STRENGTH AND DEFORMATION CHARACTERISTICS OF CEMENT TREATED SOFT BANGLADESH CLAYS

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ABSTRACT

The strength and deformation characteristics of cement treated soft Bangladesh clays are evaluated through a series of experimental investigations. Based on the rate of strength development, the unconfined compressive strength and cement content relationship can be divided into 3 zones: Inactive Zone, Active Zone and Inert Zone. The stiffness of the cemented clay is a function of cement content and curing time, as the higher cement content and curing time results higher stiffness. The significant increase in apparent preconsolidation pressure and reduction in apparent compression index are observed from consolidation tests for cement treated clay. This implies that the treated clay undergoes structuration (formation of cementation bond) up to their apparent preconsolidation pressure and afterward the destructuration (breaking of cementation bond) takes place. Ductile behavior is associated with lower strength and higher failure strain (high unit deformation). On the contrary, higher strength and lower failure strain (low unit deformation) correspond to brittle behavior. Generally, higher cement content and curing time are the main parameters to cause the stabilised mass become brittle. Effective stress paths correspond to different category of states such as normally consolidated, lightly, moderately and heavily overconsolidated states depend on amount of cementation.

Keywords: *Cementation Bond, Deformation, Engineering Behavior, Fabric, High Water Content, Strength*

1.0 INTRODUCTION

Major geotechnical problems often arise for construction in Bangladesh involving soft clays containing high water content. Such soft clay formations are available in Bangladesh, especially when the in-situ water contents are high owing to its low shear strength and high compressibility [1]. There are three types of clay in Bangladesh on the basis of plasticity, namely high plastic (C1) clay, medium plastic (C2) clay and low plastic (C3) clay. Thus, suitable ground improvement techniques are needed for deep excavation projects in these soft clays to obtain strength stability and deformation control. Now a days, cement stabilisation is one of the commonly used methods of ground improvements. An increment in strength, reduction in compressibility (deformation) and improvement of swelling characteristics as well as reduction of creep properties of soil are the main aims of cement stabilisation method.

While the conventional cement stabilisation is mainly for surface treatment, the use of cement has recently been extended at greater depth in which cement column are being installed to act as a type of soil reinforcement [2 – 4]. These methods are termed as deep cement mixing and cement jet grouting which is currently being used in various countries to improve the strength and deformation properties of soft clay for most of the deep excavation projects. To improve the strength and deformation properties of cement treated soft clay soils, they are investigated in laboratories as model tests [5 – 9].

Normally, cement stabilisation work is carried out before the start of excavation. The improved soil layer functions as a strut acting below the excavation level, which helps in limiting the movement of soil mass. Hence, in this application, the strength and deformation characteristics of stabilised clay need to be model investigated in soil laboratory. Thus, the effects of cement inclusion on strength and deformation characteristics of soft Bangladesh clays are described in this paper, in order to have a better understanding on stress-strain, stiffness and compressibility characteristics of cement treated clays.

2.0 EXPERIMENTAL INVESTIGATION

2.1. Soil Sample

Clays were collected in various districts of Bangladesh such as C1 clay from Gazipur, C2 clay from Gopalgonj and C3 clay from Khulna. The soils were collected from depth of 2-3 m from existing ground level with disturbed and undisturbed state. Its physical and engineering properties are listed in Tables 1 and 2 respectively. ASTM Type I Portland cement was used as a binding material in this study. Samples were prepared from these clays and cement slurries.

Table 1: Characteristic values of the physical and index properties of the untreated base clays

Properties	Characteristics Values		
Type of Soil	C1 clay (LL > 50%)	C2 clay (LL = 35 to 50%)	C3 clay (LL < 35%)
Liquid Limit, LL, (%)	78	47	33
Plastic Limit, PL, (%)	31	25	20
Plasticity Index, PI, (%)	47	22	13
In-Situ Water Content, w_n (%)	70	62	53
Liquidity Index, LI	0.83	1.68	2.54
*Clay (%)	73	63	56
*Silt (%)	23	29	34
*Sand (%)	4	8	10
Bulk Unit Weight, γ_t (kN/m^3)	15.05	14.67	14.45
Dry Unit Weight, γ_d (kN/m^3)	8.85	9.05	9.44
Specific Gravity, G_s	2.680	2.673	2.668
Activity of clays, A_c	0.64	0.35	0.23
Degree of saturation, S_r (%)	89	84	78
Unified Soil Classification System	CH	CL	CL

Table 2: Characteristic values of the engineering properties of the untreated base clays

Properties	Characteristics Values		
Type of Soil	C1 clay	C2 clay	C3 clay
Unconfined Strength, q_u (kPa)	50	41	58.5
Strain at Ultimate Strength, ε_f (%)	3.67	3.65	4.00
Initial Void Ratio, e_o	1.81	1.96	2.10
Preconsolidation Pressure, p'_c (kPa)	70	65	61
Compression Index, C_c	0.737	0.781	0.863
Swell Index, C_s	0.124	0.127	0.131
Shear strength at po ' = 200 kPa, s_u (kPa)	98	92	89
Shear Strain at s_u, ε_u (%)	11	10.7	10.2

2.2. Methodology of Testing

The clay paste was passed through a 2-mm sieve for removal of shell pieces and other bigger size particles. The intentional increase in water content is to simulate the water content increase taking place in the wet method of dispensing cement admixture in deep mixing and the significant increase taking place in jet grouting. The clay with its water content corresponding to the above simulating conditions and the quantity of cement resulting in clay-water or cement ratio (*wc/c*) of 2, 2.5, 4, 7.5, 10, 15 and 30. They were thoroughly mixed so as to ensure uniform dispersion of the cementing agent although the clay-water mixture.

The clay-water content (w_i) that used in this study was 120%, 150%, 200% and 250%. The mixing time was arbitrarily fixed at 10 minute. Such a uniform paste was transferred to cylindrical split moulds of 50 mm diameter × 100 mm height and 75 mm diameter × 100 mm height with connecting 50 mm height top collars and bottom ended cap taking care to prevent any air entrapment. Cylindrical moulds of 50 mm diameter × 100 mm height were used to prepare specimens for unconfined compression tests and triaxial compression tests. On the other hand, cylindrical moulds of 75 mm diameter × 100 mm height were used to prepare specimens for consolidation tests.

After 24 hours the specimens were dismantled and they were wrapped with thick polythene bags and they were stored in a room of constant temperature and humidity until their respective curing time finished.

Unconfined compression (UC) tests were carried out after 1, 2, 4, 12, 24, 52 and 104 weeks of curing period. Consolidation and unconsolidated undrained (UU) triaxial compression tests were run on samples after 4 and 12 weeks of curing. The rate of vertical displacement applied in UC tests was 1 mm/min. The effective confining pressures, p_o' for UU test was 200 kPa. A back pressure of 100 kPa was maintained to ensure high levels of degree of saturation during the triaxial test.

2.3 Parameters

According to Miura *et al.*, and Horpibulsuk [5,6], the prime parameter governing the strength and deformation of cement treated clay has been proposed and which is designated as clay-water/cement ratio, *wc/c*. The clay water or cement ratio hypothesis was also introduced. It merits controlling the input of cement to attain the strength and deformation requirement with curing time and clay-water content.

The *wc/c* is defined as the ratio of initial water content of the clay (%) to the cement content (%). The cement content, *c* is the ratio of cement to clay by weight both reckoned in the dry state. To obtain the same value of *wc/c*, it is possible to vary the water content of the clay, or the amount of cement, or both as the case might be. In order to examine up to what extent the applicability of *wc/c* is varied; the water content of clay was varied over a wide range in this study.

3.0 RESULTS AND DISCUSSION

The test results of the strength and compressibility (deformation) characteristics of cement treated clays were discussed in the following sections:

3.1. Strength Characteristics

Unconfined compression tests were performed to determine the stress-strain and stiffness characteristics of cement treated clay. The experiments were conducted with cement content (c) varies from 4 to 60% and having curing periods of 1 to 104 weeks.

Table 3 shows the strength at 4 and 12 weeks with 120%, 150%, 200% and 250% mixing water and 7.5, 10 and 15 clay-water or cement ratios for C1, C2 and C3 clays. Test results show that the increases of cement content and curing time result in significant improvement of unconfined compressive strength as well as stiffness of the treated clay. Figure 1 illustrates the effect of cement content on unconfined compressive strength of treated C1, C2 and C3 clays with different clay-water/cement ratios and at different curing periods. It is found that for 1 weeks strength, the effect of initial water content seems to be significant at all ranges of cement content. However, for 4 weeks strength, the effect of initial water content of all clay-slurry is insignificant if the cement content is less than 30%. In case of cement content more than 30%, samples of C1 and C3 clays give the higher strength as compared to that of samples C2 clay with initial water content of 120%. For clay with high initial water content, the development of lower strength could be due to the lesser cement particles per unit volume of the treated mixture.

Table 3: Unconfined compressive strength q_u in kPa for cement treated clays

Clay-water content *wc* (%)	wc/c Ratio	Cement content *c* (%)	C1 Clay Curing Time 4 w	C1 Clay Curing Time 12 w	C2 Clay Curing Time 4 w	C2 Clay Curing Time 12 w	C3 Clay Curing Time 4 w	C3 Clay Curing Time 12 w
120	7.5	16	399	533	291	405	339	438
	10	12	251	335	179	267	213	284
	15	8	149	226	106	172	126	180
150	7.5	20	383	528	277	395	318	429
	10	15	241	338	175	260	200	266
	15	10	143	217	124	169	138	185
200	7.5	26.67	381	520	272	390	314	421
	10	20	238	330	170	249	195	257
	15	13.33	134	207	95	155	112	165
250	7.5	33.33	379	511	268	401	311	409
	10	25	235	321	172	258	189	265
	15	16.67	124	187	88	160	108	166

Another possible reason of low strength development is due to the increase of average distance between the reacting clays and cement particles. The efficiency of the diffusion of calcium ion concentration also reduces with the increase in initial water content of the clay-slurry. The conclusion has been supported by the investigation of Chew *et al.* [8] for cement treated Singapore marine clay.

The above results also suggest that the difference between the 1 to 104 weeks strength is significant, except when cement content is less than 4%. As the formation of cementation bonds due to the hydration and cementation reaction increases with the increase in curing time, the rate of development of strength also increases.

Figure 1 also reveals that a larger rate of increase of unconfined compressive strength is noted with cement content in the range of 4 to 40%; while a smaller incremental rate of strength is observed for cement content more than 40%. This is observed for curing periods of 4 to 104 weeks however, the incremental rate of UC strength was found uniform in the case of 1 and 2 weeks samples. This is probably because of the cementation becomes mature after 4 weeks curing periods. Based on this observation, the unconfined compressive strength and cement content relationship can be divided into 3 zones; Inactive Zone, active Zone and Inert Zone.

The cement content up to 4% shows only very marginal improvement of unconfined compressive strength and is termed as inactive zone. This implies that a certain percentage of cement (more than 4%) is required to complete the hydration reaction between cement and clay particles. The end result of complete cementation is to increase the shear strength. The cement content between 4 to 40% is termed as active zone, as it shows significant improvement of strength with cement content. At this zone, the rate of hydration reaction is very high and thus the bridging (cementation) effect is very efficient.

Hence, the increased amount of cementation reaction products CSH (calcium silicate hydrate) and CASH (calcium aluminum silicate hydrate) caused a sharp increase in shear strength. Beyond the cement content of 40%, the rate of increase of strength reduces and seems to be asymptotic. Such region is referred here as inert zone. This is because of the completion of cementation reaction (pozzolanic reaction) due to the exhaustion of cement. It is also possible that the reactions are going on but the calcium ion solutes diffuse very slowly within the treated clay matrix such that no further improvement of strength is observed. Similar results of clay-cement matrix were observed by Kamaluddin [10] and Chew *et al.* [8].

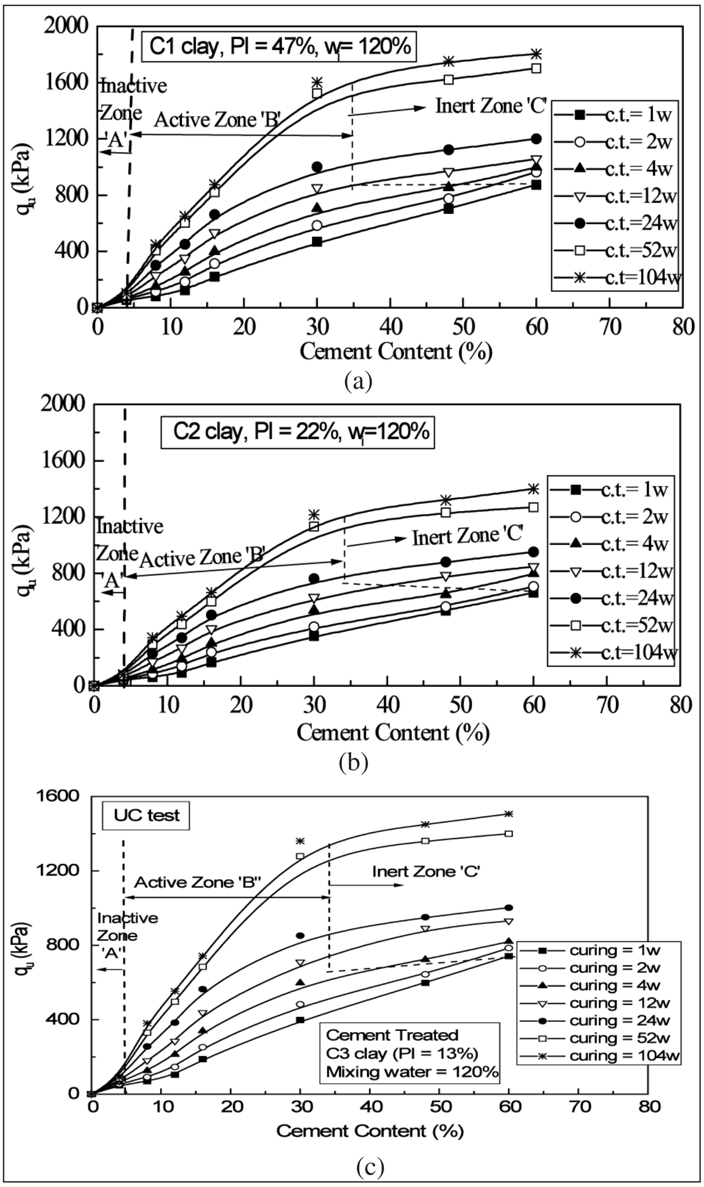


Figure 1: Unconfined compressive strength and cement content relationship at different curing periods (w_i = 120%) for (a) C1 clay, (b) C2 clay and (c) C3 clay

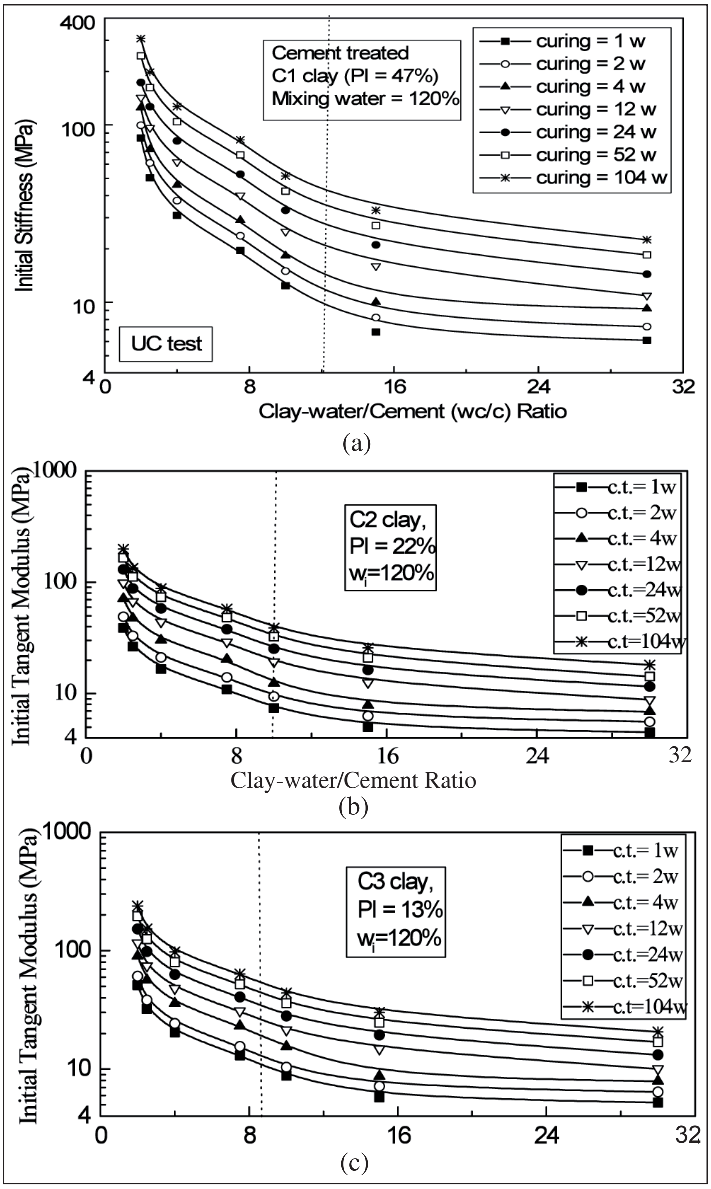


Figure 2: Relationship between initial tangent modulus and clay-water or cement ratio (w_i = 120%) for (a) C1 clay, (b) C2 clay and (c) C3 clay

3.2 Stiffness Characteristics

The stress-strain behavior of unconfined compression test for soils is generally non-linear. For this, initial stiffness or initial tangent modulus is defined as the slope of tangent at initial starting of non-linear stress-strain curve and simply abbreviated as E_i. The stiffness was found to be a function of clay-water or cement ratio, *wc/c* and curing time. Generally, higher *wc/c* ratio (i.e., lower cement content) and lower curing time correspond to the smaller values of the stiffness. Figure 2 show the relationship between initial tangent modulus and clay-water/cement ratio of treated samples of C1, C2 and C3 clays at mixing water content 120% used for clay slurries. A sharp increase of the modulus E_i can be noticed up to a *wc/c* ratio of 12, 10 and 9 for C1, C2 and C3 clays respectively and thereafter slow development occurs. The linear variations are attained at about *wc/c* 15 for all clays and high plastic clay undergoes high stiffness.

3.3 Compressibility (Deformation) Characteristics

Consolidation tests were carried out to explain the deformation characteristics of cement treated clay. Figures 3(a), (b) and (c) shows the $e\text{-}log\sigma_v$' curve for the treated C1, C2 and C3 clays respectively. All three figures contain a $e\text{-}log\sigma_v$' curve of corresponding remoulded specimen.The figures show that treated clay curves cross the untreated reconstituted clay curve before its preconsolidation pressure (σ_p') / yield stress (σ_y') and then it is displaced from the untreated reconstituted clay curve (dotted line) with increasing values of effective vertical pressure, indicating instinct characteristics of lower compressibility (deformation) of the treated mass. Beyond the σ'_p value, obviously, higher compressibility (deformation) can be noticed and at higher pressure levels, the treated clay curve tends to proceed parallel to the lower part of the untreated clay curve.

The compressibility of the untreated reconstituted sample is much steeper than those exhibited by the treated clays. The compression index (C_c) and swell index (C_s) are the slope of the ($e\text{-}log\sigma'_v$) plot at post yield stress during loading and unloading conditions respectively. The yield stress is obtained as the point of intersection of two straight lines extended from the linear portions on either end of the compression curve plotted as e against $log\sigma'_v$ [6].

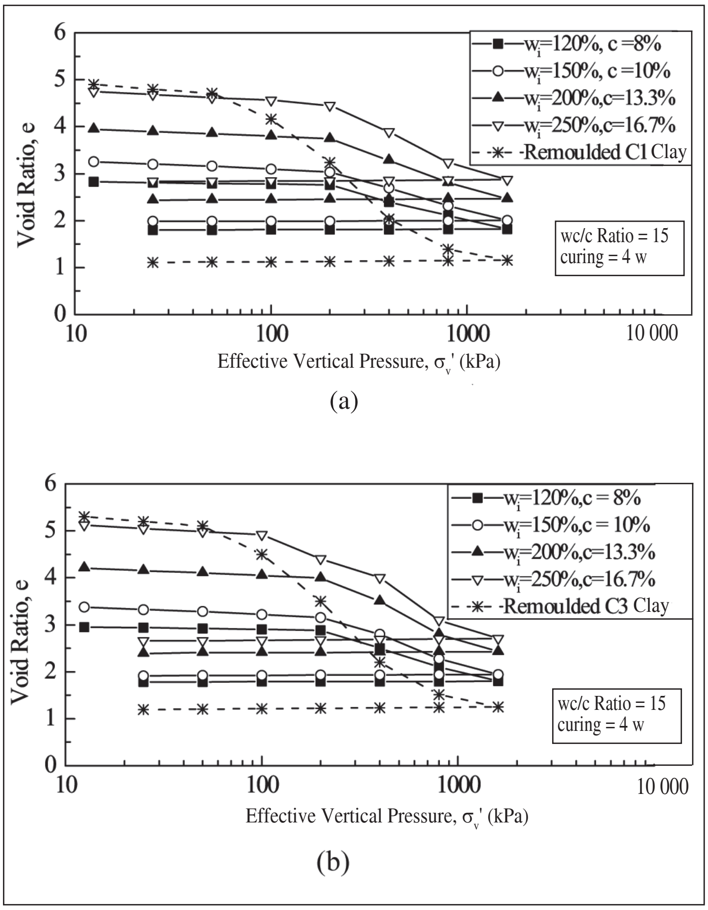


Figure 3: Void ratio-vertical stress relationship of treated and untreated clays at loading and unloading conditions for (a) C1 clay and (b) C3 clay

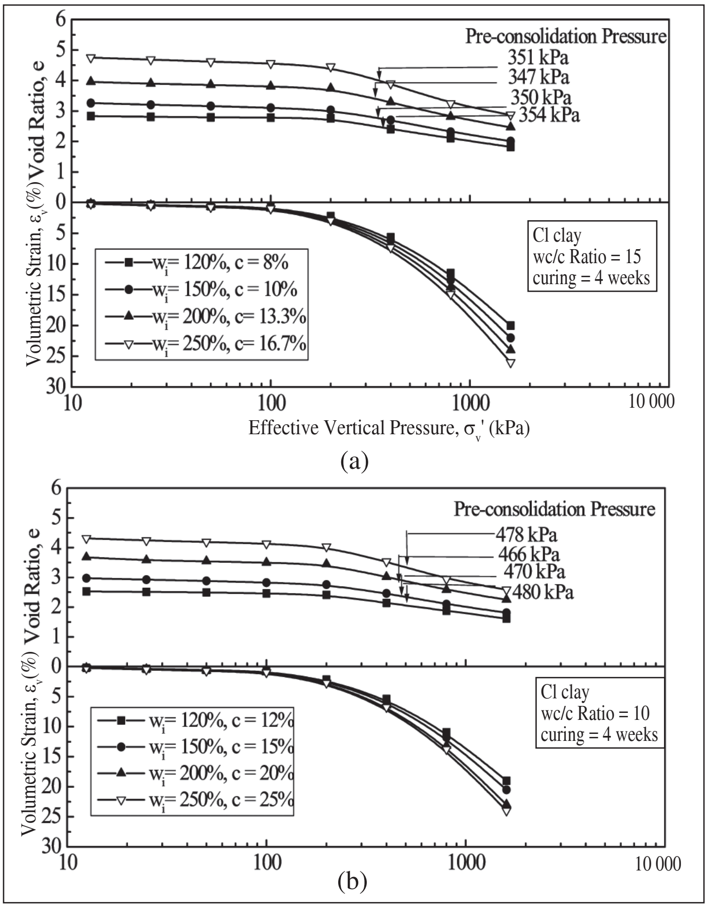


Figure 4: Compressibility of cement-stabilised clays for C1 clay and curing, 4 weeks at wc/c ratio (a) 15 and (b) 10

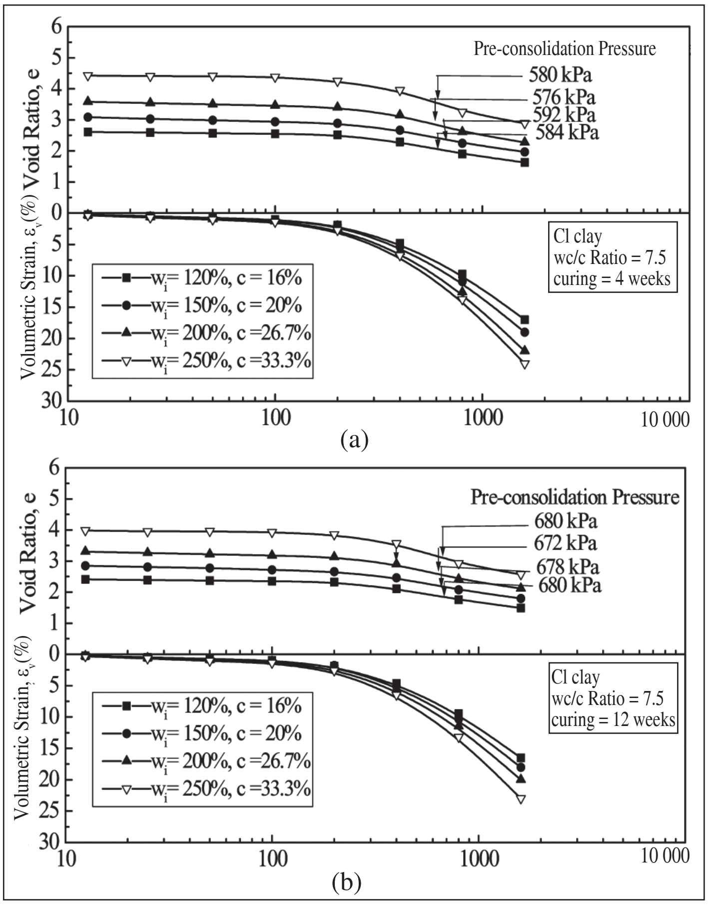


Figure 5: Compressibility of cement-stabilised C1 clays and wc/c ratio, 7.5 at curing (a) 4 weeks and (b) 12 weeks

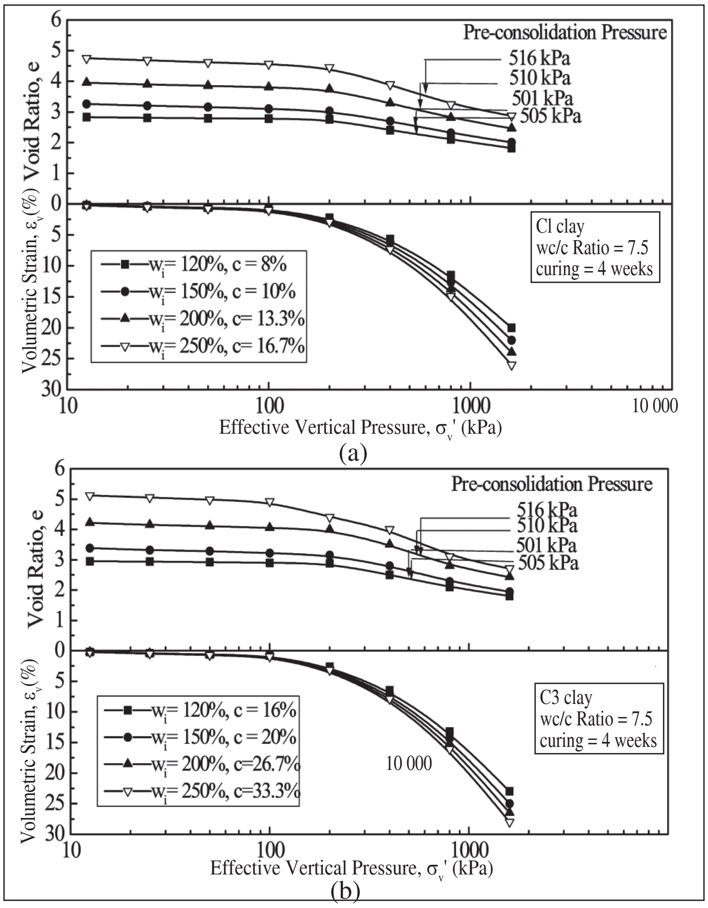


Figure 6: Compressibility of cement-stabilised clays at wc/c ratio, 7.5 and curing, 4 weeks for (a) C2 clay and (b) C3 clay

Figures 4 to 6 shows the e-logσ'_v and ε_v-logσ'_v relationships of different treated clay samples with *wc/c* ratio 7.5, 10 and 15 and mixing clay-water content (w_i), 120%, 150%, 200% and 250%. Table 4 shows the result of σ_y', C_c and C_s for C1, C2 and C3 clays at a curing period of 4 and 12 weeks. It is found that consolidation properties improved greatly by increasing the cement content and curing time. The addition of cement content increases the yield stress from about 61 to 70 kPa for the untreated clays and 350 to 680 kPa for the treated clays. The void ratio for C1 clay is lower than that of C3 clay but the void ratio for C3 clay is higher than that of C2 clay while the yield stress for C1 clay is higher than that of C3 clay however, the yield stress for C3 clay is higher than that of C2 clay. The increase of apparent yield stress is due to the effect of structuration (existing of cementation bond) of treated clay particles. Test results reveal that the void ratio of the treated samples practically changes very small amount until reach the apparent yield stress. This implies that due to the effect of structuration, the volumetric compressibility of the treated samples is very small and the stiffness is very high as long as it is within its yield stress range. The e-log$\sigma'v$ relationship graph also shows that beyond the apparent yield stress, the behavior of treated samples is almost parallel to the untreated clays. This could be due to the destructuration (breaking of cementation bond) of the cementation effect of the treated clay matrix when it is stressed beyond the yield stress. The conclusion is also similar to that observed by Miura et al. [5].

3.4 Compression Index (C_c) and Swell Index (C_s)

The deformation (compressibility and swelling) characteristics of treated clays are found to be quite different from the untreated ones. Test results show that the compression index and swell index reduce significantly due to the effect of cement inclusion in soft clay. This observation implies that the treated clay sample is consistent with the heavily over-consolidated soil behavior. The deformation characteristics of different treated clays in terms of C_c and C_s are calculated for different clay-water or cement content as shown in Figures 7 and 8 for 4 and 12 weeks curing time respectively. It is found that C_c value decreases significantly with the increase in cement content (decrease for *wc/c* ratio). For the specimens with *wc/c* ratio 10 or less, the reduction of C_c and C_s values are very marginal, more pronounced and approaching to zero. However, at *wc/c* ratio 10 or more, almost smaller change of C_c and C_s are noticed. It is also noted that the compression index (C_c) of untreated clay is much smaller than that of the treated clay samples, while swell index (C_s) of untreated clay is higher than that of treated clay samples. This observation has been consistent with the findings of Chew et al. [7] which showed that during virgin yielding, the structured soil is less compressible than the reconstituted soil. This suggests that at higher stresses (beyond the apparent yield stress), the treated samples exhibit normally consolidated behavior with larger C_c. The effect of curing time on compression indices is rather significant.

Table 4: Compressibility parameters for cement stabilised clays

Curing (weeks)	w_i (%)	*wc/c* Ratio	C1 clay (PI = 47%)			C2 clay (PI = 22%)			C3 clay (PI = 13%)		
			σ_y' (kPa)	C_c	C_s	σ_y' (kPa)	C_c	C_s	σ_y' (kPa)	C_c	C_s
4	120	7.5	584	0.822	0.004	505	0.855	0.007	525	0.882	0.009
		10	480	0.856	0.005	417	0.886	0.008	457	0.916	0.010
		15	354	0.933	0.006	305	0.963	0.009	338	0.982	0.012
	150	7.5	592	0.893	0.008	501	0.912	0.009	527	0.991	0.011
		10	470	0.906	0.009	426	0.943	0.011	450	1.082	0.013
		15	350	0.968	0.011	308	0.995	0.013	340	1.115	0.015
	200	7.5	576	0.992	0.010	510	1.065	0.014	522	1.154	0.016
		10	466	1.111	0.012	411	1.121	0.016	455	1.203	0.019
		15	347	1.126	0.014	311	1.148	0.018	336	1.228	0.021
	250	7.5	580	1.155	0.014	516	1.88	0.018	527	1.213	0.021
		10	478	1.188	0.015	414	1.201	0.020	447	1.261	0.024
		15	351	1.194	0.017	306	1.213	0.022	338	1.311	0.026
12	120	7.5	680	0.806	0.003	634	0.832	0.005	650	0.849	0.007
		10	538	0.823	0.004	501	0.866	0.006	521	0.877	0.008
		15	460	0.848	0.005	422	0.943	0.008	436	0.961	0.010
	150	7.5	678	0.857	0.007	629	0.903	0.008	644	0.945	0.009
		10	534	0.875	0.008	506	0.916	0.009	526	0.966	0.011
		15	454	0.946	0.009	418	0.978	0.011	441	1.003	0.013
	200	7.5	672	0.915	0.009	631	0.102	0.012	652	1.142	0.014
		10	541	0.928	0.011	502	1.113	0.014	529	1.182	0.016
		15	450	0.998	0.013	420	1.128	0.016	445	1.204	0.019
	250	7.5	680	1.101	0.012	638	1.157	0.016	657	1.181	0.019
		10	531	1.131	0.013	509	1.189	0.018	536	1.225	0.021
		15	443	1.154	0.015	416	1.196	0.019	438	1.287	0.024

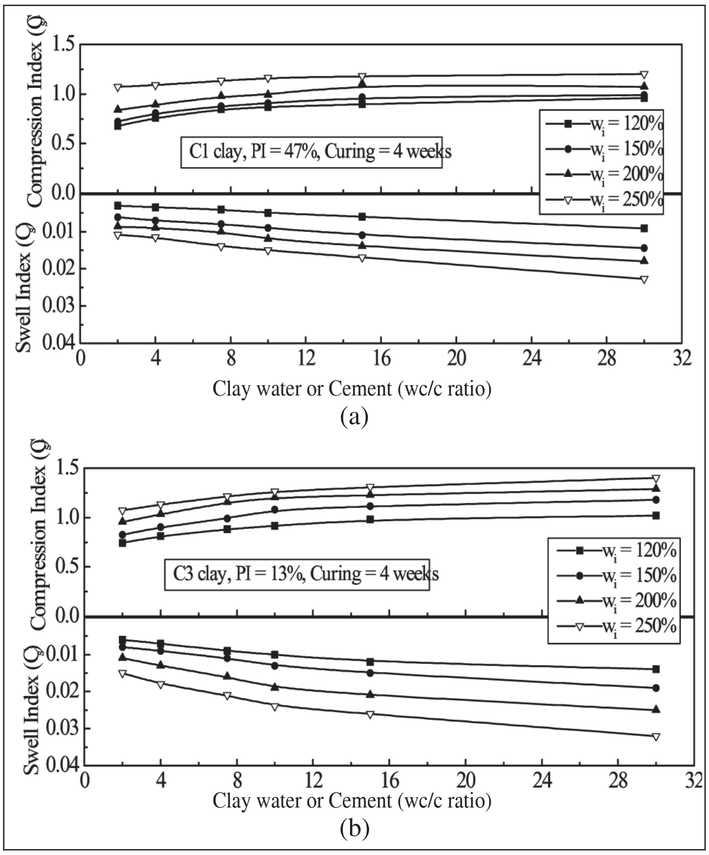


Figure 7: Effect of clay-water or cement ratio on compression and swell indices of treated clays for (a) C1 clay and (b) C3 clay (curing = 4 w)

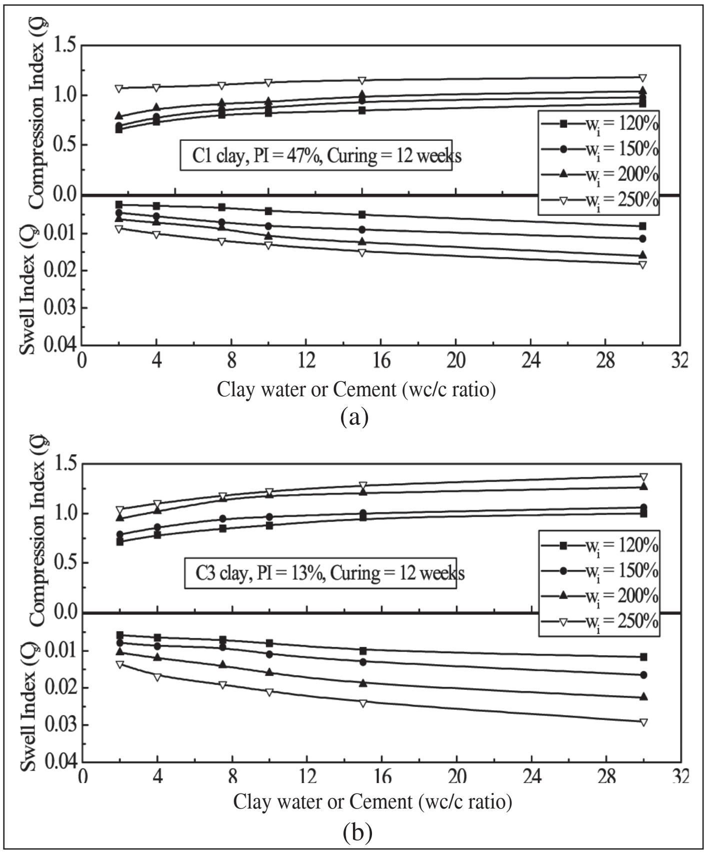


Figure 8: Effect of clay-water or cement ratio on compression and swell indices of treated clays for (a) C1 clay and (b) C3 clay (curing = 12 w)

The compression index and swell index decreases with increasing curing time. For treated clays, the apparent compression index increases with the increase in vertical stresses up to their apparent yield stress, and thereafter decreases. This implies that the treated clay undergoes structuration (formation of cementation bond) up to their apparent yield stress and afterward the destructuration (breaking of cementation bond) takes place. This result is also agrees with the results from the investigations of Chew *et al.* [8] for cement treated Singapore marine clay.

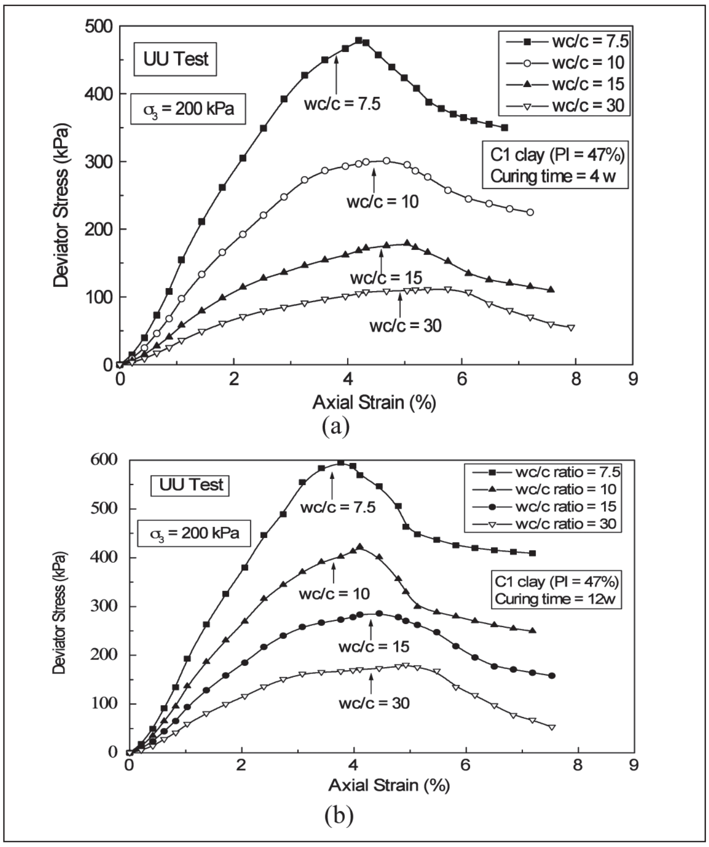
3.5 Stress-strain Characteristics

The stress-strain behavior of cement treated clay samples with curing time 4 and 12 weeks obtained from unconsolidated undrained (UU) triaxial compression tests are shown in Figures 9(a) and 9(b) respectively while Figures 10(a) and 10(b) show the stress-strain behavior from unconfined compression (UC) tests. The test results are described with comparing stabilisation effect for clay-water or cement (*wc/c*) ratio and curing time on strength (maximum stress at which sample failed) and strain (i.e., deformation per unit length).

Table 5 shows a comparison for strength and failure strain (failure unit deformation) from UC and UU tests of C1, C2 and C3 clays. The UU triaxial compression test results are compared with unconfined compression test results, it is found that strengths for UU triaxial compression test are increased to about 1.2 times than that of unconfined compression test but strains (unit deformation) for UU triaxial compression test are increased to about 2 times than that of unconfined compression test. The results for UU triaxial compression test are increased because the specimens are tested in a confined pressure state.

From Table 5, it is observed that C1 clay gained more strength than that of C3 clay, on the other hand, C3 clay gained more strength than that of C2 clay. In general, the stress-strain curves of the treated samples were found to increase abruptly up to the peak deviator strengths then suddenly decreased to low residual values upon further straining. The overall behavior of the treated samples can be categorised into brittle, quasi-brittle and ductile types. Brittle and quasi-brittle characteristics were observed for higher cement content such as wc/c ratio 7.5 and 10, rendering a comparatively lower value of strain at maximum strength (qmax) whereas ductile characteristics were observed for lower cement content such as wc/c ratio 15 and 30. Ductile samples were observed to be associated with a mild peak whereas brittle samples were observed to be associated with a sharp peak. The samples with higher cement content and curing time were observed to possess brittle behavior accompanied with low values of strains at qmax. The brittle samples always exhibited sharp peaks associated with abrupt falling characteristics. The residual strain of the brittle sample is much lower than that of the ductile sample.

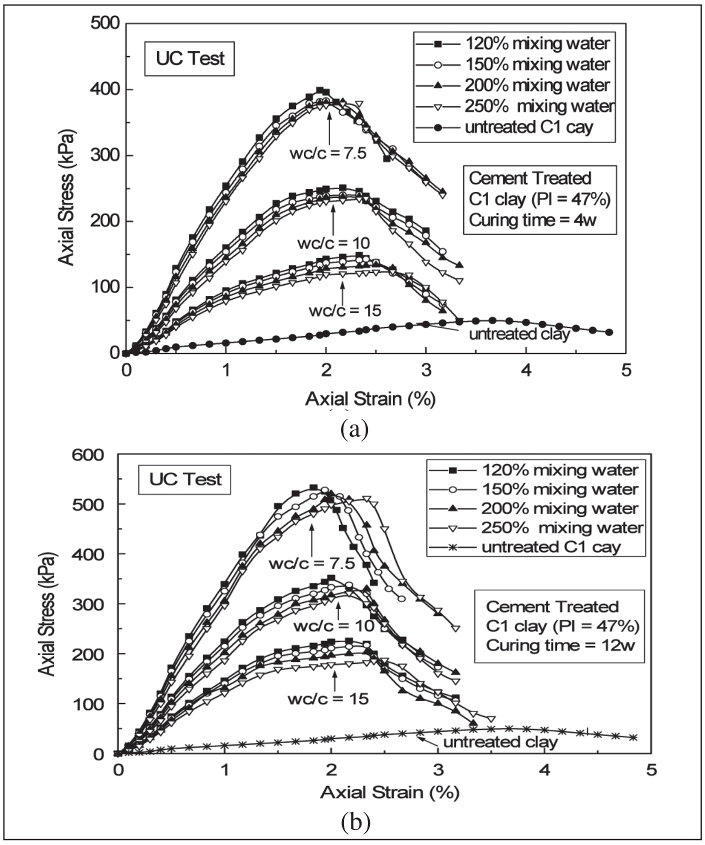
It reveals that the lower the wc/c ratio, the greater the enhancement of the cementation bond strength inducing higher strength. The test results also show that the engineering behavior of cement-stabilised clay is dependent upon the clay-water or cement ratio (wc/c) and fabric (type of clay). For the improvement of soft Bangladesh clay at high water content by cement admixture form UC and UU tests, it is concluded that high plastic clay undergoes better improvement than low plastic clay but low plastic clay undergoes better improvement than medium plastic clay.



(a)

(b)

Figure 9: Stress-strain typical relationships of cement-stabilised C1 clays from UU test at different wc/c ratio for curing (a) 4 weeks and (b) 12 weeks



(a)

(b)

Figure 10: Stress-strain typical relationships of cement-stabilised C1 clays from UC test at different wc/c ratio for curing (a) 4 weeks and (b) 12 weeks

Table 5: Comparison of undrained shear strength and axial strain at failure of cement treated clays (w_i = 120%) from UC and UU tests (σ3 = 200 kPa)

Curing Time (week)	Clay Type	wc/c Ratio	Undrained Shear Strength (kPa)		Axial Strain at Failure (%)	
			UC test	UU test	UC test	UU test
4 w	C1	7.5	200	240	1.94	1.83
		10	126	151	2.16	2.00
		15	75	93	2.33	2.17
		30	34	56	2.69	2.46
	C2	7.5	146	174	2.67	2.50
		10	92	108	2.85	2.67
		15	53	64	3.00	2.83
		30	27	45	3.23	3.01
	C3	7.5	170	219	2.40	2.33
		10	107	142	2.50	2.50
		15	63	91	2.83	2.67
		30	32	48	3.15	2.93
12 w	C1	7.5	267	299	4.19	3.76
		10	168	211	4.68	4.11
		15	113	143	5.04	4.45
		30	38	89	5.76	4.92
	C2	7.5	203	237	5.26	5.00
		10	134	160	5.64	5.14
		15	86	103	6.02	5.36
		30	30	69	5.64	6.43
	C3	7.5	219	254	5.54	4.67
		10	142	194	5.61	5.10
		15	90	129	5.94	5.41
		30	35	82	6.7	6.02

3.6 Undrained Stress Path Characteristics

The effective stress paths are defined the path of straight lines or curve lines by plotting the deviator stress versus mean effective stress. Figures 11(a) and 11(b) illustrate the undrained effective stress paths for cement treated C1 and C3 clays respectively. Overall view of the figures seems to indicate that originated from the same untreated samples possessing normally consolidated state. Figure 11 consists of stress paths of treated clays for p_o' = 200 kPa.

The stress paths evidently, belong to different category ranging from a low OCR (over-consolidation ratio) value to a high OCR value. These stress paths, corresponds to different category of states such as normally consolidated, lightly, moderately and heavily over-consolidated state; though all of the samples have a cement content value. The clay-water or cement ratios are used 7.5, 10, 15 and 30 with mixing water content 120% for each clay.

Effective stress paths for treated clays are similar to that of normally consolidated state for high wc/c ratio up to 30 (i.e, low cement content up to 4%), lightly over-consolidated state for wc/c ratio up to 15 (i.e, cement content up to 8%), moderately over-consolidated state for *wc/c* ratio up to 10 (i.e, cement content up to 12%) and heavily over-consolidated state for wc/c ratio up to 7.5 (i.e, high cement content up to 16%). Very small pore pressures are developed and the stress paths propagate approximately at constant-po', i.e., sub-parallel to q-axis. Such a behavior is generally found from natural over-consolidated clays and this type of aspect strongly supports the elastic wall concept of the Cambridge stress-strain theories; the specimens remaining on elastic wall exhibits constant plastic volumetric strain [6].

4.0 STRENGTH AND DEFORMATION RELATIONSHIP

Figure 12 illustrates the relation between εf (failure strain i.e., failure unit deformation) and *qu* (unconfined compressive strength) in an arithmetic plot in terms of *wc/c* ratio of cement stabilised samples for C2 clay while Figure 13 illustrates the relation between εf and *qu* in terms of curing time of cement stabilised samples for C3 clay. Such figures are meaningful to delineate the ductile and brittle behavior of the samples. The relationship has produced a definite trend of reduction of failure strain (unit deformation) with incremental values of cement content and curing time. At higher values of *wc/c* ratio such as 30 (i.e., lowest cement content such as 4%), significant large failure strains whereas samples with low strength produce higher values of εf with constraint in a narrow band. These samples exhibit ductile behavior during shearing.

Ductile behavior is associated with low strength and higher failure strain (unit deformation). On the contrary, higher strength and low failure strain (unit deformation) correspond to brittle behavior. Generally, higher cement content and curing time are the main parameters to cause the stabilised mass brittle. In Figures 12 and 13, the brittle characteristics can be seen at relatively higher values of *qu*, where samples cluster along the best fit line.

On the other hand, ductile behavior can be observed at the region of relatively lower values of *qu* where samples show comparatively less wide scatter. The best fit line shows the required expressions with coefficients of correlation greater than 0.90.

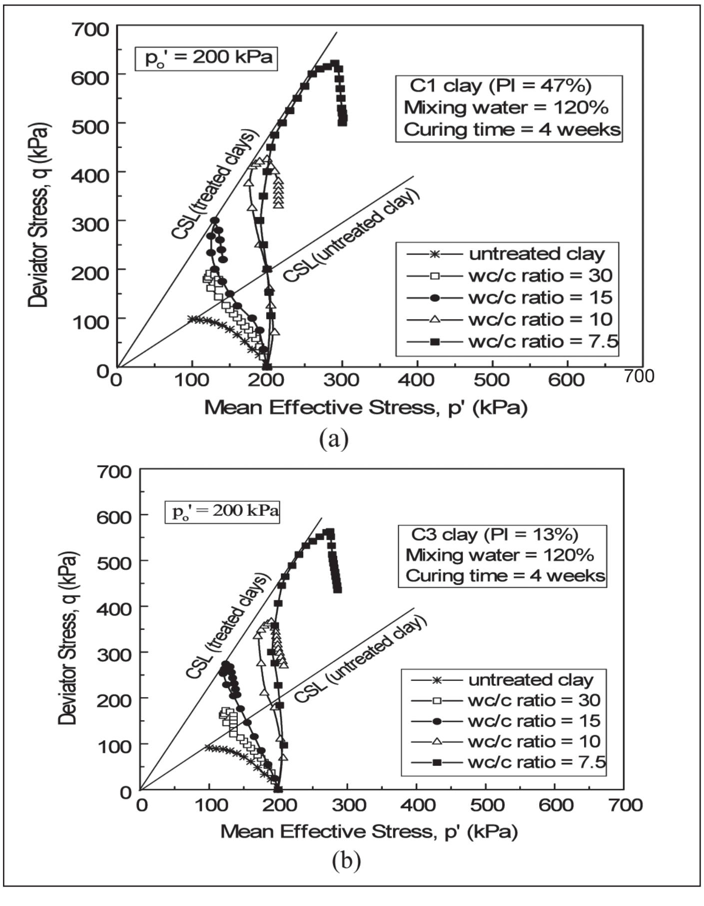


Figure 11: Undrained stress paths of cement treated clays (a) C1 clay and (b) C3 clay

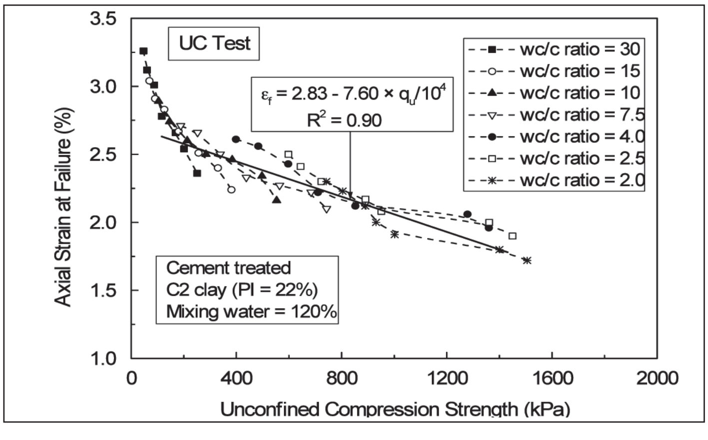


Figure 12: Relationship between qu and axial strain at failure shown in terms of wc/c ratio for cement treated C2 clay

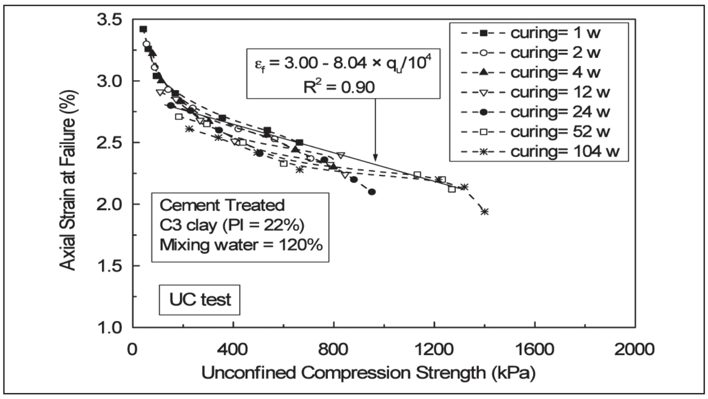


Figure 13: Relationship between qu and axial strain at failure shown in terms of curing time of cement treated C3 clay

The expressions for relation of εf (in %) and *qu* (in kPa) plot in terms of *wc/c* ratio for cement stabilised Bangladesh clays are linear equations as follow:

$\varepsilon_f = 2.34 - 7.01 \times q_u/10^4$ for high plastic (C1) clay

$\varepsilon_f = 3.00 - 8.04 \times q_u/10^4$ for medium plastic (C2) clay and

$\varepsilon_f = 2.83 - 7.60 \times q_u/10^4$ for low plastic (C3) clay

The mathematical expressions show that C1 clay has achieved lower failure strain than that of C2 clay and C3 clay. While, Kamaluddin [10] reported that the relationship (ε_f, q_u) for cement stabilised Bangkok clay at low mixing water content, such as $\varepsilon_f = 3.3 - 19 \times q_u /10^4$.

5.0 CONCLUSIONS

Strength and deformations characteristics of cement treated soft Bangladesh clays are studied through a series of unconfined compression, consolidation and unconsolidated undrained triaxial compression tests. From the test results, the following conclusions can be drawn:

i) The unconfined compressive strength and stiffness of cement treated Bangladesh clay increases with the increase of cement content and curing time. The resulting effect of improvement of strength leads to the formation of more structured for cemented clay.

ii) Cement content of less than 4% does not show any effective improvement of strength and deformation properties of soft Bangladesh clays however, beyond 4% and up to 40% cement content can be envisaged as Active Zone. Beyond 40% cement content is defined as Inert Zone. These zonal demarcations are observed only for 4 weeks curing periods. However, further investigation needs to be conducted to verify the extended range of Inert Zone by adding higher cement content and at longer curing periods.

iii) The significant increase in apparent pre-consolidation pressure (pc')/yield stress ($\sigma y'$) and reduction in volumetric strain are observed from consolidation tests of cemented clay samples at in-situ stress range. This is due to the structuration (existing of bond strength) of clay particles due to the inclusion of cement. The consolidation behavior of cemented clay seems to be consistent with that of the over-consolidated clays. This implies that the cemented clay undergoes structuration up to their yield stress and then the progressive destructuration (breaking of bond strength) takes place.

iv) The higher the value of cement content (lower *wc/c* ratio), the greater is the enhancement of the yield stress and decrease of compression index and swell index accompanied with gradual reduction of compressibility. The (εv, $log\sigma' v$) relationships show that the higher the cement content and curing time, the lower the volumetric strain incurred by the cemented sample.

v) The reduction in compression index (C_c) and swell index (C_s) are observed from consolidation tests of cemented clay samples at in-situ stress range. This is due to the structuration of clay particles due to the inclusion of cement. The swelling behavior of cemented clays seems to be consistent with that of the overconsolidated clays.

vi) The characteristic shape of (q-εs) curve also suggests that the deviator stress increases to a peak value and then strain softens to a lower residual value. The stress paths evidently explain the strength and deformation behavior of clays that belong to different category ranging from a low OCR (over-consolidation ratio) value to a high OCR value. These stress paths, correspond to different category of states such as normally consolidated, lightly, moderately and heavily over-consolidated state depend on amount of cementation.

vii) For the improvement of soft Bangladesh clay at high water content by cement admixture in shallow and deep foundations, in which the water content of the clay varies from 120% to 250%, the *wc/c* value is the prime parameter governing the engineering behavior of cement stabilised clays both in considered strength and deformation behavior, whereas the effect of fabric can be negligible.

viii) Ductile behavior is associated with low strength and higher failure strain (unit deformation) while, higher strength and low failure strain (unit deformation) correspond to brittle behavior.

ix) The relations between unit deformation i.e., strain, εf (in %) and strength, *qu* (in kPa) plot in terms of *wc/c* ratio can be expressed as:

$\varepsilon_f = 2.34 - 7.01 \times q_u/10^4$,
$\varepsilon_f = 3.00 - 8.04 \times q_u/10^4$ and
$\varepsilon_f = 2.83 - 7.60 \times q_u/10^4$

for stabilised high, medium and low plastic clays respectively.

x) For the improvement of soft Bangladesh clay at high water content by cement admixture, it is concluded that high plastic clay undergoes better improvement than low plastic clay. However, low plastic clay undergoes better improvement than medium plastic clay. ■

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