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Curing Time Effect on Behavior of Cement Treated Marine Clay

H. W. Xiao, and F. H. Lee

Abstract**—**Cement stabilization has been widely used for improving the strength and stiffness of soft clayey soils. Cement treated soil specimens used to investigate the stress-strain behaviour in the laboratory study are usually cured for 7 days. This paper examines the effects of curing time on the strength and stress strain behaviour of cement treated marine clay under triaxial loading condition. Laboratory-prepared cement treated Singapore marine clay with different mix proportion S-C-W (soil solid-cement solid-water) and curing time (7 days to 180 days) was investigated through conducting unconfined compressive strength test and triaxial test. The results show that the curing time has a significant effect on the unconfined compressive strength q_u , isotropic compression behaviour and stress strain behaviour. Although the primary yield loci of the cement treated soil specimens with the same mix proportion expand with curing time, they are very narrowly banded and have nearly the same shape after being normalized by isotropic compression primary stress p'_{py} . The isotropic compression primary yield stress p'_{py} was shown to be linearly related to unconfined compressive strength q_u for specimens with different curing time and mix proportion. The effect of curing time on the hardening behaviour will diminish with consolidation stress higher than isotropic compression primary yield stress but its damping rate is dependent on the cement content.

Keywords**—**Cement treated soil, curing time effect, hardening behaviour, isotropic compression primary yield stress, unconfined compressive strength.

I. INTRODUCTION

CEMENT stabilization has been widely used to improve the engineering properties of the clayey soils (e.g. [1]-[4]). It is well known that there are two major chemical reactions which are induced by the addition of cement to clay and govern the soil cement stabilization process: the primary hydration reaction of the cement and water and the secondary pozzolanic reactions between the lime released by the cement and the clay minerals (e.g. [5]-[6]). The hydration reaction leads to the initial gain in strength because of the formation of primary cementitious products and drying up of the soil-cement mix. The secondary pozzolanic reaction, also termed as solidification, occurs once the pore chemistry in soil system achieves a sufficiently alkaline condition. This occurs when sufficient concentration of OH^- ions is present in the pore water due to the hydrolysis of the lime. The resulting alkalinity of the pore water promotes dissolution of silica and alumina from the clays, which then react with the Ca^{2+} ions, forming calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), which are the secondary cementitious products. These compounds crystallize and harden with time, thereby enhancing the strength of the soil cement mixes.

During treatment period, the curing temperature, stresses, time and humidity affect the strength development of the treated soil. In general, the longer the curing period, the better is the strength development, due to the pozzolanic reaction [5]. It has been shown that the strength increases with curing time irrespective of soil types [7]. Similar test results were obtained with Portland cement or fly ash cement [8]. The curing time effect on the physical properties, unconfined compressive strength and compressibility characteristics of cement treated soils were investigated in the laboratory [2], [9], [10], but most of the studies were based on the unconfined compressive strength test and oedometer test. This paper examines the effects of curing time on the strength and stress strain behaviour under unconfined compression and triaxial loading condition. Laboratory-prepared cement-treated Singapore marine clay specimens with different soil: cement: water (S: C: W) proportions and curing time were investigated.

II. EXPERIMENTAL INVESTIGATION

Singapore Upper Marine Clay and Ordinary Portland Cement (OPC) were used to prepare specimens in this study. The Singapore Upper Marine Clay was obtained from 4 to 5m depth, at an offshore dredge site near Pulau Tekong, Singapore. Its properties have been discussed by Tan *et al.* [11]. The properties of OPC were given by Chin *et al*. [12]. Different mix proportions were used to investigate the effect of curing time on the yielding and hardening behaviour and strength of cement treated marine clay. The mix, that S: C: W, proportions selected for this study (Table I) are fairly representative of the range of water-cement (W:C) and soil-cement(S:C) ratios used in deep mixing and jet-grouting studies and projects involving soft, fine-grained soils, which was given by Lee *et al.* [4].

Before the cement slurry was introduced, the natural soil was remoulded and mixed with the prescribed amount of water to achieve 100% moisture content. Cement slurry with certain water-cement ratio associated with the mix proportion was then added to marine clay in a Hobart Mixer and mixed with a rotational speed of 125rpm for around 10 minutes.

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After mixing, the mixture was placed into a cylindrical PVC mould with a diameter of 50mm and a height of 100mm. The sample preparation procedure is similar to that reported by Chin *et al*. [12]. The specimens were cured fully drained under water with cylindrical mould without loading up to 7 days, 28 days, and 90 days respectively. Some specimens were cured up to 6 months. All specimens were trimmed to dimension of 38 mm diameter by 76mm height and tested through triaxil instrument after different curing time. Table I and Table II summarize the configurations and results of the triaxial specimens tested respectively.

TABLE I
SUMMARY OF SPECIMEN TESTED

Mix proportion (s:c:w)	Cement content [a] Aw(%)	Total Water content [a] Cw(%)	Test in this study [b]
10:1:11	10	100	UCT,ICT,CIU,CID
20:3:23	15	100	UCT,ICT
5:1:6	20	100	UCT,ICT,CIU,CID
2:1:4	50	133	UCT,ICT,CIU,CID
1.3:1:3.45	77	150	UCT,ICT
1:1:3	100	150	UCT,ICT
10:1:7.9	10	72	UCT,ICT
6:1:5	17	71	UCT,ICT
4:1:3.6	25	72	UCT,ICT

Aw is the ratio of mass of cement solid to mass of soil solid, Cw is the ratio of otal mass of water to total mass of solid

CIU/CID: isotropic consolidated undraiend/drained compression test,

TABLE II
UMMARY OF TEST RESULTS FOR CEMENT TREATED MARINE CLAY SPECIMENS

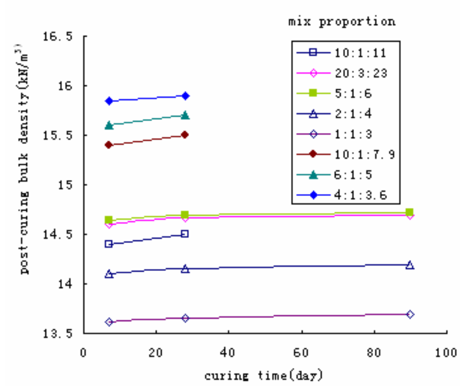
ion	Curing time(days)	p'_{py} (kPa)	G_s [a]	w [a] (%)	γ [a] (kN/m^3)	q_u (kPa)
1	7	135	2.682	93.00	14.40	220
	28	190	/	92.33	14.50	329
3	7	210	2.676	92.82	14.60	320
	28	285	2.671	91.08	14.67	512
	90	385	2.667	90.43	14.69	640
	7	260	2.67	91.06	14.65	412
	28	370	2.665	85.47	14.84	619
	90	480	2.66	80.09	15.03	812
	180	535	/	79.85	15.15	896
	7	240	2.65	107.96	14.10	385
	28	360	2.645	83.73	14.85	650
	90	450	2.64	78.84	15.05	818
	180	525	2.638	67.02	15.59	915
3.45	7	250	2.641	124.62	13.49	439
	28	350	/	122.34	13.53	618
	7	300	2.63	122.54	13.62	478
	28	525	/	119.65	13.65	927
	90	600	/	117.90	13.69	998
0:1:7.9	7	270	2.682	66.47	15.40	430
	28	/	/	66.03	15.60	651
6:1:5	7	500	2.68	64.73	15.66	844
	28	/	/	64.43	15.80	1066
4:1:3.6	7	600	2.665	63.38	15.85	980
	28	/	/	62.31	15.90	1586

[a] G_s, w, γ is post-curing specific gravity, water content and unit weight of specimen tested respectively.

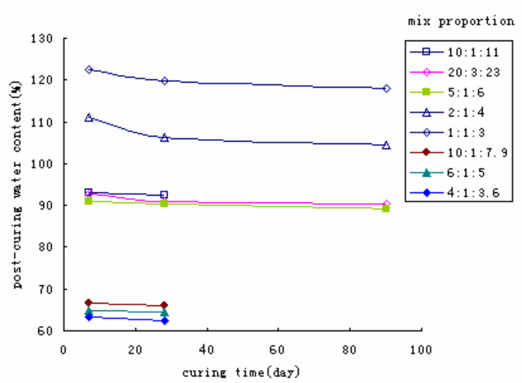
III. TEST RESULTS AND ANALYSIS

A. Physical Properties

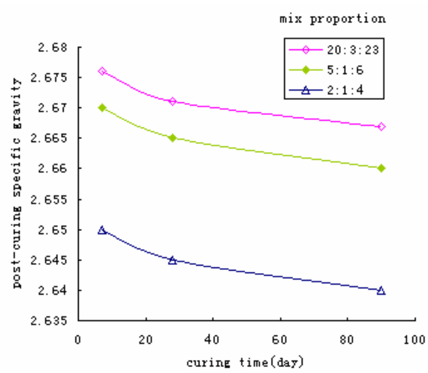
The variation of physical properties including post-curing unit weight, water content, and specific gravity versus curing time for different mix proportion is shown in Fig. 1. As can be seen, the post-curing unit weight increases with curing time while post-curing water content and specific gravity decreases with curing time.



(a) post-curing bulk density versus curing time



(b) post-curing water content versus curing time

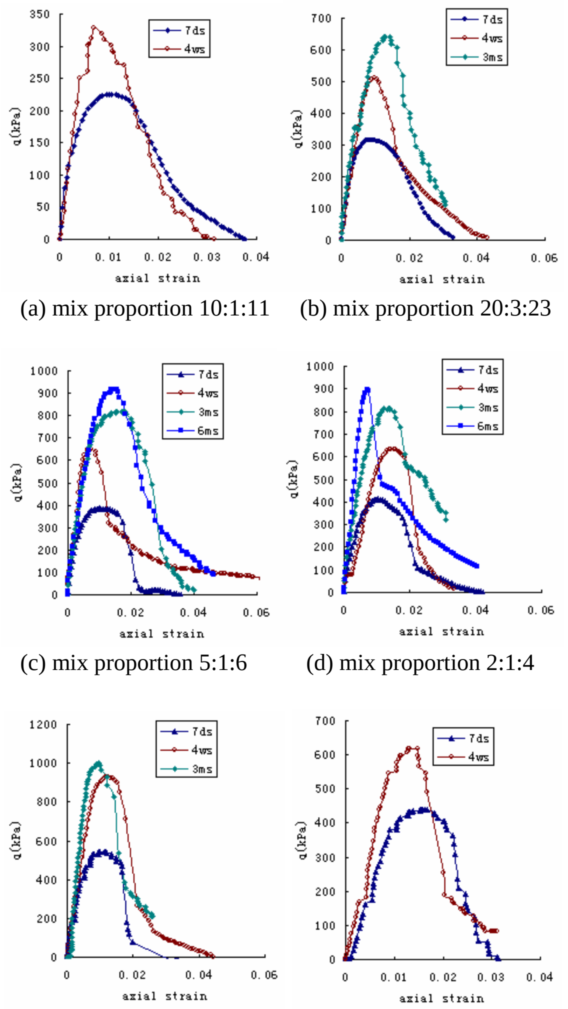


(c) post-curing time specific gravity versus curing time

Fig. 1 Post-curing physical property for specimens with different mix proportion and curing time

B. Unconfined Compressive Strength Test

The results of unconfined compressive strength tests of samples with different curing time and mix proportion are presented in Fig. 2. As this figure shows, the unconfined compressive strength q_u increases significantly with curing time despite of mix proportion. However, the rate of increase after the first 4 weeks is not as high as that before the first 4 weeks.



(a) mix proportion 10:1:11 (b) mix proportion 20:3:23

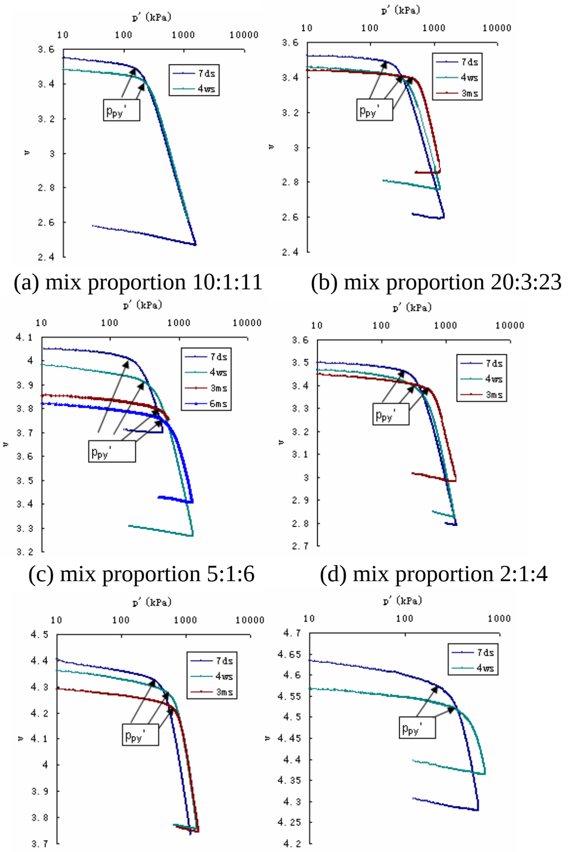
(c) mix proportion 5:1:6 (d) mix proportion 2:1:4

(e) mix proportion 1.3:1:3.45 (f) mix proportion 1:1:3

Fig. 2 Unconfined compressive strength for specimens with different mix proportion and curing time

C. Isotropic Compression Test

The isotropic compression curves obtained from triaxial tests are summarized in Fig. 3 for samples with different mix proportion and curing time. As can be seen, the initial specific volume decreases with curing time while the isotropic compression primary yield stress p'_{py} determined by using Rotta et al.'s method[13] increases with curing time. However, the rate of change appears to moderate after 4 weeks. Although Fig. 3 (b) and Fig. 3 (d) indicate that the compression index decreases with curing time, the change in compression index with curing time seems to be small.



(a) mix proportion 10:1:11 (b) mix proportion 20:3:23

(c) mix proportion 5:1:6 (d) mix proportion 2:1:4

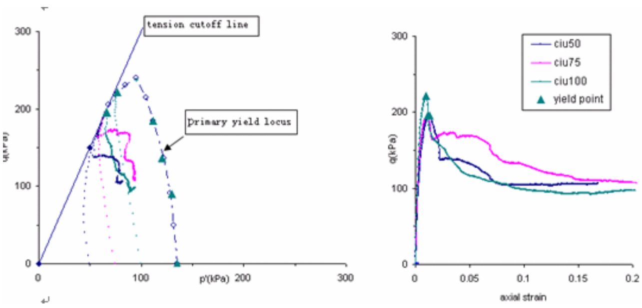
(e) mix proportion 1.3:1:3.45 (f) mix proportion 1:1:3

Fig. 3 Isotropic compression behaviors for specimens with different mix proportion and curing time

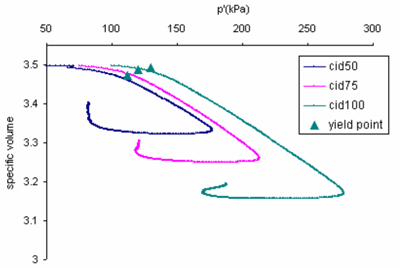
D. Primary Yield Stress and Yield Locus

The difficulties in determining the yield point of soils have been reported by many researchers (e.g., [14]-[15]). Rotta *et al*. stated that for artificially cemented soil, the gradual onset of the breakage of the cement bonds, the grading of the soil and the micro-features of the cememtitious agent can significantly add difficulties in identifying the yield point for cemented soils [13]. Several methods for defining the yield point were proposed by different researchers. For example, Rotta *et al*. proposes the point where the stress-strain curve deviates from its initial linear trend as the primary yield point [13], at which breakage of bonds first commenced.

In this study, Rotta et al.'s method was introduced to determine the yielding points for the primary yield locus, which is consistent with Cuccovillo & Coop's work [16]. As Fig. 4 shows, the primary yielding points can be obtained from the isotropic compression curve and compression plots of consolidated-drained triaxial compression (CID) tests. It can be seen from Fig. 4 and Fig. 5 that for all specimens under consolidated-undrained triaxial compression (CIU) tests, primary yielding occurs at or shortly before peak strength although the stress path may be quite different depending on the confining stress. Fig. 4 shows that all peak strength points of CIU tests fall reasonably well onto a single yield locus formed by the primary yield points from isotropic compression and CID test. This indicates that a reasonably consistent primary yield locus for cement-treated marine clay can be determined.



(a) primary yield locus and stress path (b) stress-strain curve under CIU test

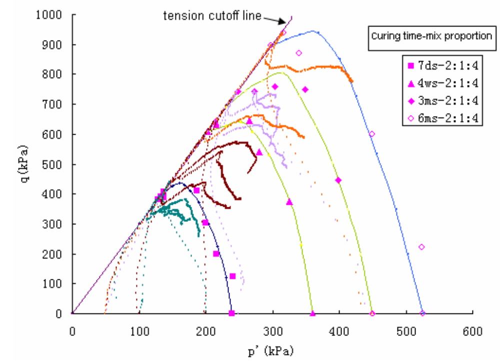


(c) compression space under CID test

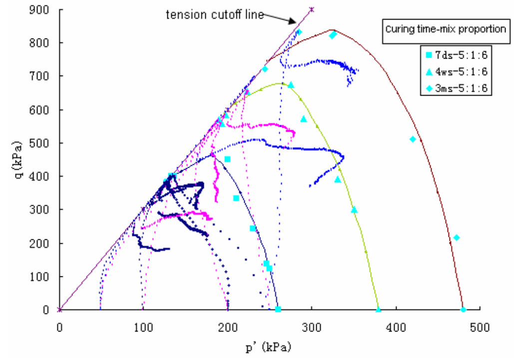
Fig. 4 Determination of primary yield locus (mix proportion 10:1:11)

E. Triaxail Compression Test with Consolidation Stress below Isotropic Compression Primary Yield Stress

The deviator stress-strain curve of triaxial compression test, compression space of CID test and stress path of CIU test are shown in Fig. 5-8 for specimens with different curing time and consolidation stress lower than isotropic compression primary yield stress p'_{py} . For example, in test 7ds-2:1:4-ciu50 the sample with mix proportion 2:1:4 and 7 days of curing time was subjected to an isotropic consolidation pressure of 50 kPa and then sheared at a constant confining pressure of 50kPa under undrained condition. As it can be seen clearly from Fig. 6 and Fig. 7, curing time has significant effect on peak strength of specimen in CIU test and compression index of specimen in CID test for specimen with the same mix proportion and consolidation stress. For all specimens in CIU test, although the peak deviator stress is reached at the roughly the same shear strain, the peak deviator stress increases substantially with curing time before 28 days. For all specimens in CID test, the compression index decreases obviously with curing time before 28 days. Fig. 8 shows that the curing time also has an effect on the specimens in CID test, with a longer curing time leading to a lower strain to peak strength and higher peak strength for the specimens with the same mix proportion. However, although both the increase in peak strength and decrease in compression index persist after 28 days, the respective rates are clearly lower than those before 28 days.

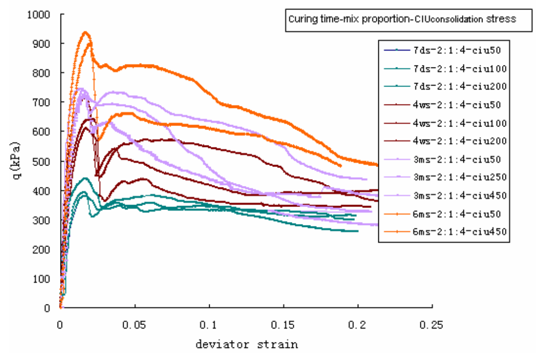


(a) cement content 50% and total water content 133%



(b) cement content 20% and total water content 100%

Fig. 5 Primary yielding and stress path for specimens with consolidation stress below isotropic primary yield stress and different curing time



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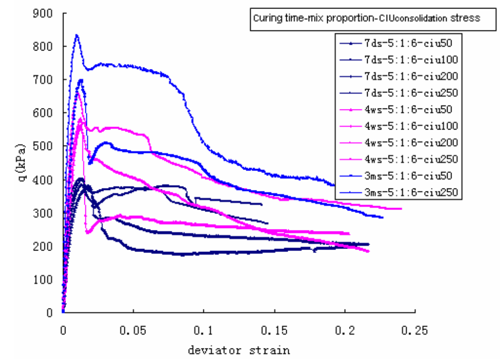
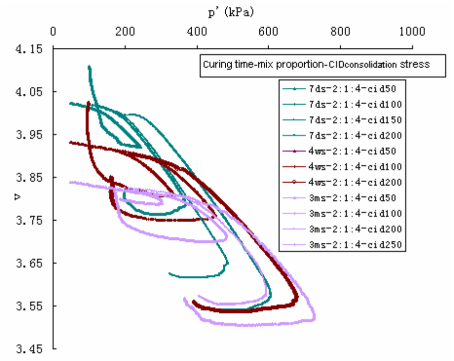


(b) cement content 20% and total water content 100%

Fig. 6 Deviator stress strain relationship under CIU test for specimens with consolidation stress below isotropic primary yield stress and different curing time



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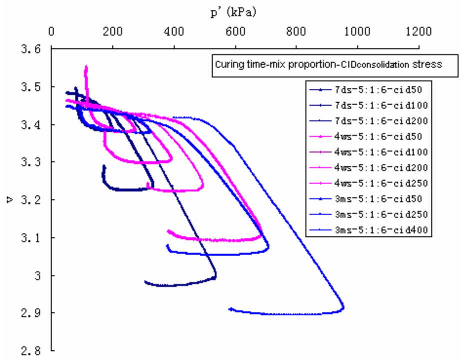
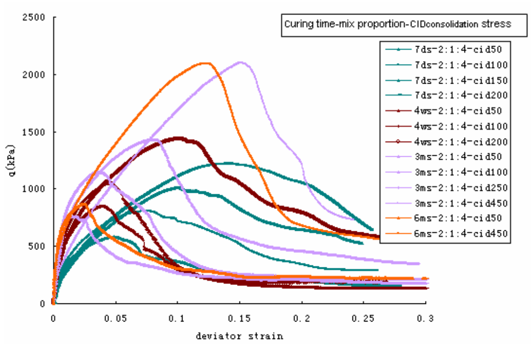


(b) cement content 20% and total water content 100%

Fig. 7 Compression spaces under CID test for specimens with consolidation stress below isotropic primary yield stress and with different curing time



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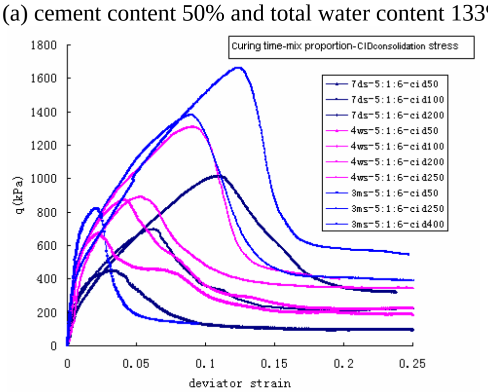


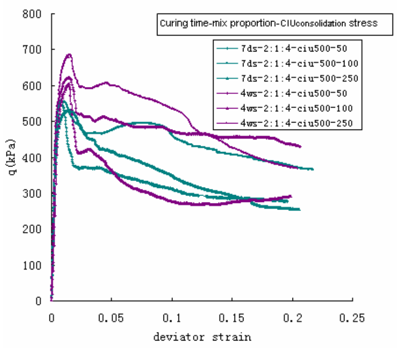
(b) cement content 20% and total water content 100%

Fig. 8 Deviator stress strain relationship under CID test for specimens with consolidation stress below isotropic primary yield stress and different curing time

Fig. 5 shows that, for specimens with the same mix proportion, the isotropic compression primary yield stress p'_{py} increases with curing time. However, as the results show, the behaviour of the samples with different curing time can be broadly categorized according to their yield ratio, defined herein as the ratio of the isotropic primary yield stress p'_{py} to consolidation stress or initial effective stress p'_i . Samples which were sheared undrained at high yield ratio (>>2) showed stress path approximately vertical at the initial stages and failed along the tensile failure envelope before peak point (Fig. 5), accompanied by drop in stiffness (Fig. 6). Specimens sheared undrained at lower yield ratio(~ 2) show stiff response up to peak strength, which suggests an elastic behaviour up to the peak strength appearing between 1% and 2% of shear strain or axial strain (Fig. 5 and Fig.6). Samples which were sheared drained at high yield ratio showed nearly elastic behaviour before peak strength (Fig. 8). Samples which had the same curing time and were sheared drained at low yield ratio showed large volumetric compression up to the peak strength appearing usually at higher range of shear strain than that of CIU tests. Fig. 8 shows that under higher confining stress (i.e. consolidation stress), the point of peak strength is reached well after primary yield point.

F. Triaxial Compression Tests with Maximum Consolidation Stress above Isotropic Compression Primary Yield Stress

Fig. 9-12 show the deviator stress-strain curve in CIU test and compression space in CID test for specimens with different curing time and maximum consolidation stress above isotropic compression primary yield stress p'_{py} . For example, in test 7ds-2:1:4-ciu500-50 the sample with mix proportion 2:1:4 and 7 days of curing time was subjected to a maximum isotropic consolidation pressure of 500 kPa and isotropically swelled back to 50kPa and then sheared at a constant confining pressure of 50kPa under undrained condition. Figures 9 and 10 show that, for specimen with maximum consolidation stress p'_0 of 500kPa, curing time has some effect on peak strength in CIU test and compression index in CID test for specimen with mix proportion 2: 1: 4 while curing time effect on peak strength and compression index diminishes for specimen with mix proportion 5: 1: 6. This indicates the time effect on the post-primary yielding stress-strain behaviour is dependent on the cement content. However, for specimens with maximum consolidation stress p'_0 of 1000kPa, curing time has virtually no effect on the peak strength in CIU test and compression index in CID test although it appears to have some effect on the initial specific volume due to the difference in the post-curing water content among the specimens with different curing time.



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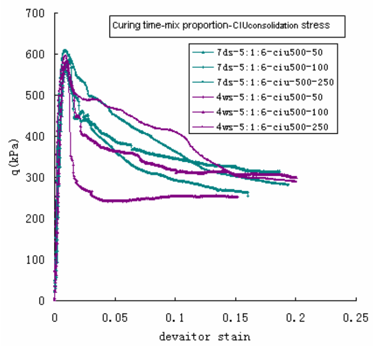
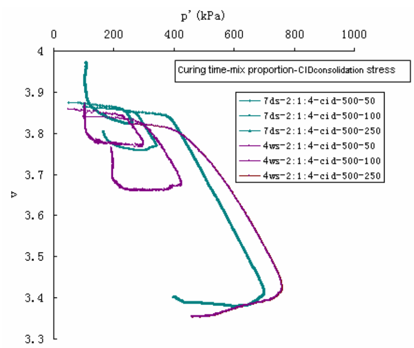


(b) cement content 20% and total water content 100%

Fig. 9 Deviator stress strain relationship under CIU for specimens with maximum consolidation stress p_0' of 500kPa and different curing time (some data for specimen with mix proportion 5:1:6 and 7 days of curing time are from [18])



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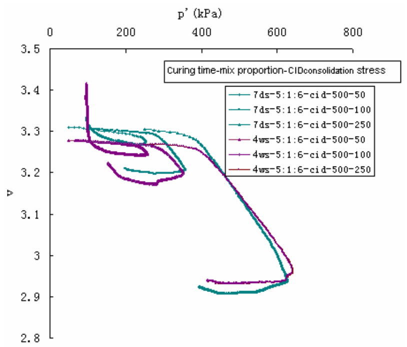
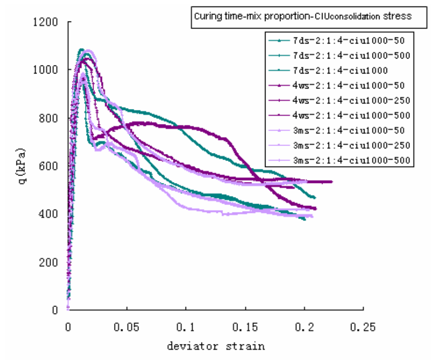


(b) cement content 20% and total water content 100%

Fig. 10 Compression spaces for specimens with maximum consolidation stress p_0' of 500kPa and with different curing time (some data for specimen with mix proportion 5:1:6 and 7 days of curing time are from [18])



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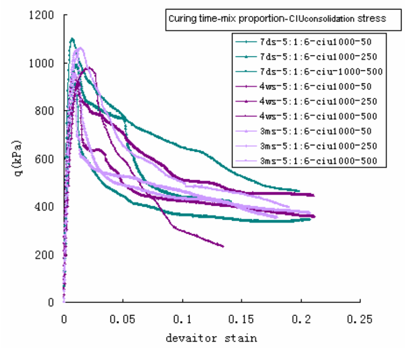
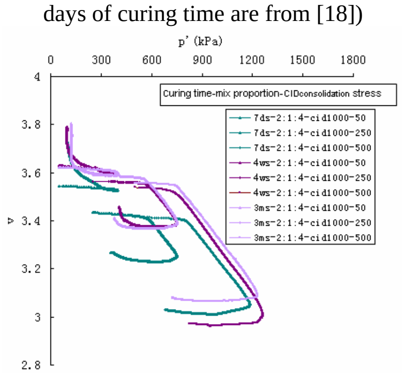


(b) cement content 20% and total water content 100%

Fig. 11 Deviator stress strain relationship under CIU for specimens with maximum consolidation stress p_0' of 1000kPa and different curing time (some data for specimen with mix proportion 5:1:6 and 7 days of curing time are from [18])



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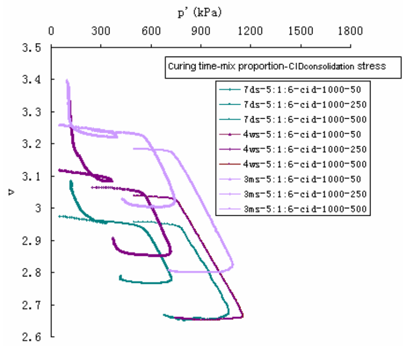


(b) cement content 20% and total water content 100%

Fig. 12 Compression spaces for specimens with maximum consolidation stress p_0' of 1000kPa and with different curing time (some data for specimen with mix proportion 5:1:6 and 7 days of curing time are from [18])

G. Curing Time Effect on the Primary Yielding Behavior

Specimens with different curing time in Figs. 4 to 8 were all tested under effective confining stress (consolidation stress) less than isotropic compression primary yielding stress. As Fig. 5 shows, although the primary yield locus expands with curing time for different mix proportion, the shape seems to be maintained. Fig. 13 shows that after normalized by isotropic compression primary yield stress, all primary yield loci are very narrowly banded and have nearly the same shape. Fig. 14 shows that isotropic compression primary yield stress p'_{py} is linearly related to unconfined compressive strength q_u for all specimens with different mix proportion and curing time.

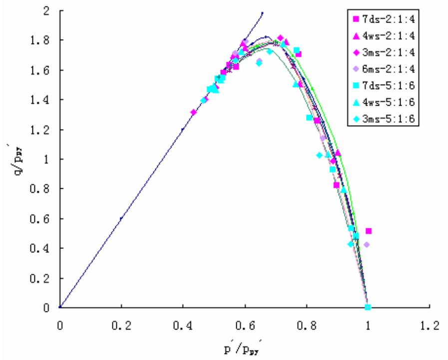


Fig. 13 Normalized primary yield locus for specimens with different cement mix proportion and curing time

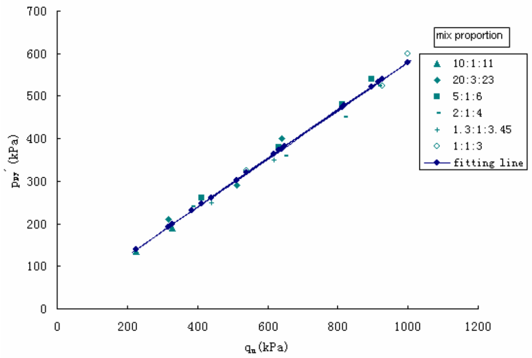
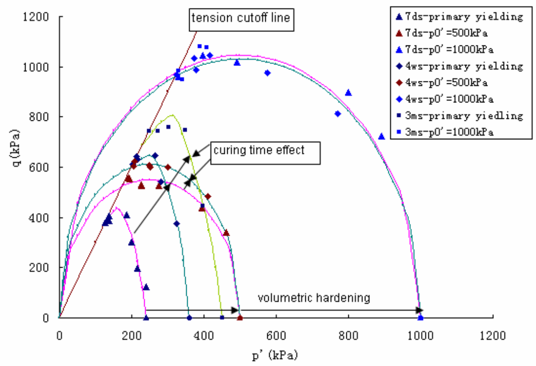


Fig. 14 Relationship between isotropic yielding stress p'_{py} and unconfined compressive strength q_u for specimens with different cement mix proportion and curing time

H. Curing Time Effect on the Hardening Behavior

Yield loci of specimens with different mix proportion and curing time are shown in Fig. 15, which indicates that yield locus expands with curing time and isotropic compression stress p'_0 (maximum consolidation stress) or volume change(i.e., volumetric hardening). For specimens with mix proportion 2:1:4 and p'_0 value of 500kPa, the yield locus with 28 days of curing time is higher than that with 7 days of curing time while for specimens with mix proportion 5:1:6, the yield locus is almost the same. This indicates curing time effect on strain hardening behaviour is more evident for samples with higher cement content. However, for all specimens with isotropic compression stress p'_0 of 1000kPa, the yield locus is almost unchanged with different curing time. This indicates that curing time effect will diminish as isotropic compression stress increases. Thus the curing time effect on the hardening behaviour is dependent on both cement content and isotropic compression stress.

Fig. 15 also shows that for specimens with curing time of 28 days, the primary yield locus lies at least partially above the yield locus corresponding to isotropic compression pressure of 500kPa while for specimen with curing time of 7 days, the primary yield locus lies totally below the same yield locus. This indicates that although the yield locus expands with isotropic compression or volume change, the stress ratio at the top will reduce due to the loss of structure. As stated before, the primary yield locus also expands with curing time without changing the shape. For specimens with 28 days of curing time, the difference between the isotropic compression yield stress p'_0 and the primary yield stress p'_{py} is not prominent so that the volumetric hardening is not sufficient to offset the curing time effect and the structure loss and the primary yield locus lies partially above the yield locus with p'_0 value of 500kPa. However, as the isotropic compression yield stress is obviously higher than the primary yield stress, the yield locus corresponding to the isotropic compression yield stress (e.g., 1000kPa) lies above the primary yield locus despite of the curing time. This is also consistent with the coupled effect of density and cementation on the stress strain behaviour of cemented soils (e.g. [17]).



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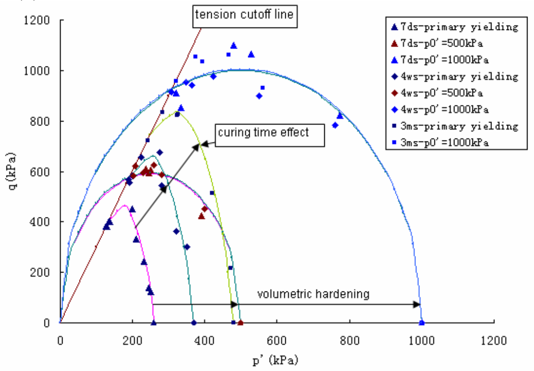

(b) cement content 20% and total water content 100%

Fig. 15 Yield loci of specimens with different mix proportion and curing time

IV. CONCLUSION

The results and discussion presented above show that curing time has some effect on the physical property of cement treated soil samples. The curing time has a significant effect on the unconfined compressive strength and isotropic compression behaviour. Curing time effect on the stress strain behaviour under triaxial loading condition is dependent on the consolidation stress and cement content. For specimens with consolidation stress lower than isotropic compression primary yield stress, the peak strength in CIU test increases while the compression index in CID test decreases significantly with curing time less than 28 days. The increase in peak strength and decrease in compression index is still can be seen after 28 days but it's not as much as that before 28 days. The curing time also has an effect on the specimens in CID test, with a longer curing time leading to a lower strain to peak strength and higher peak strength for the specimens with the same mix proportion. For specimens with consolidation stress higher than primary isotropic compression yield stress, the curing time effect is influenced by the consolidation stress and cement content.

Although the primary yield loci of the cement treated soil specimen with the same mix proportion expand with curing time, they are very narrowly banded and have nearly the same shape after being normalized by isotropic compression primary yield stress, which is linearly related to unconfined compressive strength q_u . The curing time effect on the hardening behaviour is dependent on both cement content and isotropic compression stress and will moderate as isotropic compression stress increases beyond the primary yield stress.

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