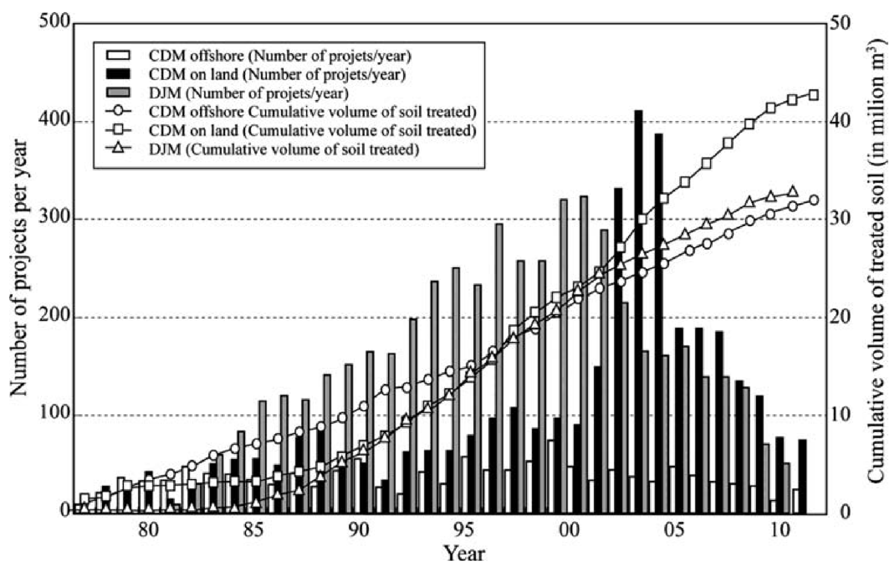
- Ion exchange at the surface of clay minerals
- bonding of soil particles
- filling of void spaces by chemical reaction products.



$$2(3CaO \cdot SiO_2) + 6H_2O = 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2$$

The deep mixing method utilizes mixing blades or augers to manufacture a stabilized soil column of predetermined size and shape in situ

Photo credit:
http://www.treviicos.com/Technologies/DeepMixingPiles



Statistics of deep mixing method works in Japan.

Ref: Kitazume and Terashi "The Deep Mixing Method"

What is the quantity of cement stabilized soils used/to be used in HK?

Tung Chung East reclamation
Mainly beneath the 4.95km long seawall. Vol. ≈ 3 million m^3

Boundary Crossing Facilities BCF
No published data, mainly for additional strengthening works. My rough estimate : Vol. ≈< 1 million m^3

Third Runway System 3RS
No published data, my rough estimate based on about 230,000 soil cement clusters and average length >20m: Vol. ≈> 20 million m^3

Table 6. Summary of evaluations, information, and testing considerations for highway applications of DMM.

Geotechnical Issues	Engineering Evaluations	Information for Assessment and Analysis	Field Testing	Laboratory Testing
• Deep mixing (for support of embankments, piers, abutments, retaining walls, and culverts)	• Settlement • Stability • Load transfer platform • Lateral movement of adjacent structures if they might be affected by the proposed construction • Compatibility of soil with stabilizers • Suitability of soil for deep mixing	• Subsurface profile • Soil characterization • Tolerable settlement of facility • Factor of safety and/or reliability against slope instability • Compressibility parameters • Shear strength parameters • Unit weights • Chemical and mineralogical composition of soil • Presence of buried obstructions/ utilities • Identification of on/offsite disposal location (for wet mixing)	• Standard penetration test (SPT) • Cone penetration test (CPT) • Field vane shear strength • Geophysical testing • Observation wells/ piezometers • Near-surface ground temperature	• In situ water content • Organic content • pH • Loss on ignition • Conductivity • Chloride and sulfide content • Atterberg (liquid and plastic) limits • Grain size distribution • Consolidation of existing site soils • Shear strength of existing site soils • Unconfined compressive strength of soil-binder mixtures

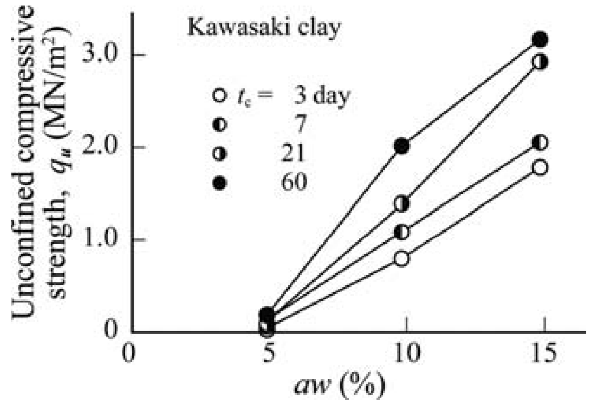
Ref: FHWA Design Manual: Deep Mixing for Embankment and Foundation Support

Table 9. Factors affecting strength of deep mixed soil.

Category	Factors
Characteristics of binder	• Type of binder(s) • Quality • Mixing water and additives
Characteristics and conditions of soil (especially important for clays)	• Physical, chemical, and mineralogical properties of soil • Organic content • pH of pore water • Water content
Mixing conditions	• Amount of binder • Mixing efficiency • Timing of mixing/remixing
Curing conditions	• Temperature • Curing time • Humidity • Wetting and drying, freezing and thawing, etc.
Loading conditions	• Loading rate • Confining pressure • Stress path (e.g., compression, tension, and simple shear)

Ref: FHWA Design Manual

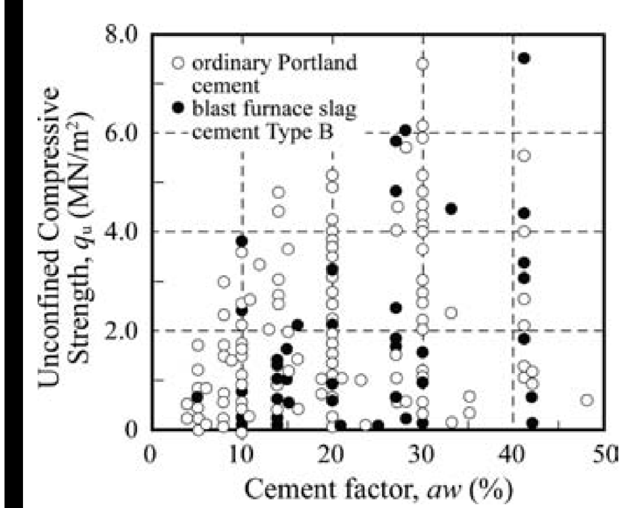
We normally expect an increase in UCS with the amount of binder content



Cement factor (aw) is defined as the ratio of dry weight of binder to dry weight of soil to be stabilized.

Influence of amount of cement on strength (Terashi *et al.*, 1980).

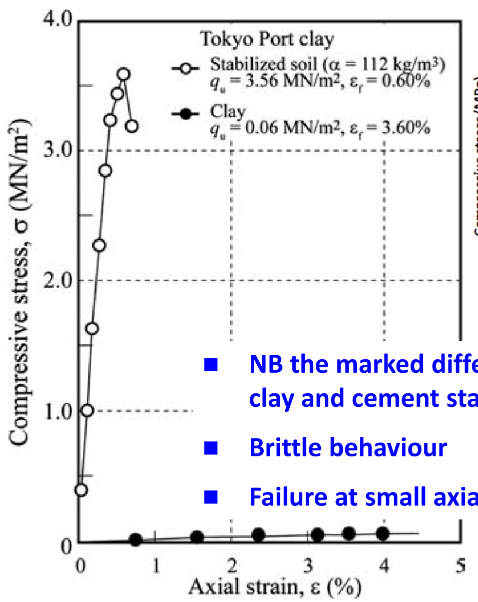
But it also critically depends on the soil types and environmental conditions

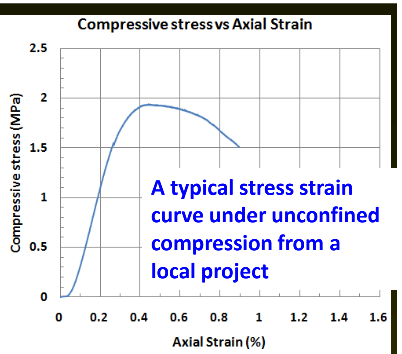


Shows the effect of different soil types on the UCS of the cement soils *(pH and humic acid are two dominating factors)*

NB
Cement factor (also called binder factor) is defined as the ratio of dry weight of binder to dry weight of soil to be stabilized.

Ref: Babasaki et al.,1996

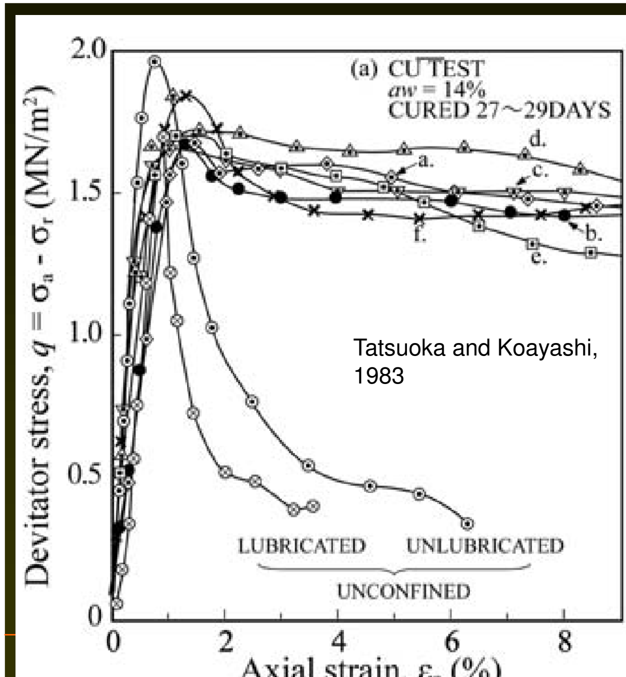




A typical stress strain curve under unconfined compression from a local project

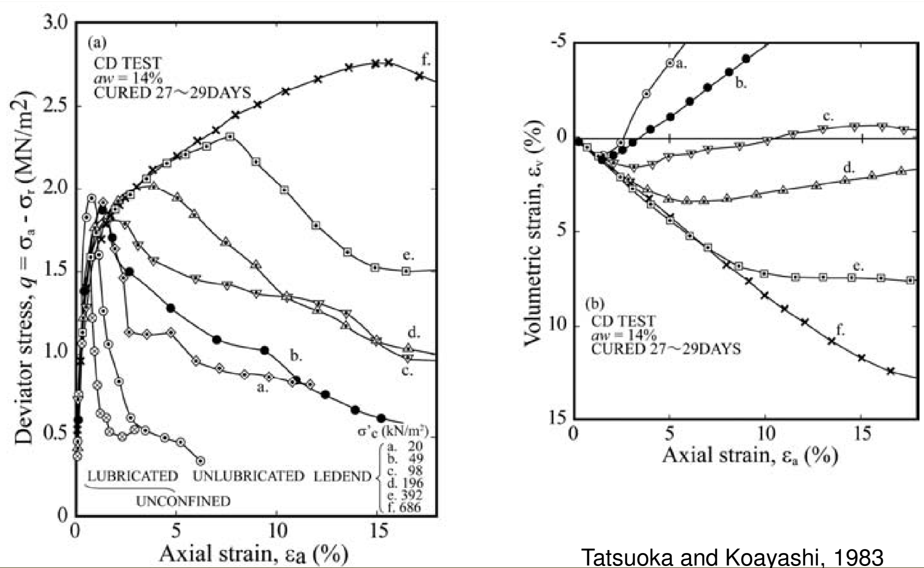
- **NB the marked difference between parent clay and cement stabilized clay**
- **Brittle behaviour**
- **Failure at small axial strain**

Stress–strain of in-situ cement stabilized soil (Sugiyama *et al.*, 1980).



Cement stabilized soil specimens under unconfined compression and Consolidated Undrained (CU) triaxial tests.

Note the residual strength under unconfined and confined situations

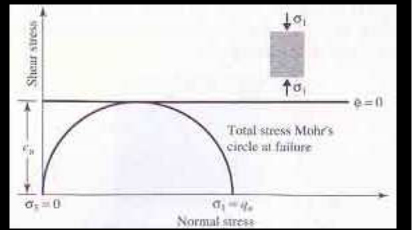


Tatsuoka and Koayashi, 1983

Cement stabilized soil specimens under unconfined compression and Consolidated Drained (CD) triaxial tests. Note that cement soil behaves as oc clay.

Shear Strength

- There is no consensus (universally) regarding the most appropriate strength envelope for deep cement mixed soils for use in stability analyses.
- Japanese practice is shown in the next slide.
- FHWA recommends that a reasonable but conservative strength envelope be used and that a total stress friction angle of ϕ = 0 and no tensile strength should be considered.

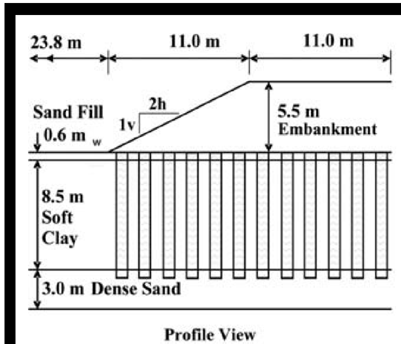


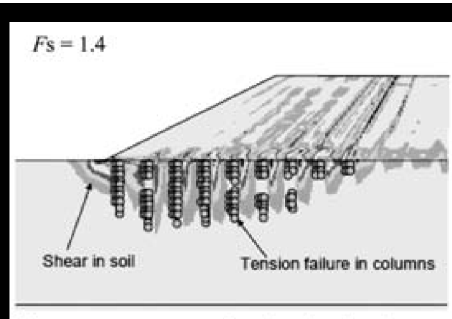
Shear Strength

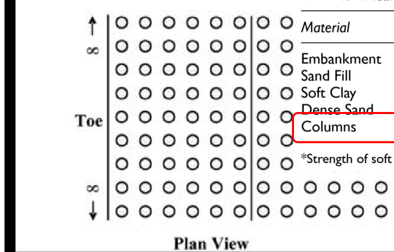
- The angle of internal friction, ϕ′ of stabilized soil = 0 (for consolidation pressure < consolidation yield pressure)
- ϕ′ of stabilized soil same = unstabilized soil (for consolidation pressure > the yield pressure

See supp slide

- The undrained shear strength, c_u of the stabilized soil is almost constant as long as the consolidation pressure is low.
- When the consolidation pressure > consolidation yield pressure, the undrained shear strength increases with increasing consolidation pressure.







Mean material properties (Filz and Navin, 2006; Adams *et al.*, 2009).

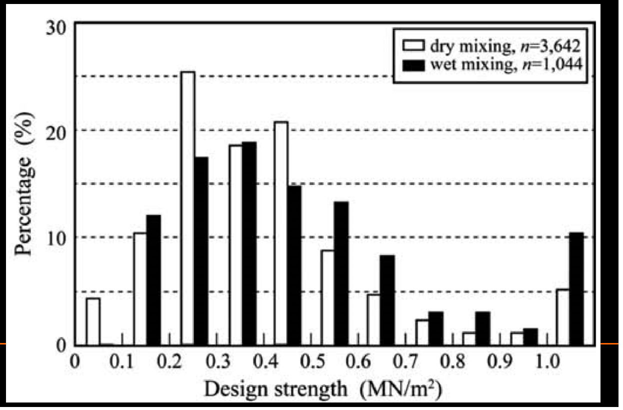
Material	γ (kN/m³)	E (kN/m²)	ν	C (kN/m²)	ϕ (deg)
Embankment	19.6	29,900	0.3	0	35
Sand Fill	18.1	12,000	0.33	0	30
Soft Clay	15.1	$200s_u$	0.45	*	0
Dense Sand	22.0	47,900	0.26	0	40
Columns	15.1	207,000	0.45	689	0

*Strength of soft clay varies with depth.

Numerical simulations of the embankment supported by a group of individual cement column.
Filz and Navin (2006) and Adams et al. (2009)

Design UCS values

- In the United States, the 28 day to 56 day UCS for deep cement mixing projects ranged from about 0.7 to 2.1 MPa.
- Statistics of deep mixing improved grounds in Japan compiled by the Public Works Research Center in 2004 showed that most of the project specified 28 day UCS is < 1 MPa. (see figure)



Design UCS values

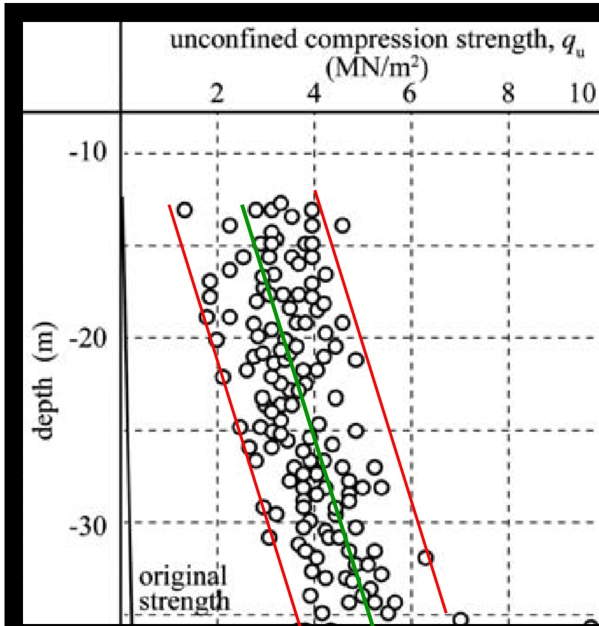
- How about the design UCS values for our local major projects using deep cement mixing?
  - BCF under the HKZM bridge and related project (??)
  - Third Runway project (≈ 0.8 – 1.4 MPa)
  - Tung Chung East reclamation project (≈ 1 MPa)

Variability of Field Strength

- According to the Japanese accumulated data, the Coefficient of Variation (COV) is shown below: (Coastal Development Institute of Technology, 2008).

On land dry mixing	On land wet mixing	Marine wet mixing
50 -68 %	15 – 50 %	20 – 48 %

- According to 7,873 UCS results obtained from different projects carried out in the United States, the COV ranges from 34% to 79% with an average value of 56%



Data from a Japanese project using wet cement mixing under marine condition.

- Strength varies linearly with depth
- Mean strength = 2.5 to 4.5 Mpa. UB/LB = mean ± 1.5 MPa
- COV ≈ 15% - 35%

Differences between lab strength and field strength

Adv of lab specimen : better quality control (e.g. more thorough mixing)

Adv of field product : effects of confinement, potentially higher curing temp.

Coastal Dev. Institute of Technology (CDIT) :

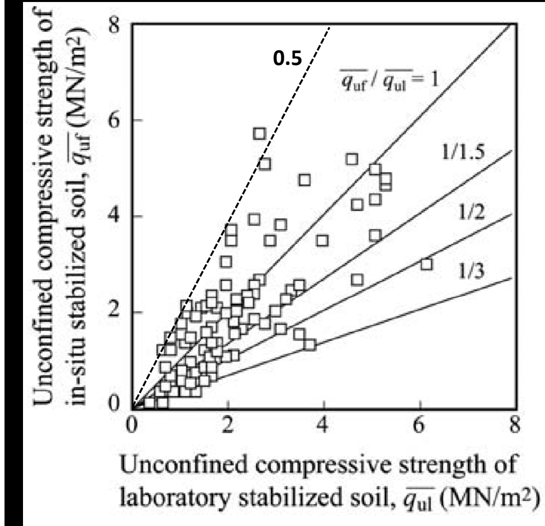
Field strength = 20 – 100 % of lab mixed specimens

EuroSoilStab :

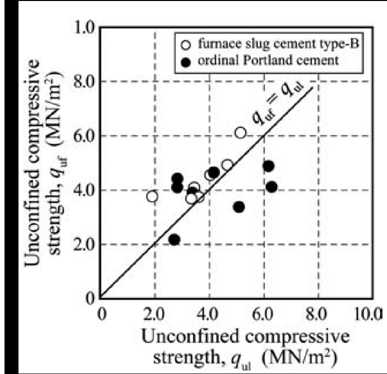
Field strength = 20 - 50 % of lab mixed specimens

FHWA DM :

Field strength = at least 50 % of lab mixed specimens



(a) Stabilized soils of on-land constructions (wet method, clay).

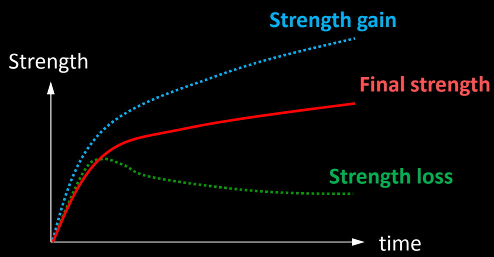


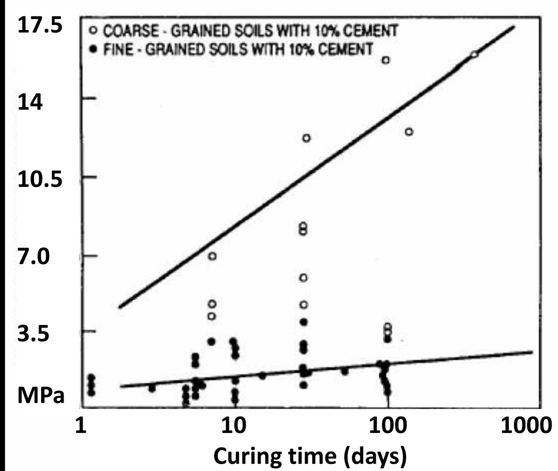
Marine construction (wet mixing) Ref: Coastal Development Institute ofTechnology,2008)

Ref: Public Works Research Center,2004

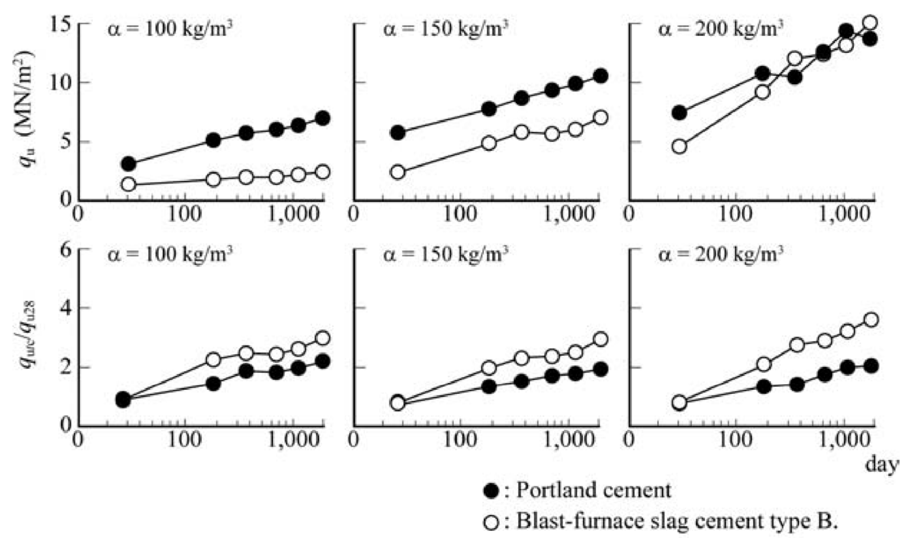
Long Term strength

- Favourable factor – curing
- Unfavourable factor - deterioration in the periphery of the stabilized soil column



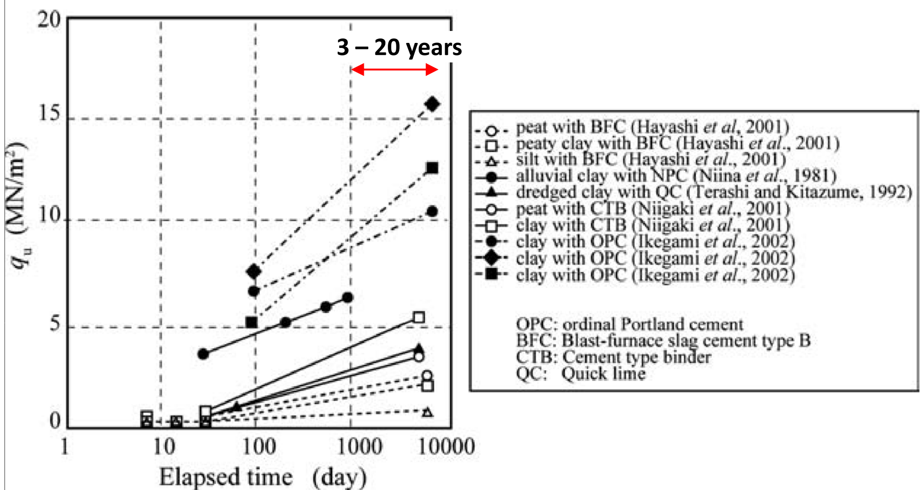


Effect of curing time on unconfined compressive strength of cement treated soils (Mitchell 1976).

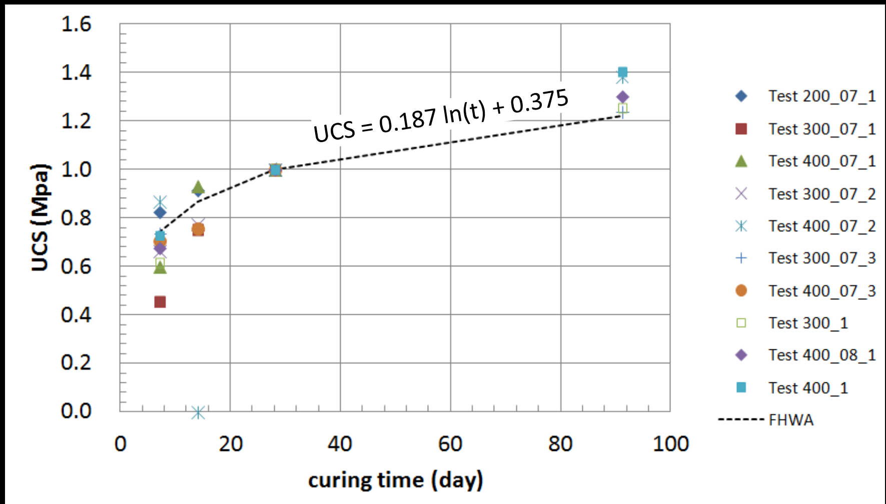


Stabilized Yokohama Port clay.

Ref: Saitoh, 1988

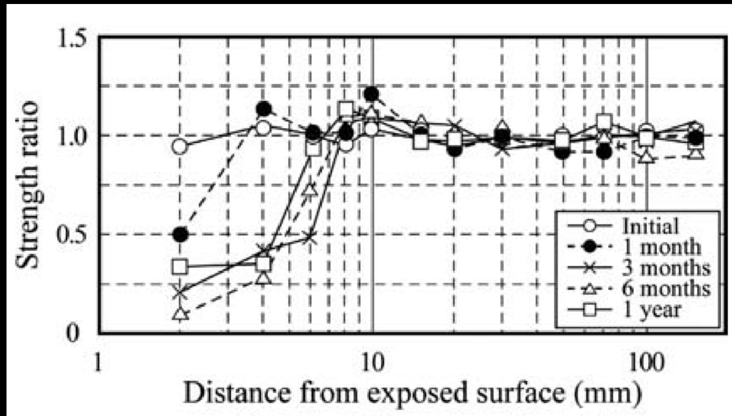


strength of stabilized soil increases almost linearly with the logarithm of elapsed time irrespective of the type of soil, and the type and amount of binder



UCS normalized with 28-day strength
Data from tests conducted in the Public Works Central Laboratory for a local project

deterioration in the periphery of the stabilized soil column

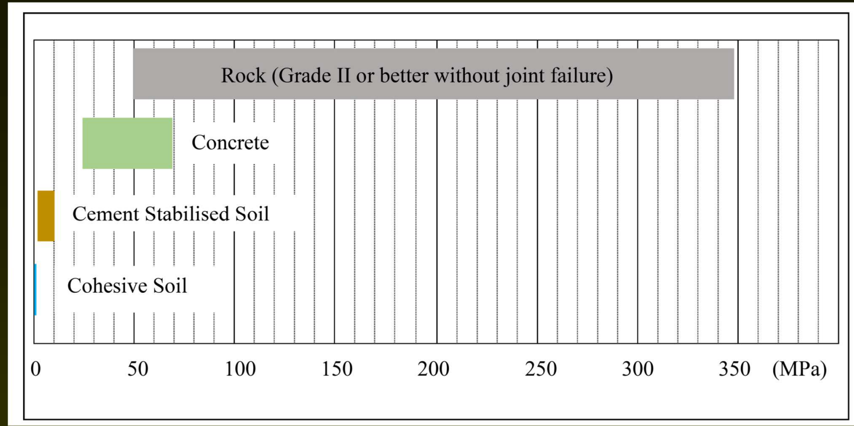


Exposed to seawater

Lab test results. Strength measurement from needle penetration tests.

Ref. Kitazume et al 2003.

Part B - Relevant Testing Standards



Approximate values of UCS of different construction materials

References

Major References

1. BS 1377-7:1990 "Methods of Test for Soils for Civil Engineering Purposes – Part 7: Shear Strength Tests (Total Stress)"
2. BS 1924-2:1990 "Stabilized Materials for Civil Engineering Purposes – Part 2: Methods of Test for Cement-Stabilized and Lime-Stabilized Materials"
3. ASTM D2166/D2166M-16 "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil"
4. CS1:2010 "Construction Standard CS 1:2010 Testing Concrete"

Other References

1. ASTM D2938-95 "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimen"
2. ASTM D7012-14 "Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures"
3. ASTM D4543-85 "Standard Practices for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances"
4. ASTM C42/C42M-03 "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete"
5. Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support. Publication no. FHWA-HRT-13-046. October 2013
6. Kitazume, M. & Terashi, M.: The Deep Mixing Method. 2013.

Part C - RECOMMENDED TEST METHOD

- For cored cement soil specimens tested in the lab, volume of air cannot be totally eliminated
- Cement soil specimens in 63 to 100 mm diameter are commonly encountered
- Cored cement soil specimen can retain a stable shape as concrete cores
- UCS of cement soil specimen ranged between 0.5 MPa to 9 MPa

Scope

- Test method is applicable to cement soil formed in field or in laboratories.
- Diameter of cores is preferably between 63 mm and 100 mm, with UCS values below 10 MPa.

Apparatus

- The machine shall be of **sufficient capacity** to apply load at a **steady** and **suitable** rate of axial deformation
- Mechanical load frames, conventional triaxial test set-up without addition of pressurizing fluid and Universal Testing Machine (UTM) are considered applicable.

Photo credit : FT

Photo credit : PWCL

- Following items should be considered:
  - ✓ Specimen size and strength
  - ✓ Calibration range of built-in or external force and displacement measuring devices
  - ✓ Coaxility of the set-up
  - ✓ Safety measures

See supp slide

Photo credit : FT

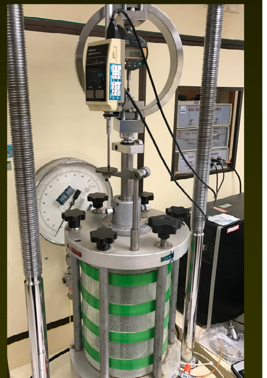


Photo credit : PWCL

Curing

- Development of compressive strength depends, inter alia, on moisture content of specimen and curing environment.
- Stabilised soil is mostly cured below seabed or underground with negligible migration of water.
  - → procedure should be taken to prevent moisture exchange after sampling, during transportation to laboratories and before testing.

a. Cores/specimens should not be curing directly under water.

b. It is recommended to store sealed cores/specimens in a controlled environment (i.e. above 95% of relative humidity and at temperature about 20 – 25 ℃) .

Sample preparation (Length to diameter L/D ratio)

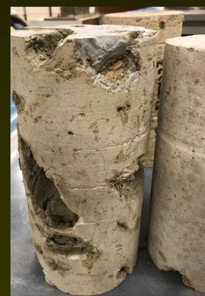
- Several factors (e.g. L/D ratio of specimen, smoothness of platen, end surface condition of specimen etc.) affect friction between specimen ends and the platens
- Typical diameter and L/D ratio

Type	Approx. core/sample size (mm)	L/D
Soil	74 , 100	2*
Concrete	100 , (>75)	1.0 – 1.2 *
Rock	61 , 84	2.0 – 2.5

* L/D = 1.9 - 2.1 in accordance with Geoguide 3 (for UU, CU and CD triaxial tests); length may vary from 8% under-size to 12% over-size in accordance with BS 1377-7:1990 (i.e. equivalent to L/D = 1.84 – 2.24) without significantly affecting the results.

* Smaller ratio is adopted so that measured UCS of concrete core are comparable with concrete cube.

- Cement soil extracted from ground are usually not continuous over a sufficient length, containing intermittent voids and imperfections
- There are possible constraints of headroom for placing specimens in the loading system (e.g. triaxial set-up)



Considering practicability and UCS test results collected so far,

- L/D ratio of 2 is recommended
- Specimen with L/D ratio between 1.5 (inclusive) and 2 can be tested provided that lubricated ends are provided and correction factors recommended by FHWA (2013) is applied to measured UCS
- ASTM C42-03 recommends a height correction for L/D < 2 :

L/D	2.00	1.75	1.50	1.25	1.00
Correction Factor	1	0.98	0.96	0.93	0.87

** Values not specified in the table can be determined by interpolation*

FHWA. (2013). Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support (Publication No. FHWA-HRT-13-046). Federal Highway Administration, U.S. Department of Transportation, 2013.

Sample Preparation (Checking of Flatness, Perpendicularity and Parallelism)

- Test data show that flatness, perpendicularity and parallelism will affect UCS values of rock cores.
- Large deviation in flatness, perpendicularity and parallelism will cause various problems in triaxial test, e.g. sitting errors and additional moment induced on specimen.
- Considering the strength of cement soil ranging between soil and rock, requirement on flatness, perpendicularity and parallelism should be checked.

Testing Standards	Materials	Requirements: Flatness tolerance for the prepared end surface	Requirements: Perpendicularity tolerance for prepared end surface with respect to the axis	Requirements: Parallelism tolerance for the prepared end surface
BS 1377-7:1990	Cohesive soil	Nil	Nil	Nil
ASTM D2166M-16	Cohesive soil	Nil	Nil	Nil
BS 1924-2:1990	Laboratory mixed cement stabilised material [(1)]	< 0.03 mm	< 1 mm in 200 mm	Nil
BS EN 12390-1:2012	Concrete	< 0.06% of specimen diameter	< 0.7% of specimen diameter	Nil
ASTM C39/C39M-17a	Concrete	< 0.05 mm	< 1 mm in 100 mm	Nil
CS1:2010	Concrete	< 0.06% of specimen diameter	< ± 1.0 mm	< ± 2.0 mm
ASTM D4543-85 [(2)]	Rock	< 0.025 mm	< 0.43% of specimen diameter	Nil

Note: (1) Requirements on specimen from drilled cores are not specified.
(2) Both ASTM D2938-95 and ASTM D7012-14 refer to ASTM D4543-85 for preparation of rock specimen.

Sample Preparation (Checking of Flatness, Perpendicularity and Parallelism)

- Considering the strength of cement soil, it is recommended to adopt the requirements in CS1:2010.
- Orientation of measurements can be slightly adjusted to avoid soft spots or surface irregularities.

15.5.3 Tolerances

The tolerances of the prepared specimen shall be as follows:

(a) **Flatness**. The flatness tolerance for the prepared end surfaces shall be ± 0.06 % of the core diameter, in millimetres.

(b) **Perpendicularity**. The perpendicularity tolerance for the prepared end with respect to the axis of the specimen as datum axis shall be ± 1.0 mm.

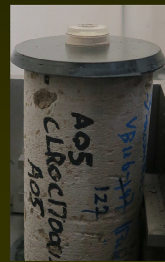
(c) **Parallelism**. The parallelism tolerance for the prepared top surface with respect to the bottom surface of the specimen as datum face shall be ± 2.0 mm.

Sample preparation (Cutting)

- To facilitate the compliance of flatness, perpendicularity and parallelism, rock saw cut is found satisfactory in preparing a cylindrical soil cement specimen
- The rock saw cut facility must be properly set up, including the necessary safety measures

Sample preparation (Capping)

- There are pros and cons of using end caps
  - Provide a smooth, parallel and uniform bearing surface to avoid stress concentration at undue surface
  - Have difficulty to select a capping compound with matched deformation and strength characteristics
  - Quality affected by workmanship and skill of technicians
- End caps should only be used as a last resort, e.g. specimen could not be tested without capping
- Reference can be made to CS1:2010 for the materials and preparation of end caps.



Loading rate

- Loading rates specified under various standards :

Testing Standards	Materials	Loading Rate	Remarks
BS 1377-7:1990	Cohesive soil	≦ 2 %/min	Strain rate control
ASTM D2166M-16	Cohesive soil	0.5 – 2 %/min (1)	Strain rate control
BS 1924-2:1990	Cement stabilised soil	1 mm/min (2)	Strain rate control
BS EN 12390-3:2009	Concrete core	0.6 ± 0.2 MPa/s	Stress rate control
ASTM C39/C39M-17a	Concrete core	0.25 ± 0.05 MPa/s	Stress rate control
CS1:2010	Concrete core	0.2 – 1.0 MPa/s (3)	Stress rate control
ASTM D2938-95	Rock core	Rate that can produce failure in a test time between 2 and 15 min (4)	Stress rate or strain rate control
ASTM D7012-14			

Note:
(1) Time to failure should not exceed about 15 minutes.
(2) For specimen height of 100 to 200 mm, strain rate is around 0.5-1%/min.
(3) For concrete cube and concrete cylinders, CS1:2010 specifies a stress rate of 0.6 ± 0.2 MPa/s in compressive strength test.
(4) Strain rate control is usually used in Hong Kong and a typical value is around 0.18 mm/min.

Loading Rate

Preliminary and trial study was carried out to evaluate the effect of strain rates of test on UCS values:

- Soil was obtained from Chap Lap Kok (Moist light grey CLAY)
- Specimens were prepared in accordance with Japanese laboratory Mix Test Procedure (Kitazume & Terashi, 2013)
- Height of 50mm and with length of 110mm
- OPC content : 300 kg/m^3
- Water cement ratio : 0.7
- Bulk density of specimen : 1.55 Mg/m^3

- A total of 6 specimens were prepared and subject to 3 different loading rates after specimens were cured for 7 days
- The results are shown below:

Loading Rate	1 mm/min				0.1 mm/min	10 mm/min
UCS (MPa)	1.05	0.99	0.83	1.06	**0.98**	**1.12**
	Average = **0.98**					

Note: Specimen height = 110 mm, hence 1 mm/min = 0.9%/min

- **Effect of loading rates** on measured UCS values was **not significant**.
- Rate of axial strain is recommended to be within 0.5 – 2% /min.

Calculation, plotting and reporting of results

Area correction

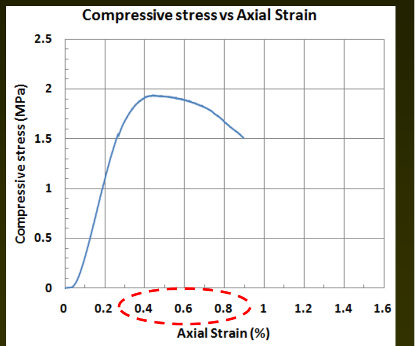
- Normally required for soils (especially very soft cohesive soils)
- Normally not required for concrete and rock

- Soil cement normally fails in a brittle manner with small failure strain (commonly < 1%), area correction is not as critical as in soils.
- To cater for testing of potentially weak specimens (e.g. specimen with short curing time, low cement content), area correction factor is recommended routinely.
- Assume specimen deforms as a right cylinder, the axial compressive stress, σ_1, in the specimen for each set of readings is calculated:

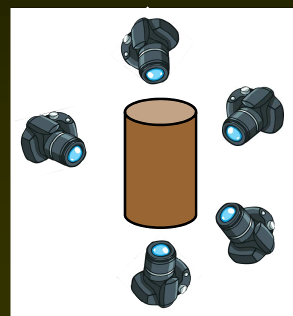
$$\sigma_1 = \frac{P(1-\epsilon)}{A_0}$$

Unconfined Compressive Strength

- Maximum value of compressive stress which the specimen can sustain
- Monotonic hardening behavior was not observed in UCS test results collected from local projects
- To cover these type of specimens, it is recommend to terminate the test:
  - Compressive stress drops to 2/3 of maximum value, or
  - Axial strain reaches 15%, or
  - At a stress level specified by the designer



- Adequate photos to show the appearance and condition of each specimen before and after test.
- To provide more information to designer to assess the quality of cement mixing works (e.g. condition of voids and cracks), it is recommended to take photo in every 120 degree and two end surfaces before test.
- To show the mode of failure, taking photos after tests are recommended.



Conclusion

- Background of developing guidelines on UCS test of cement soil
- Salient features of the Interim Guidelines
  - ✓ Scope
  - ✓ Apparatus
  - ✓ Curing
  - ✓ Sample preparation (L/D ratio, Cutting, Capping, Checking)
  - ✓ Loading rate
  - ✓ Calculation, plotting and reporting of results

Future Works

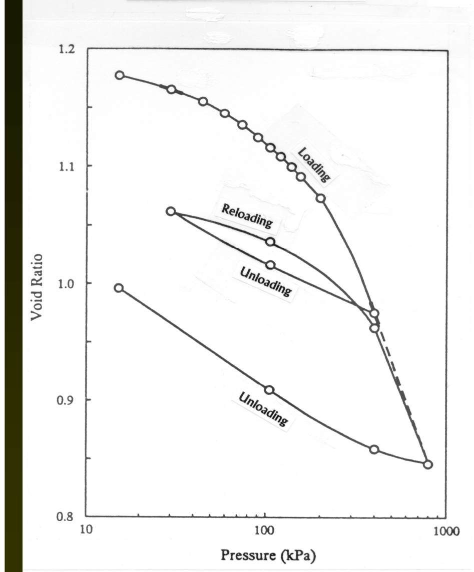
- Endeavour to collect more test data and undertake a review for enhancing the guidelines
- Following issues are suggested to be further reviewed and studied:
  - ✓ Effect of loading rate
  - ✓ Effect of L/D and capping
  - ✓ Effect of curing (duration and temperature)
  - ✓ Stress strain behaviour
  - ✓ Measurement and interpretation of elastic modulus

Thank You…

Question and Answer…

SUPPLEMENTARY SLIDES

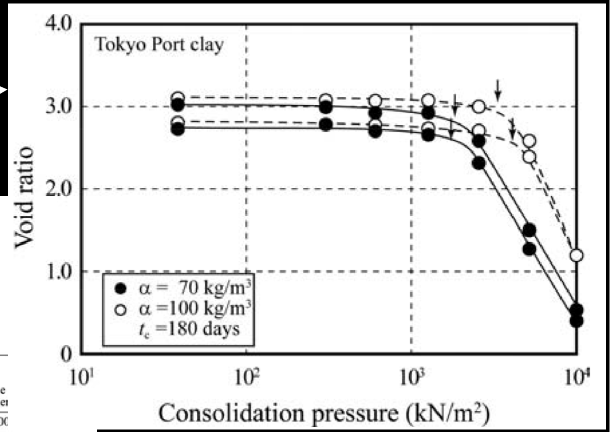
e-log σ plot from Oedometer test

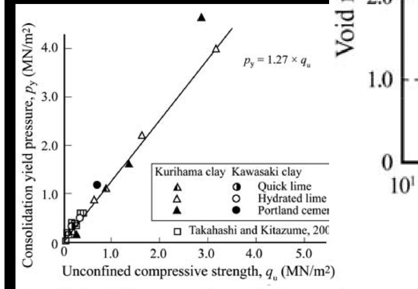


A firm dark grey SILT/CLAY taken from Chek Lap Kok Formation 25m below the new airport platform (49% silt + 51% clay) (LL = 53%, PL = 26%, w_o = 45%)

A e – log σ´plot for a SILT/CLAY procured from Chek Lap Kok formation 25m below the new airport platform

A e – log σ´plot for a cement stabilized clay





Consolidation yield pressure and unconfined compressive strength (Terashi *et al.*, 1980; Takahashi and Kitazume, 2004).

Consolidation yield pressure is found to be very close to the UCS values

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Ref: (Kawasaki et al.,1978)

Load cell or proving device		
Capacity (kN)	Max. stress (for 100 mm specimen) (MPa)	Remarks
10	1.27	Note minimum calibrated load
20	2.55	
30	3.82	

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END