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The Chemical-Physical Combined Method for Improving Clay Slurry in Land Reclamation

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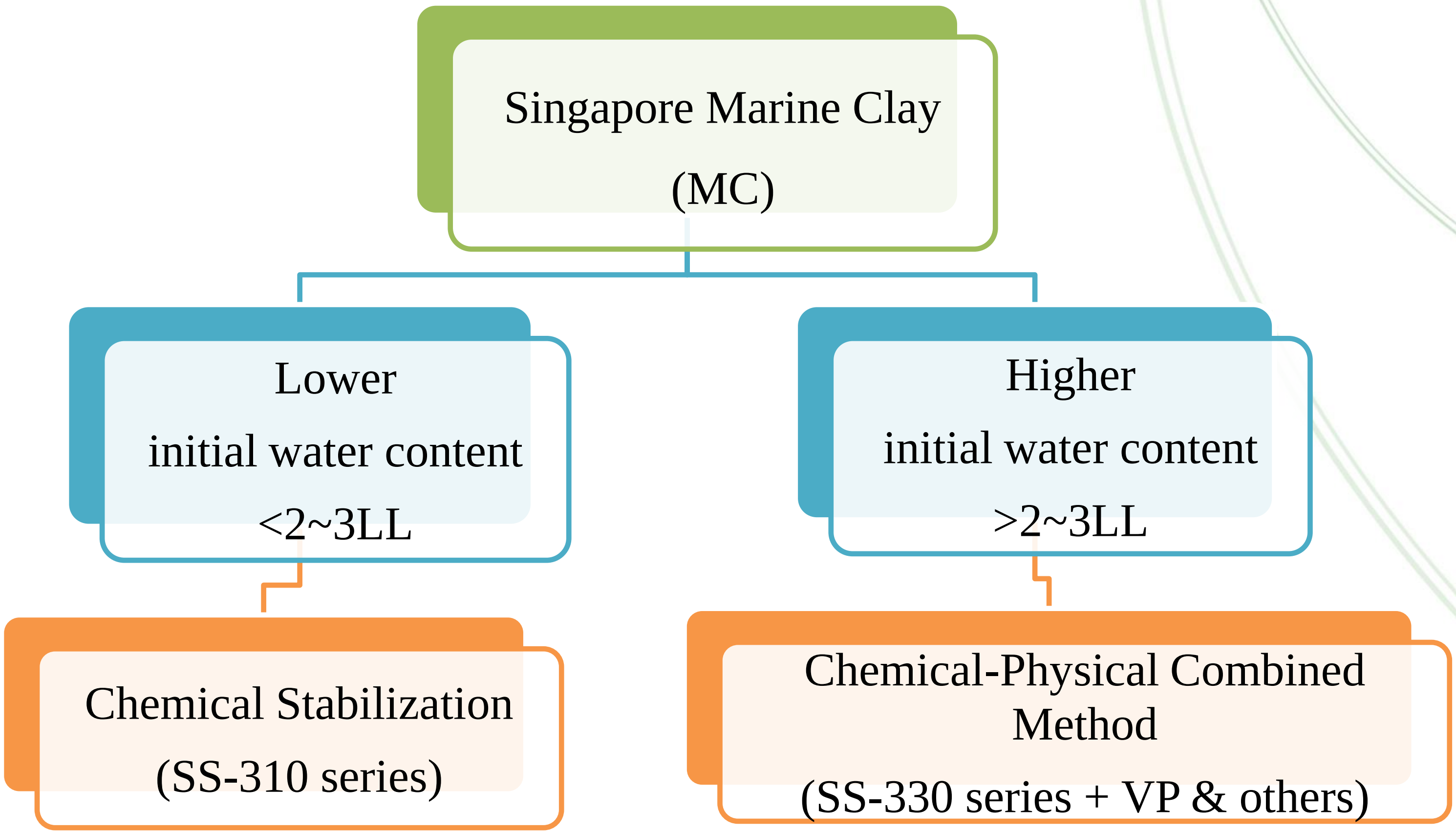
List of Content

Introduction

- Demanding on reclaimed land for fast economic development seems higher and higher, especially in China and South East Asia region.
- Utilizing the dredged or excavated marine clay for land reclamation becomes more popular and the way is economical, green and eco-friendly.
- Vacuum preloading incorporated with vertical drains is the most commonly-used method to improve such very soft ground, but with limited ultimate bearing capacity (6-8 t/m^2). Further soil strengthening may have to be applied.
- Limited study and application on the Non-Linear Finite Strain (NFS) Consolidation of very soft soils to monitor and predict such consolidation with large deformation.
- Few successful chemical stabilization engineering practice for improvement of soft marine clay, except a reclaimed land for an international airport in Japan in early 2000s.
- No theory and application of combining both chemical stabilization and physical treatment for such very soft ground have been found before this paper.

Introduction



Clay Slurry Improved by VP

- The general range of LL for Singapore MC is around 50% to 95% and its plasticity index (PI) around 30% to 65% (Arulrajah and Bo 2008).

- In our study, two types of Singapore MCs were used as follows:

Table 1: Typical Basic Properties of Singapore Marine Clay (MC)

No	Properties	MC-I	MC-II
1	Specific Gravity, G_s	2.66	2.66
2	Natural Water Content, w	60%	54%
3	Liquid Limit, LL	79%	57%
4	Plastic Limit, PL	34%	27%
5	Plasticity Index, PI	45%	30%
6	Organic Content	3.8%	4.5%
7	Grain Size Distribution		
	a) Sand	3%	4%
	b) Silt	48%	45%
	c) Clay	49%	51%

Clay Slurry Improved by VP

- 3-D consolidation tests device

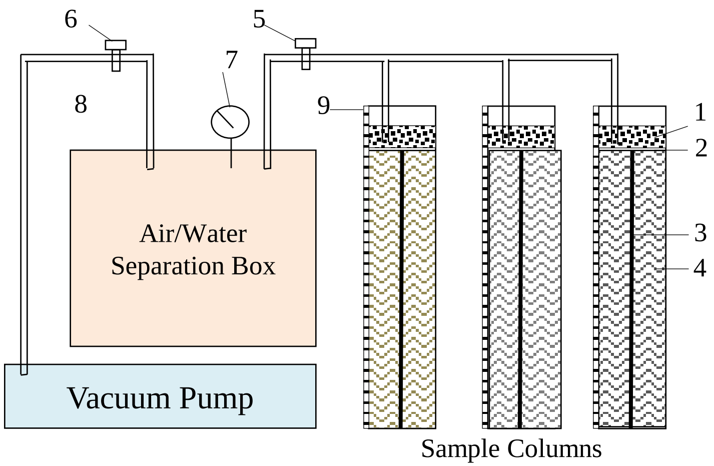


FIG. 1a. 3-D NFS Consolidation Test by VP (1: Sand; 2: Geotextile; 3: Vertical drain; 4: Clay samples; 5: Pressure control valve; 6: Vacuum control valve; 7: Pressure Meter; 8: Tubes; 9: Ruler.)

- Clay slurries at different initial water contents: 1.4LL, 2.0LL, 3.0LL and 4.0LL
- To simulate field situation: a slurry sample at 4.0LL was soaked under sea water for a month
- The fall cone test was selected to determine the undrained shear strength (Cu).

Clay Slurry Improved by VP

➢ Achieved Cu value vs. initial water content

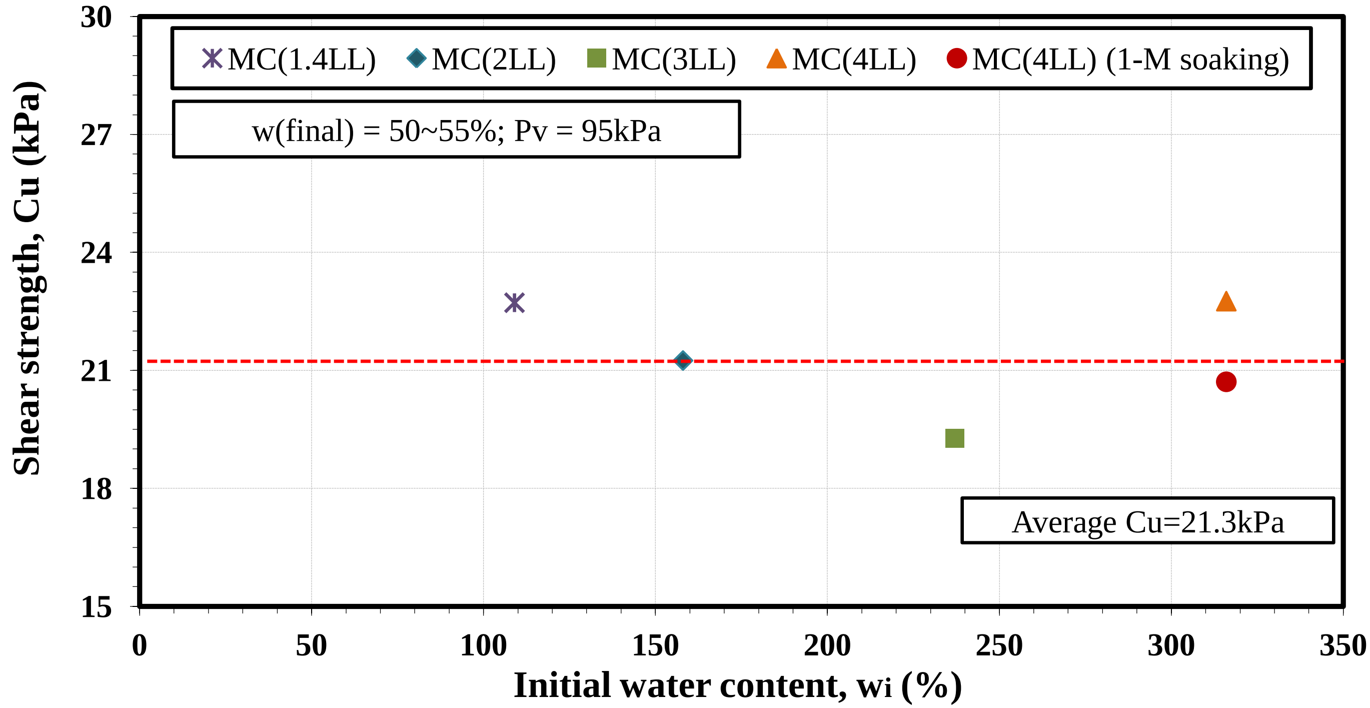
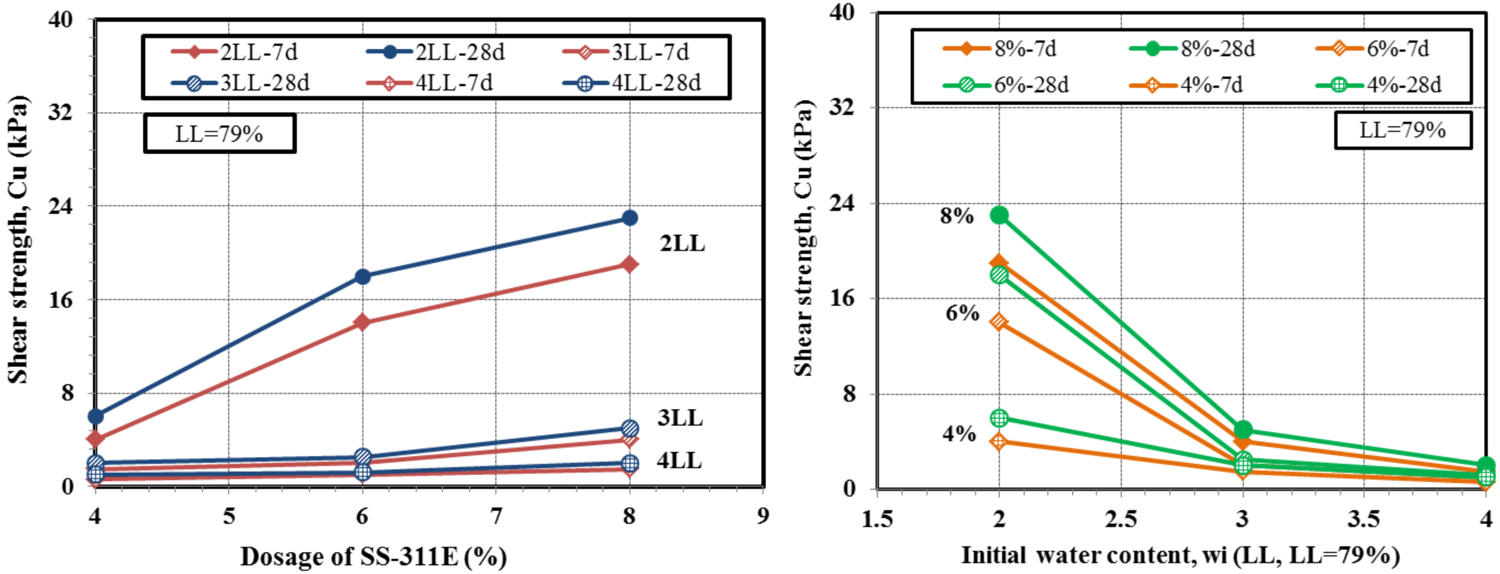


FIG. 1b. Results of 3-D NFS Consolidation for Pure Marine Clay Slurry

- The final water contents: 50% to 55%
- The Cu values achieved are quite close; average is about 21kPa
- There is not much difference between the soaked and un-soaked pure MCs.

Chemical Stabilization for Clay Slurry

- The sub-series products SS-311E & H were selected for chemical stabilization tests
- Initial water contents: 2LL, 3LL and 4LL
- Chemical dosages: 4%, 6% and 8% (% by dry soil weight)



(a) Effect of dosage of SS-311E (b) Effect of initial water content

FIG. 2. Affecting factors on Cu at different curing time

- Lower initial water content, higher Cu value; higher dosage, the higher Cu value
- Cu value increases as the curing time increases
- The chemical stabilization looks quite effective for lower initial water content (especially <2LL) but is ineffective for higher initial water content (>3LL).

Chemical Stabilization for Clay Slurry

- Cu value achieved with different initial water contents and chemical dosages

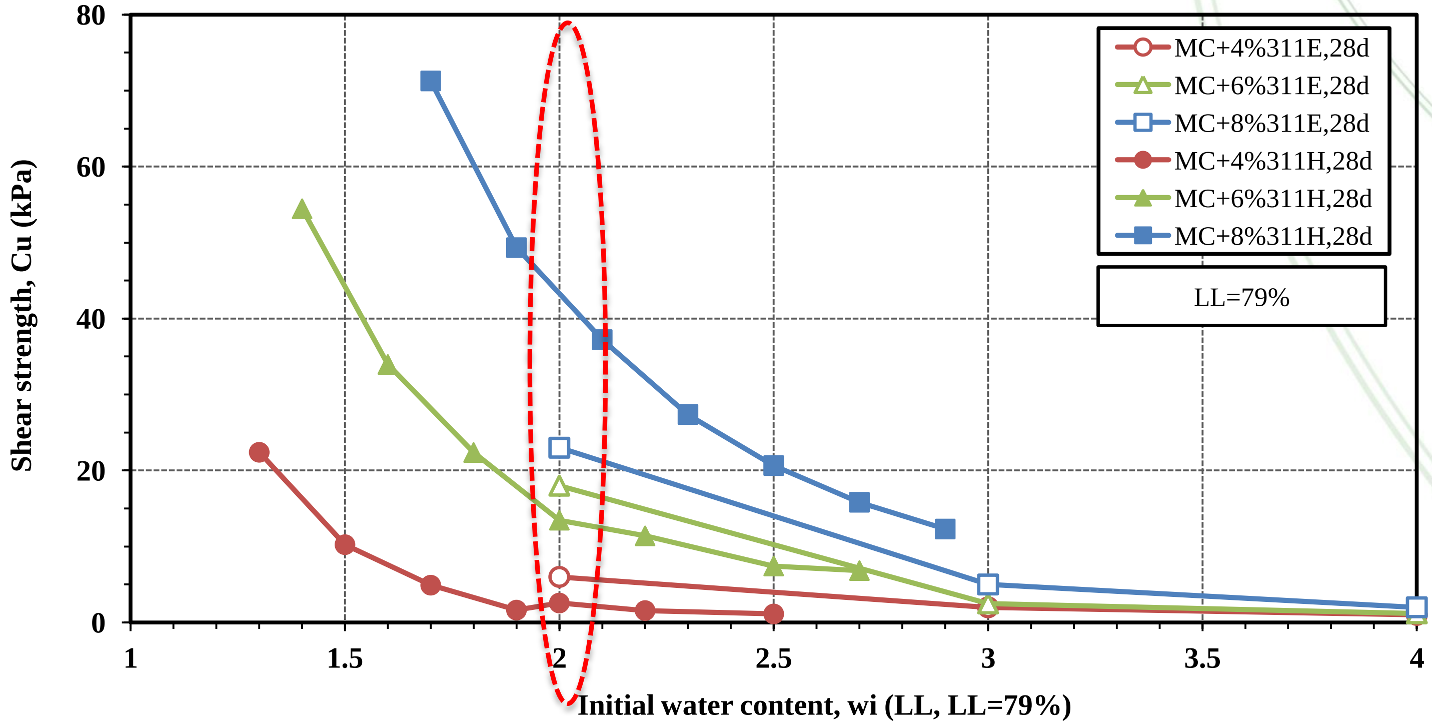


FIG. 3. Cu achieved with different initial water contents and chemical dosages

- 2LL could be the turning point to identify the applicable range of the chemical stabilization
- Further investigations were thus concentrated on more samples with the initial water content not higher than 2LL

Chemical Stabilization for Clay Slurry

- Investigation of the stabilization effectiveness of each chemical binder

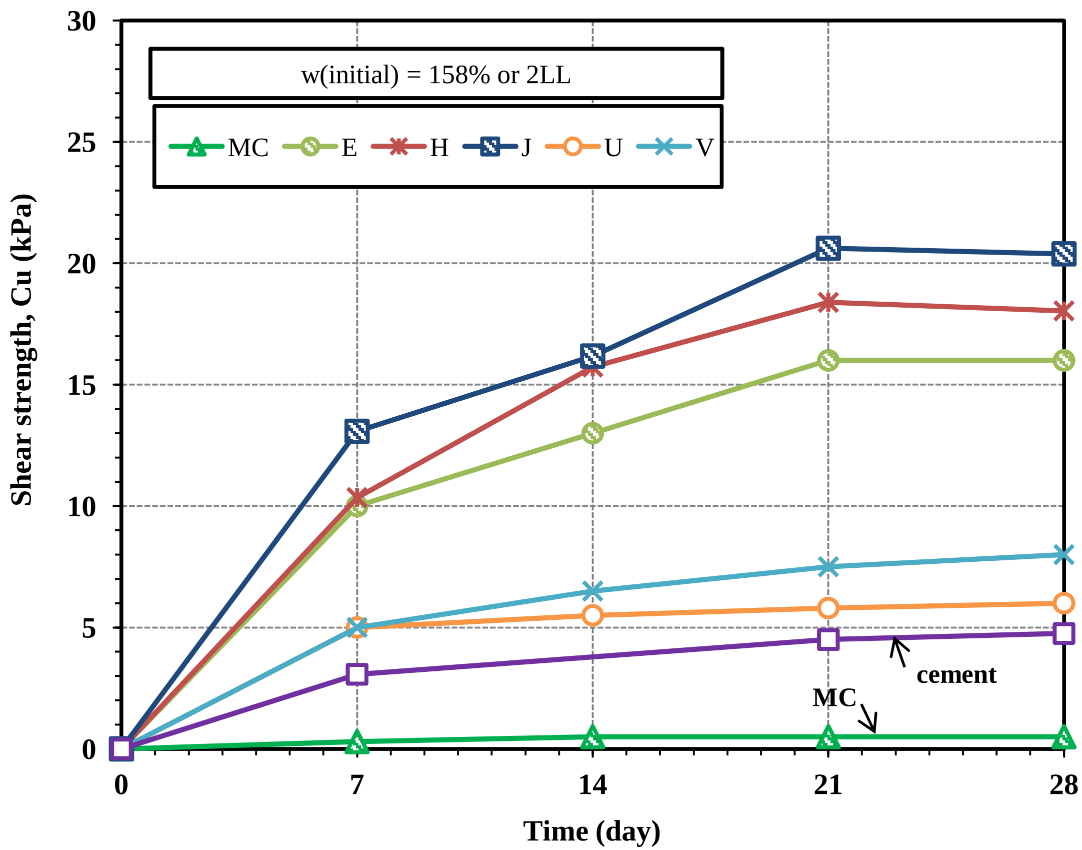


FIG. 4. Cu vs. curing time (a) Cu by SS-311 binders and cement

- Initial water content = 2LL
- 6% chemical stabilizers for marine clay: SS-311 sub- series and cement
- Cement stabilization: very poor at 28 days.
- The Cu values stabilized by SS-311 series: encouraging and the average Cu achieved is around 18~20kPa at 28 days.

Note: In (a), E: MC+311E; H: MC+311H; J: MC+311J; U: MC+311U; V: MC+311V; cement: MC+cement.

Chemical Stabilization for Clay Slurry

➢ SS-311H was selected for the long-term tests and pure MC as a testing reference

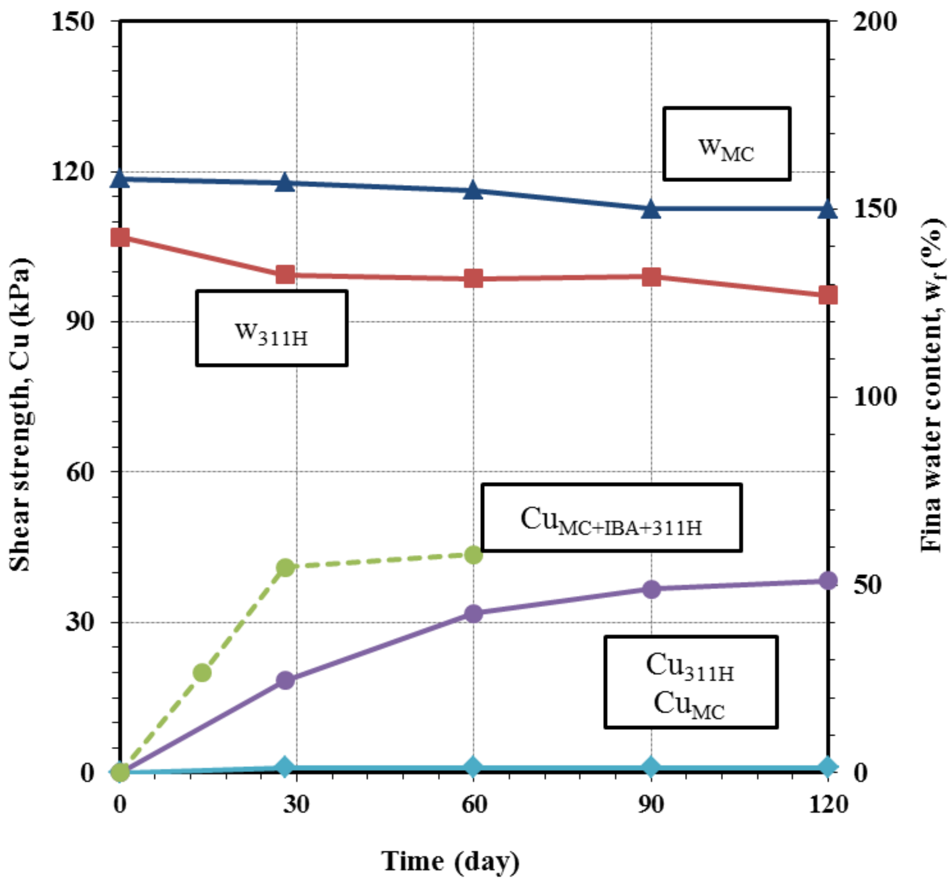
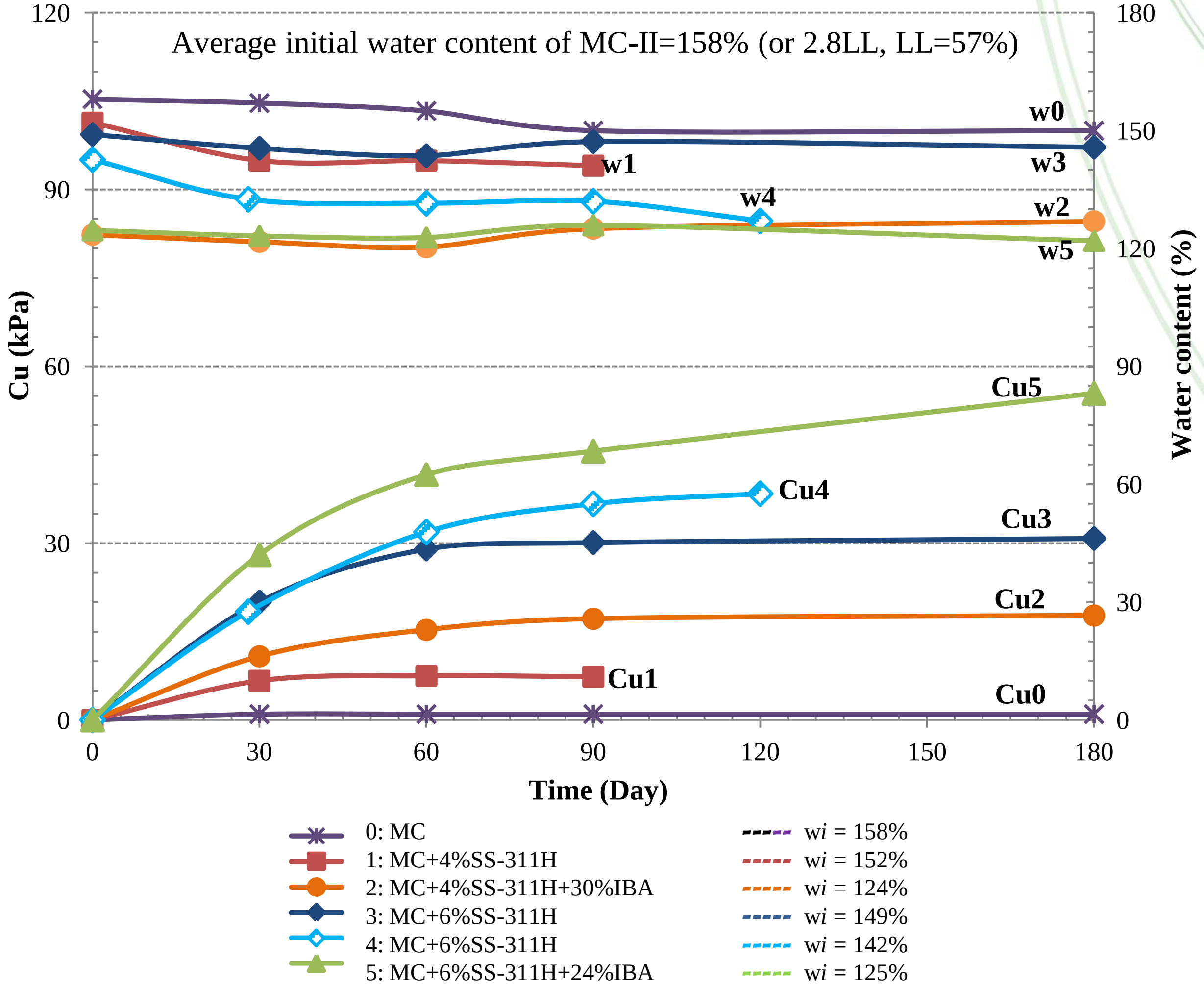


FIG. 4. Cu vs. curing time (b) Cu and water content vs. time

- Cu: continuously increase to 40kPa at 120 days
- The estimated ultimate bearing capacity: around 200kPa or $20t/m^2$
- The shear strength of the pure MC remains as almost zero.
- The water content of stabilized MC: reduced more because of introduction of the powder chemical
- Even with the 2LL or 158% initial water content, the MC stabilized by chemical can still achieve significant high shear strength.
- As curing time increases, the Cu value has a trend to increase further.

Chemical Stabilization for Clay Slurry

- Updated results of MC-II mixture stabilized by SS-311H after 6 months



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Chemical Stabilization for Clay Slurry

- Summary of strength and water content of three samples at different curing days

No.	Sample	30-day		60-day		90-day		180-day	
		Cu (kPa)	w (%)	Cu (kPa)	w (%)	Cu (kPa)	w (%)	Cu (kPa)	w (%)
1	MC+4% SS-311H+30%IBA	10.8	121.7	15.29	120.33	17.18	125.06	17.72	126.9
2	MC+6% SS-311H	20.02	145.5	32.82	143.59	30.1	147.19	30.8	145.76
3	MC+6% SS-311H+24% IBA	28.03	123.17	41.62	122.77	42.73	125.88	55.42	121.9

- Sample 1 and 2 (MC+4% SS-311H+30%IBA and MC+6% SS-311H) show stable strength from the period of 90 days to 180 days.
- Due to on-going chemical reaction, sample 3 (MC + 6% SS-311H + 24%) still shows significant increasing trend of strength from 90 days to 180 days : 42.73 kPa to 55.42 kPa.
- Water content values for all three samples are relatively stable throughout the testing period.
- Sample 3 (MC + 6% SS-311H + 24% IBA) does not follow traditional soil behaviour: though water content is stable, the strength increases.
- Improvement using Chemical Method (SS-311H) and also the addition of IBA is an effective way of increasing strength of pure MC.

Chemical-Physical Combined Method (CPCM)

➢ A large number of in-house tests using the 3-D consolidation cells were carried out to verify the effectiveness of CPCM on improvement of MC with higher initial water content.

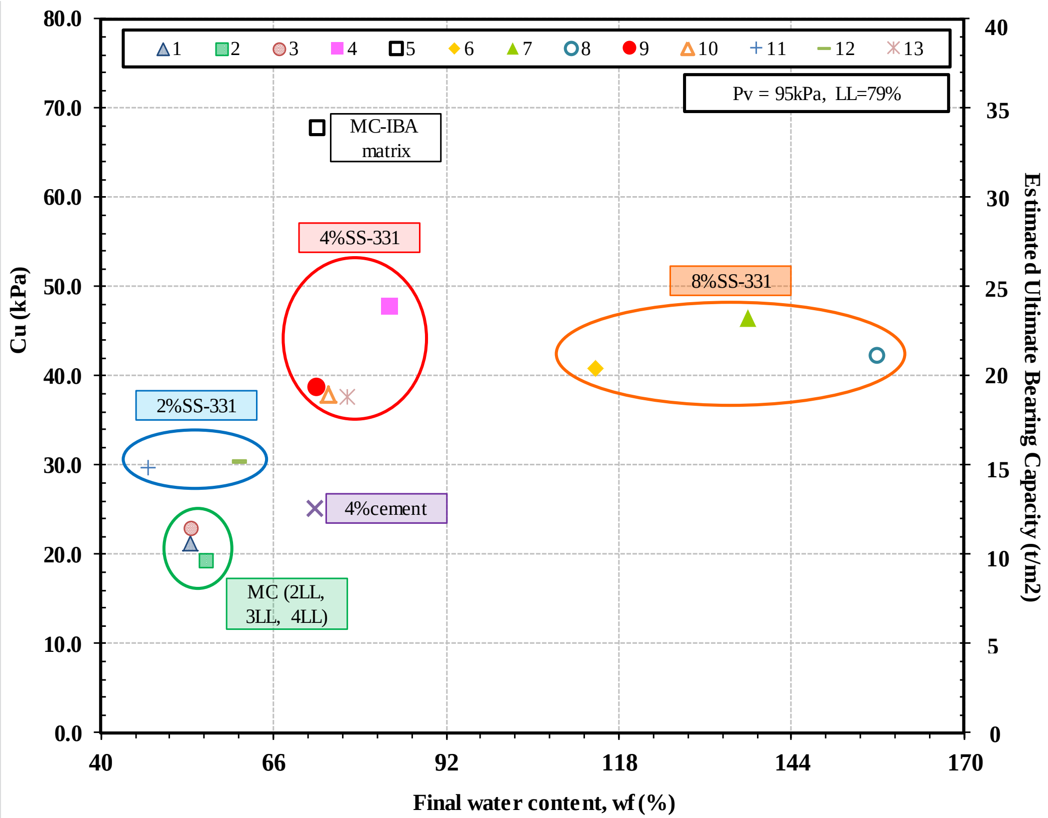

FIG. 5a. Testing results of Singapore MC by CPCM

- Singapore MC with different initial water content at 2LL, 3LL and 4LL has been used for tests.
- The average Cu value of pure MC achieved by VP is 21kPa which is used as the reference.
- The Cu values achieved after CMCP with the selected chemical binders are generally 2 to 3 times of that of pure MC under VP only.
- It proves that CPCM can achieve much higher strength than what vacuum preloading does.
- Though the initial/final water contents have big differences, the final strength looks quite closer.

Note: 1: MC(2LL); 2: MC(3LL); 3: MC(4LL); 4: MC(2LL)+4%331E(6-M soaking); 5: MC(2LL)+4%331E+20%IBA(6-M soaking); 6: MC(4LL)+8%331D(1-M soaking); 7: MC(4LL)+8%331E(7-M soaking); 8: MC(4LL)+8%331H(1-M soaking); 9: MC(4LL)+4%331H; 10: MC(3LL)+4%331H; 11: Column, MC(200%)+2%SS-331H(1-M soaking); 12: Column, MC(270%)+2%SS-331H(1-M soaking); 13: Column, MC(270%)+4%SS-331H(1-M soaking).

Chemical-Physical Combined Method (CPCM)

- The final water content and its corresponding dry density were investigated (Fig. 5b).

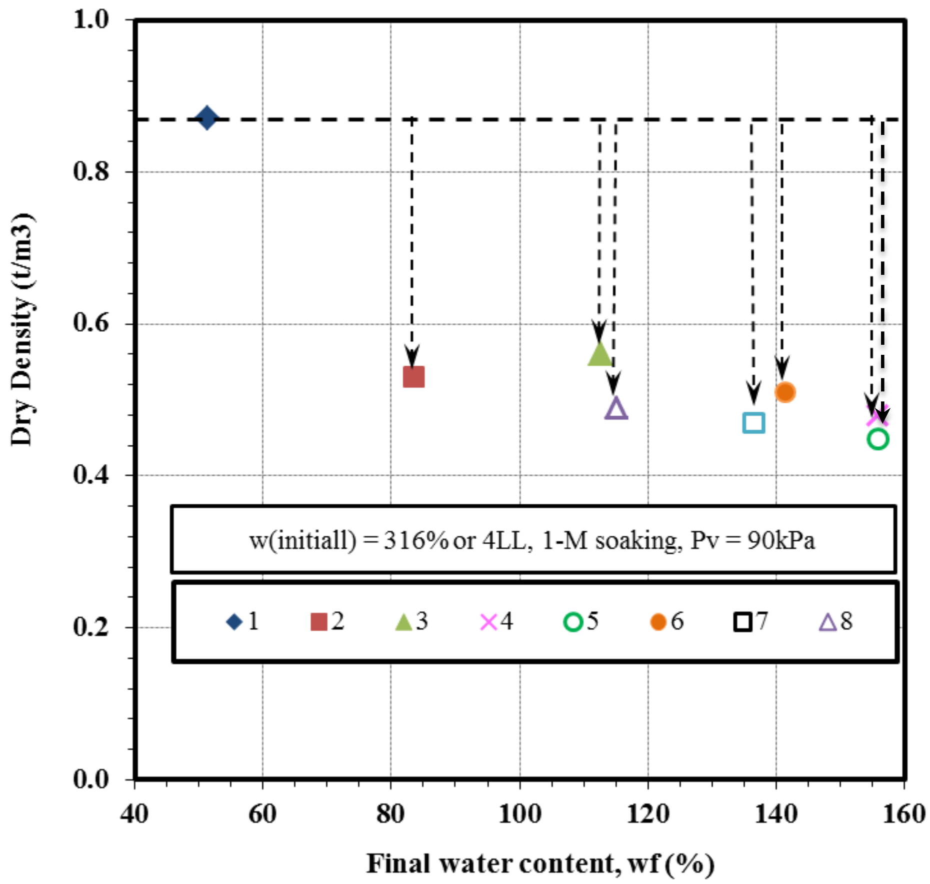

FIG. 5b. Testing results of Singapore MC by CPCM

- The higher dosage applied the higher final water content remained and lower dry density is resulted.
- This behaviour indicates a fact that the original MC has lost its original characters and developed to be a new structure with new chemical and physical properties under chemical reaction and physical compaction.
- This transformed soil has light-weight but higher strength, which is greatly different from conventional understandings on consolidation of natural soils and may have great potential impacts to both technical and commercial aspects.

Note: 1: MC; 2: MC+4%331H; 3: MC+6%331H; 4: MC+8%331H; 5: MC+8%331A; 6: MC+8%331B; 7: MC+8%331C; 8: MC+8%331D

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Chemical-Physical Combined Method (CPCM)

- In addition, a higher figure of the higher Cu value (>65kPa) can be seen in Fig. 5a which was achieved by a MC mixture with additional 20% of IBA (incineration bottom ash) and SS-331E.

- Disregard of environmental and chemical effects of IBA, the higher Cu value resulted by introducing the IBA with sand-size range indicate that at the same conditions, the coarser the mixture, the higher the strength can be resulted.

- A Chinese Zhujiang MC was selected to verify the effectiveness and universal property of CPCM. Its LL, PI and clay content are 50.4%, 25% and 34.5% respectively, which are lower than those of Singapore MC.

- The initial water content of each MC sample was fixed at 4LL. The Cu values achieved are averagely about 2 times of that of pure MC by VP.

- It has proven again that CPCM is capable to achieve much higher strength than what vacuum preloading can and the universal property of applying CPCM is confirmed by different material sources.

- It should be noted that the LL after CPCM has increased for China MC from 50.4% to 55~70% and this change also supports the fact of the new transformed soil after CPCM found with Singapore MC.

Conclusions

1. VP with vertical drains is one of few proven engineering approaches to improve soft clay with higher water content because it has no instability issue.

2. Chemical stabilization is more effectively applicable to Singapore MC when its initial water content is not higher than 2~3LL, and it can achieve 40kPa or higher in shear strength which could be sufficient to the general requirement in bearing capacity for most ordinary foundations.

3. CPCM is a totally new methodology for very soft clay and clay slurry and it has been proven by different MCs to be more effective in increasing the strength of very soft reclaimed foundations; furthermore a new material after applying CPCM has been transformed and this transformed soil has light-weight but with higher strength.

4. Further studies on CPCM in both laboratory- and field-scale have to be conducted in order to investigate the details in mechanism of the chemical-physical reactions, application methodologies, optimized chemical binders and so on with different soil sources.

Acknowledgements

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2. Authors would like to thank NEA for allowing them releasing the data while appreciation also goes to Engineering Technology Research Co., Ltd of CCCC Fourth Harbor Engineering Co., Ltd for testing data sharing.

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THANK YOU!