Clay-Water/Cement Ratio is the Prime Parameter for Fine Grained Soil Improvement at High Water Content

M. M. Rahman[1], A. Siddique[2] and M. K. Uddin[3]

[1]Dept. of Civil Engineering, Dhaka University of Engineering & Technology, Gazipur, Bangladesh
[2]Dept. of Civil Engineering , Bangladesh University of Engineering and Technology, Dhaka, Bangladesh
[3]Institute of Appropriate Technology, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

E-mail: mokhlesur_2005@yahoo.com

ABSTRACT

The in-situ deep mixing technique has been established as a means to effect columnar inclusions into soft ground to enhance the bearing capacity and reduce settlement. Since the inception of this method, developments in the plant and machinery, as well as associated field techniques, have surpassed the basic understanding of developments of soil strength in high water content clays admixed with cement. In this paper, an attempt is made to identify the factors governing the engineering behavior of cement stabilized soft clays. It helps not only to control the input of cementing agent to attain strength development with curing time, clay type and clay-water content, but also to understand the subsequent geotechnical engineering behavior of stabilized soft clays. The cementation bond strength increases as the clay-water/cement ratio (wc/c) decreases. It is demonstrated by the test results of consolidation, the yield stress in K_o-consolidation of samples increases with the decrease in wc/c, and samples having the same wc/c develop practically the same level of yield stress. The stress~strains behavior and strength characteristics in the unconfined compression test are practically the same as long as the wc/c is identical. It is revealed that clay-water/cement ratio wc/c is the prime parameter for such fine grained soil improvement.

KEYWORDS: cementation bond, clay-water/cement ratio, plasticity, geotechnical behavior, fabric, high water content.

1. INTRODUCTION

Soft clay formations in Bangladesh, especially when the in-situ water contents are high, unless they are markedly naturally cemented, have large potential for settlement with low inherent shear strength [12]. There are three types of fine grained soil (clay) in Bangladesh on the basis of plasticity, namely high plastic (C1) clay, medium plastic (C2) clay and low plastic (C3) clay. Preloading on such clay deposits with vertical drains (such as PVD or sand drain) can enhance the inherent shear strength and reduce the compression in a long time consolidation process [12]. An alternative means is to enhance the level of cementation bond by use of admixtures like cementing agents. The resistance to compression and consequent strength development in such a cemented state of clay increase with increasing curing time.

It is not practicable to admix a cementing agent with a large volume of in-situ soft clay. Hence, in-situ deep mixing methods (DMM) have been developed during the last three decades primarily to effect columnar inclusions into the soft ground to transform such whole soft ground to composite grounds. In Japan from 1975, the research and development of this method was started and put into practice by the Port and Harbour Research Institute [8]. The behavior of the group column type DMM improved ground has been investigated by [5] and [11]. The increase in strength with time of surrounding clay adjacent to soil-cement columns was experimentally and numerically studied by [9].

Investigations by [10] and [8] concentrated on the basic aspects involved in the strength development of high water content clays with cementing agents. [5] and [7] investigated the laboratory strength and deformation characteristics of stabilized soft clays at particular clay-water content. For improvement of soft clays by the deep mixing technique, the water content of the clay is varied by dispensing cement admixture using the wet method, there is no such works in Bangladesh. Thus, the behavior of the stabilized clay material in various conditions cannot be explained by the study at a particular level of water content. This paper proposes a new factor in laboratory model tests, clay-water/cement ratio (wc/c) as a standard parameter for investigating the geotechnical behavior improvement of cement-stabilized soft clays at high water content.

2. EXPERIMENTAL INVESTIGATION

2.1 Soil samples

Clay samples were collected in various districts of Bangladesh such as C1 clay from Gazipur, C2 clay from Gopalgonj and C3 clay from Khulna. The soil samples were collected from depth of 2 - 3 m from existing ground level with disturbed and undisturbed state. Its index properties are presented in Table 1. Type I Portland cement was used in this study. Test specimens were prepared from these clays and cement slurries.

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 clays with its water content corresponding to the required simulating levels quantity of cement resulting in clay-water/cement ratio (wc/c) of 7.5, 10 and 15 was thoroughly mixed so as to ensure uniform dispersion of the cementing agent. The clay-water content (wc) would be 120%, 150%, 200% and 250%. The mixing time was arbitrarily fixed at 10 minute. The 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 high top collars and bottom ended cap, taking care to prevent any air entrapment. Specimens of 50 mm diameter × 100 mm height were used for unconfined compression and tri-axial compression tests and 75 mm diameter × 100 mm height were used for consolidation and direct shear tests. After 24 hours the cylindrical samples were dismantled. All the cylindrical samples were wrapped in thick polythene bags and these were stored in a room of approximate constant temperature (25 ± 2^{oC}) until the lapse of different planned curing times. Consolidation, direct shear and tri-axial compression tests were carried out after 4 and 12 weeks of curing but Unconfined compression (UC) tests were run on samples after 1, 2, 4, 12, 24, 52 and 102 weeks of curing. The effective normal and confining pressures for direct shear and tri-axial compression tests respectively were 50, 100, 200 and 400 kPa. A back pressure of 100 kPa was maintained to insure the degree of saturation at all levels of testing.

2.3 Parameters

The parameter that can be identified by [4] and [8], is clay-water cement ratio, wc/c, which is the ratio of initial water content of the clay, wc(%) to the cement content, c(%). 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 to what extent the applicability of wc/c is varied the water content of clay is varied over a wide range in this research.

3. TEST RESULTS

3.1 Consolidation test

Table 2 presents the compressibility data of the cement stabilized samples having the same and different wc/c values but with different combinations of clay-water content (wc) and cement content(c). Compressibility parameters were calculated from the (e, $\log\sigma_v'$) and (ε_v, $\log\sigma_v'$) relationships of clay-cement mixtures at wc/c ratios of 15, 10 and 7.5 after 4 and 12 weeks of curing. The compression index (C_c), swell (C_s) and yield stress (σ_y') are presented in Table 2. The C_c and C_s are the slopes of the loading and unloading curves, 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 $\log\sigma_v'$ [2].

The clay-cement mixtures were made up from four conditions of initial clay-water content (w_i): 120%, 150%, 200% and 250% with three type clays: C1 clay, C2 clay and C3 clay. The (e, $\log\sigma_v'$) and (ε_v, $\log\sigma_v'$) relationships are plotted so as to take care of the effect of the difference in void ratio for the vertical stresses less than the yield stress as shown in Figs. 1 and 2 respectively.

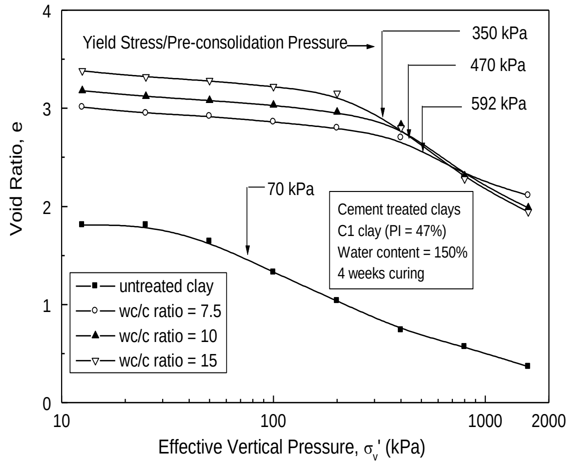


Fig. 1: Effect of wc/c ratio on e - $\log\sigma_v'$ relationships of type C1 clay

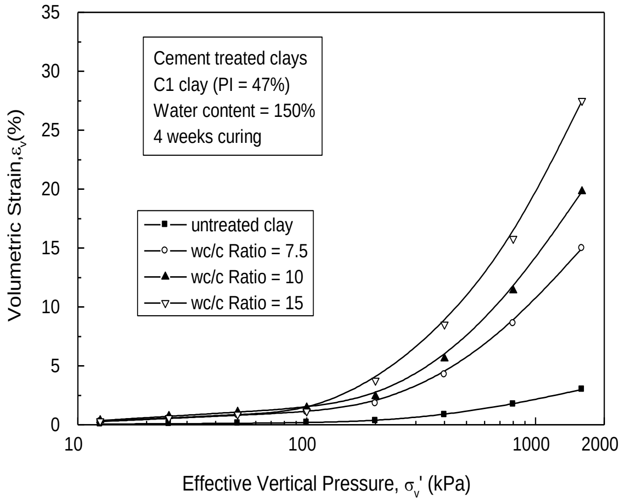


Fig. 2: Effect of wc/c ratio on ε_v - $\log\sigma_v'$ relationships of type C1 clay

The variations of compression index and swell index with wc/c are explained in Figs. 3 and 4 respectively. In this range, the cementation component is the dominant factor to resist compression. It is found that the yield stress and the deformation behavior at pre-yield stress of all samples having identical wc/c are practically the same. But samples with a higher clay water contents are stable at higher void ratios and provide a higher compression indices beyond yield stress, especially for samples made up at a high water content of 250% as shown in Table 2. This is due to the break up of cementation bond, which is similar to the behavior of naturally cemented clay.

Table 1: Physical and Index Properties of the Untreated Clays

Properties	Characteristics Values		
Type of Soil	C1 clay (LL > 50%)	C2 clay (LL =35-50%)	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: Compressibility Parameters for Cement Stabilized Clays

Curing (weeks)	wc (%)	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	1.188	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
Untreated clays			70	0.737	0.124	65	0.781	0.127	61	0.863	0.131

Table 3: Unconfined Compressive Strength (q_u) in kpa for Cement Stabilized Clays

Admix-ture	w_i (%)	wc/c Ratio	C1 Clay		C2 Clay		C3 Clay	
			Curing Time		Curing Time		Curing Time	
			4 w	12 w	4 w	12 w	4 w	12 w
Cement	120	7.5	399	533	291	405	339	438
		10	251	335	179	267	213	284
		15	149	226	106	172	126	180
	150	7.5	383	528	277	395	318	429
		10	241	338	175	260	200	266
		15	143	217	124	169	138	185
	200	7.5	381	520	272	390	314	421
		10	238	330	170	249	195	257
		15	134	207	95	155	112	165
	250	7.5	379	511	268	401	311	409
		10	235	321	172	258	189	265
		15	124	187	88	160	108	166
Untreated clays			50		41		58.5	

Table 4: Shear Strength Parameters (c' and ϕ') for Cement Stabilized Clays

Para-meters	w_i (%)	wc/c Ratio	C1 Clay		C2 Clay		C3 Clay	
			Curing Time		Curing Time		Curing Time	
			4 w	12 w	4 w	12 w	4 w	12 w
c' in kPa	120	7.5	131	141	82	87	104	115
		10	116	134	77	82	91	101
		15	112	129	73	77	87	96
	150	7.5	114	128	74	80	86	99
		10	101	117	69	75	75	83
		15	97	112	64	69	70	78
	200	7.5	109	118	69	76	82	89
		10	96	112	65	70	71	79
		15	91	105	61	65	67	74
	250	7.5	101	110	64	71	75	80
		10	88	103	60	65	66	73
		15	83	97	55	59	63	69
ϕ' in degree	120	7.5	13.6	13.0	17.5	16.4	16.0	14.2
		10	12.9	12.2	15.4	14.6	14.1	13.0
		15	11.8	11	13.1	12.8	12.5	11.3
	150	7.5	12.2	12.0	13.5	13.1	15.4	15.2
		10	11.6	10.9	12.0	11.3	13.5	12.6
		15	10.5	9.8	10.1	9.8	12.0	10.8
	200	7.5	11.4	11.1	14.7	14.0	13.0	12.5
		10	10.8	10.1	12.9	12.3	11.4	10.6
		15	9.9	9.2	11.0	10.7	10.2	9.4
	250	7.5	10.6	10.4	13.3	12.9	11.8	11.0
		10	10.0	9.5	11.7	11.1	10.5	9.6
		15	9.2	8.6	9.9	9.5	9.1	7.9
c'	Untreated clays		15.2		13.5		11.6	
ϕ'	Untreated clays		6.4		8.0		7.1	

Table 5: Comparison of Shear Strength and Axial Strain at Failure of Cement Stabilized Clays (p_o' = 200 kPa and w_i = 120%) from CIU and CID Tests

Curing Time (week)	Clay Type	wc/c Ratio	Shear Strength (kPa)		Axial Strain at Failure (%)	
			CIU test	CID test	CIU test	CID test
4 w	C1	7.5	643	706	4.07	4.60
		10	485	521	5.12	5.56
		15	372	456	5.50	6.00
		30	276	335	5.68	6.54
	C2	7.5	474	561	4.71	4.95
		10	350	413	5.88	5.93
		15	271	365	6.31	6.73
		30	201	268	6.53	7.21
	C3	7.5	547	646	4.51	4.89
		10	402	474	5.74	5.83
		15	318	419	6.19	6.31
		30	228	317	6.41	6.92
12 w	C1	7.5	811	958	3.59	4.11
		10	606	715	4.38	4.87
		15	461	620	4.76	5.26
		30	340	445	4.93	5.64
	C2	7.5	564	645	3.88	4.34
		10	498	545	4.48	5.05
		15	389	426	4.88	5.73
		30	271	311	5.23	6.14
	C3	7.5	736	842	3.70	4.21
		10	541	638	4.56	4.92
		15	428	561	4.93	5.43
		30	306	404	5.09	5.86

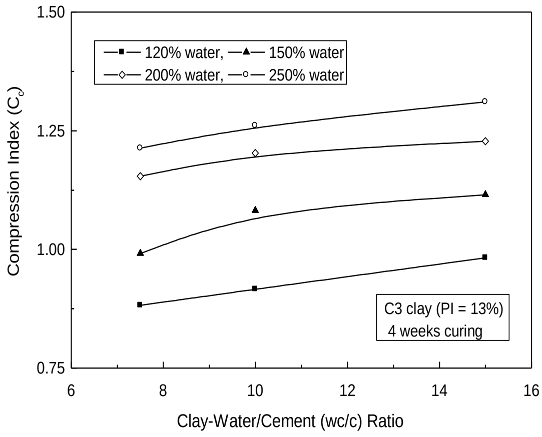


Fig. 3: Effect of clay-water/ cement (wc/c) ratio on compression index of type C3 clay

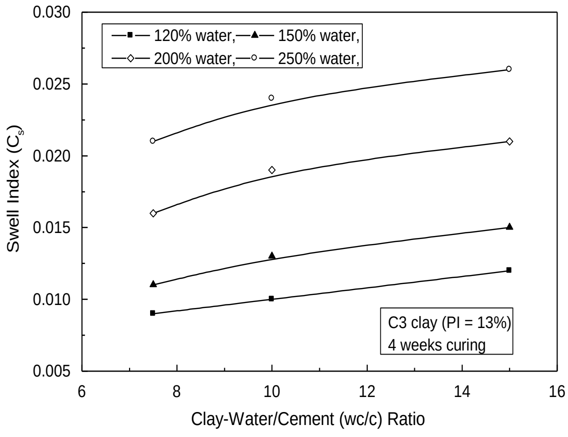


Fig. 4: Effect of clay-water/ cement (wc/c) ratio on swell index of type C3 clay

The compression indices at post yield state of clay-cement mixtures having identical initial clay-water content are in almost the same order, even if they are made up from different cement content. It is also clear from Table 2 that the lower the value of wc/c, the greater enhancement of yield stress and the lower compression index and swell index. The clay-water/cement ratio affects not only the deformation characteristic, but also the rate of hardening related to hydration and pozzolanic reactions. The higher the curing time, the greater the enhancement of the yield stress and the lower compression index and swell index. Results for same wc/c and curing periods, the higher the water content, the lower the enhancement of the yield stress and the higher the compression index and swell index. Also, the results for same wc/c and curing periods, C1 clay is gained more yield stress and lower compression indices than C3 clay but C3 clay is gained more yield stress and lower compression indices than C2 clay. Comparing the effect for variables wc/c, curing time, water content and clay type on improvement of compressibility properties, the role of wc/c has prompter, initiative and more effective.

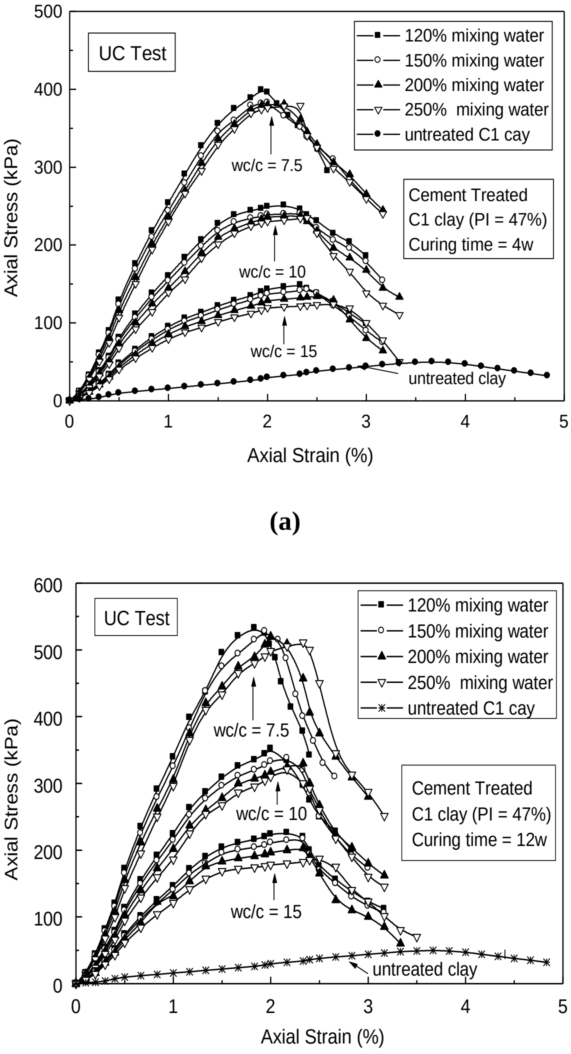
3.2 Unconfined compression test

Table 3 shows unconfined compression strength of samples with different initial water contents and different levels of cementing agent but the same wc/c ratio, at 4 and 12 weeks curing time for stabilized clays. The wc/c range included in the table is 7.5, 10 and 15. The stress-strain behavior of stabilized samples for typical C1 clay having the same clay-water/cement ratio are shown Figs. 5a and 5b for 4 and 12 weeks curing respectively. It reveals that the higher curing time, the higher strength and the lower strain. Shear types of failures were observed. The stress-strain curves shows that the samples exhibit a strength that reaches a peak and then reduces gradually as straining continues. In general, stress-strain curves of the stabilized samples were found to increase abruptly to peak values, then suddenly decreased to low residual values at low clay-water/cement ratio and long curing time. From the aspect of stress-strain relationships, the overall behavior was categorized into brittle, quasi-brittle and ductile. Higher strain, low strength and mild peak were found to be associated with ductile behavior for samples having higher clay-water/cement ratio, whereas, lower strain, higher strength and sharp peak exhibited brittle behavior for samples having lower clay-water/admixture ratio. For the improvement of soft clay at high water content by cement admixture, it is concluded that C1 clay undergoes better improvement than C3 clay but C3 clay undergoes better improvement than C2 clay because the pH values have been measured 8.3, 6.6 and 7.8 for C1, C2 and C3 clays respectively. If pH value exists above 7, soil solution is alkaline and pH value exists below 7, soil solution is acidic in nature. Thus, the C2 clay has a large reserve of potential acidity, so a relatively large amount of cement is needed to first exhaust the reserve acidity, and thereafter, to raise the pH value to the desired value at which the cement-clay reactions are enhanced.

Fig. 6 shows that the lower the wc/c, the greater the enhancement of the cementation bond strength inducing higher strength. Fig. 5 shows that same the wc/c but different water content, the enhancement of the cementation bond strength reaches about the same levels. Thus, the wc/c is a structural parameter for stabilized soft clays.

3.3 Direct shear test

The shear strength parameters (c', ϕ') for the stabilized clays in drained direct shear tests are shown in Table 4. The effective cohesion and friction angle of samples contained higher cement (lower wc/c ratio) were greater than those of samples contained lower cement (higher wc/c ratio). This is possibly due to the effect of stiffness and more lubricating effect in cement stabilized condition that prevents soil slippage and frictional movement. The apparent cohesion of cement stabilized C1 clay were higher than that of cement



(a)

(b)

Fig.5: Stress-strain variations of type C1 clay at different wc/c for curing (a) 4 week and (b) 12 week

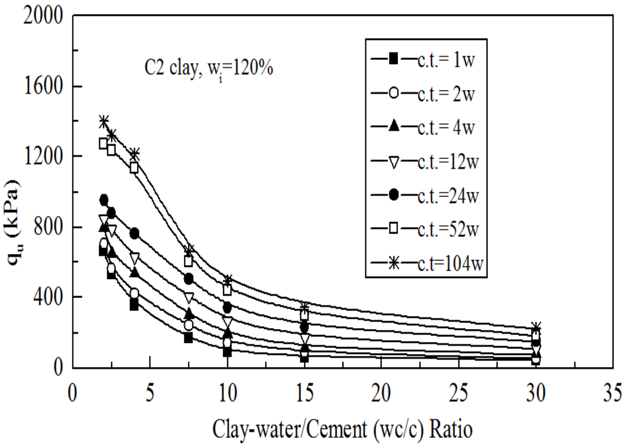


Fig. 6: Strength variations with wc/c for stabilized type C2 clay

stabilized C2 and C3 clays but the friction angle of cement stabilized C1 clay were lower than that of cement stabilized C2 and C3 clays. This is again possibly due to disappearance of cluster and lubricating effect of water due to larger spacing of fabric. The friction angle is decreased but the cohesion is increased with increasing curing time because the soil slippage and frictional movement are less prevented due to hydration of cementation at high water content. The cohesion of treated clays is decreased with increasing clay-water content because the stiffness and non-lubrication are decreased due to hydration of cementation at high water content.

The effect of clay-water/cement ratio and curing time on effective cohesion and friction angle for stabilized clays are shown in Figs. 7 and 8 respectively at w_i = 120% with curing = 4 and 12 weeks. The cohesion of treated clays is abruptly decreased with increasing wc/c ratio because the stiffness and non-lubrication are decreased due to less cement content. The variation of cohesion with the wc/c ratio up to 9 is nonlinear type, beyond wc/c ratio 9**,** the variation of cohesion is linear type decreasing relationship for the stabilized clays. The friction angle of treated clays is abruptly decreased with increasing wc/c ratio because the slippage and frictional movement are less prevented due to less cement content.

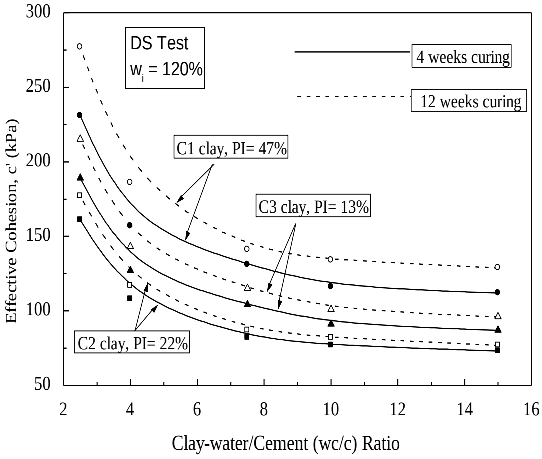


Fig. 7: Effective cohesion variations with wc/c of stabilized clays for curing 4 and 12 weeks

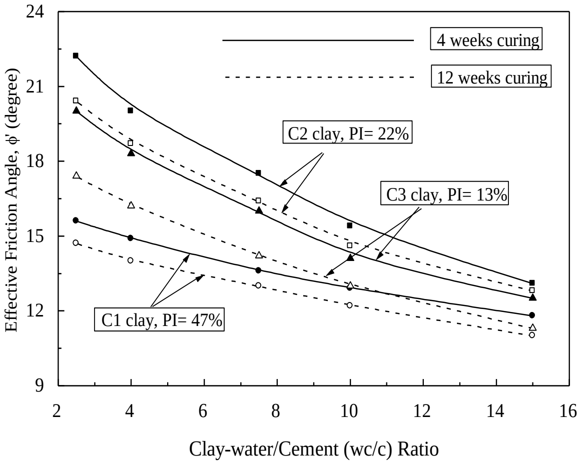


Fig. 8: Effective friction angle variations with wc/c of stabilized clays for curing 4 and 12 weeks

3.4 Triaxial compression test

Table 5 shows the effect of clay-water/cement ratio, wc/c on the shear strength manifested by the results of isotropically consolidated undrained and drained triaxial compression (CIU and CID) tests, with effective cell pressures (p_o') from 200 kPa. A general trend exists in Table 5 that the maximum deviator shear strength increases with decreasing clay-water/cement (wc/c) ratio. It has also been found that generally the axial strain at the maximum deviator stress reduces with decreasing wc/c ratio. It has been found from Table 5 that shear strengths obtained from CID triaxial compression test are increased to average about 1.15 times than those obtained in CIU test but failure strains for CID test are increased to average about 1.10 times than those obtained from CIU tests.

Fig.9 shows that the improvement of the samples having high wc/c ratio (i.e. 30 and 15) has been found to be much smaller peak deviator stress than those having the samples of low wc/c ratio (i.e. 7.5 and 10). It can be seen from figures that q-ε_a relationships are largely dependent on wc/c ratio. After reaching the peak deviator stress, all the q-ε_a relationships have been found to fall under varying rates depending on the parameter, wc/c, revealing that cement is the paramount factor that controls the post-treatment relationships of q-ε_a relationships.

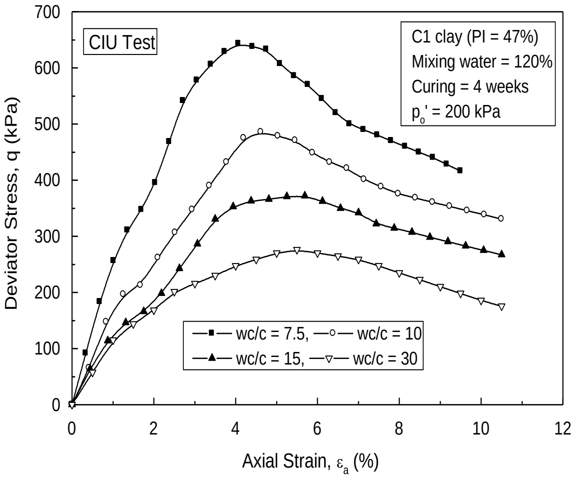


Fig. 9: Effect of wc/c ratio on deviator stress-axial strain of type C1 clay from CIU test

Fig. 10 shows that the higher the curing time, the greater the peak deviator stress and lower the axial strain. Results for same wc/c, p_o' values and curing periods, C1 clay is gained more peak shear strength than C3 clay but C3 clay is gained more peak shear strength than C2 clay. Fig. 11 shows that the samples consolidated to higher consolidation pressure attain higher values of maximum deviator stress. Fig. 12 shows that same the wc/c but different water content, the peak deviator stresses reach about the same

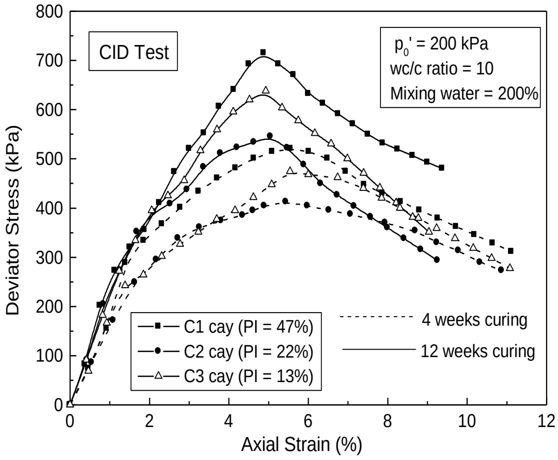


Fig. 10: Effect of curing time and clay type on deviator stress-axial strain from CID test

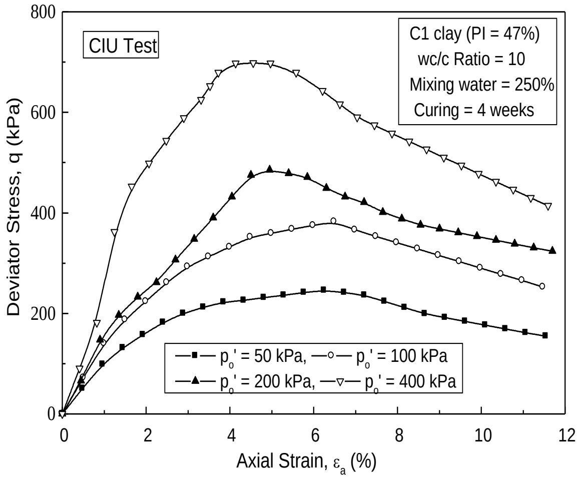


Fig. 11: Effect of pre-shear pressure on deviator stress-axial strain of type C1 clay from CIU test

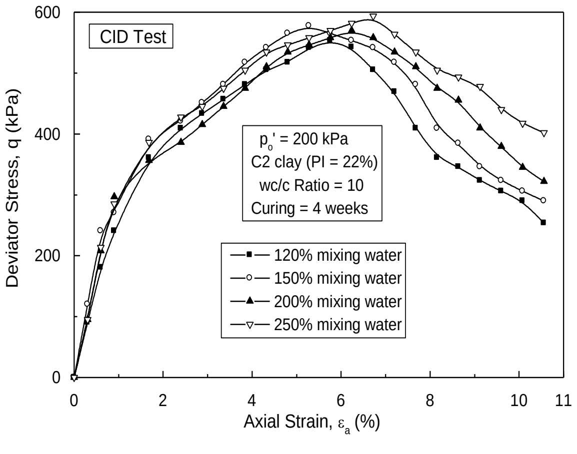


Fig. 12: Effect of water content on deviator stress-axial strain of type C2 clay from CID test

levels. Hence, wc/c ratio is a convenient parameter to adjust cement content in water to get the same level of strength with the same curing time. From the above test results, it is revealed that the wc/c is the prime parameter influencing the engineering behavior of cement-stabilized clay. [3], [4] and [8] also supported the same clay-water/cement (wc/c) ratio's concept.

4. ANALYSIS AND DISCUSSION

From the above test results, it is revealed that the wc/c is the prime parameter influencing the engineering behavior of cement stabilized soft clays. Often the treatment of clays are done conventionally in highway stabilization involves mixing of the clay in a relatively dry state with cement and the water content specified for compaction. What happens to the clay in the presence of moisture and cementing agents is that the clay gets transformed into modified clay i.e., grouping of particles takes place due to physicochemical interactions with clay ~ cement ~ water interactions [1]. Since these are at the particle level, it is not possible to get a homogeneous mass which can exhibit the desired levels of strength. External compaction effort is needed to transform this modified soil to a soil state with locked in pre-stress so as to act as an engineering material. The same is not the case when high water content clays are mixed with cement. It is not the clay to which admixture is made available but to an interacting clay-water system. The interacting clay-water system cannot be identified by clay but by water content. This aspect has been amply elaborated by [8] and [10].

It is useful to explain the engineering behavior of cement-stabilized clay based on its microstructure. It is preferable to use structure of clay type to refer to the fabric that is an arrangement of particles, particle group and pore spaces in the soil as well as cementation. A cluster is a grouping of particles or aggregates into large fabric units and a fabric composed of grouping of clusters. The microstructure of untreated and cement treated clays are shown in Figs. 13 and 14 respectively. The cementing agents can be considered to

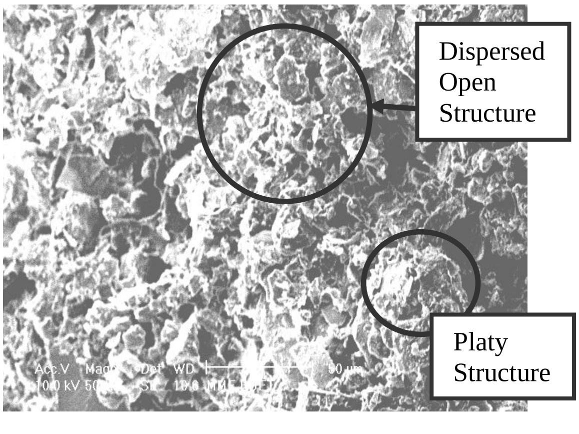


Fig. 13: SEM image of untreated (remoulded) for type C1 clay

drift to the spacing between clusters due to the electro-chemical nature of interaction and to weld the fabric by gel as subsequent hydration of cement takes place. Hence, there is a clay-water/cement ratio reflecting the contribution of the final structure formed as flocculated and reticulated clay-cement cluster. This structure is a combination of fabric and cementation, play a significant role in the strength and deformation behavior.

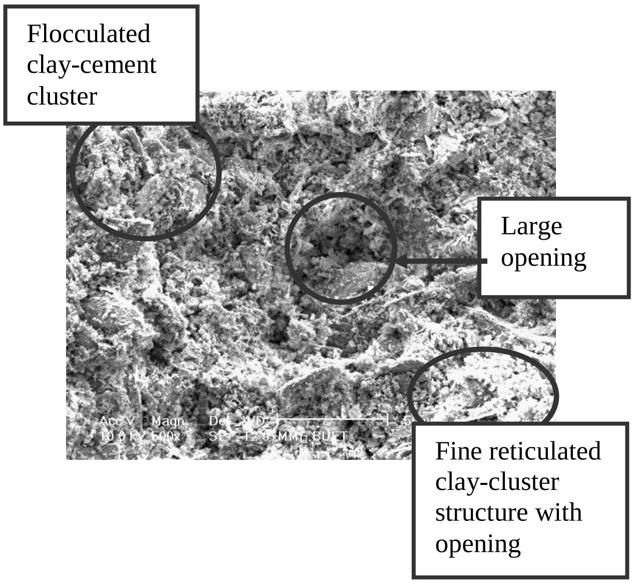


Fig. 14: SEM image of wc/c ratio 7.5 for type C1clay (4 weeks curing time and 120% mixing water)

The liquid limit state for different soft clays is the state that the micro fabric will form such that the addition of cement alter the liquid limit as long as the liquid limit is determined with the initial setting of cement. On the contrary, when the dry clay is mixed with water to be closer to the plastic limit along with cement, it will exhibit the prosperity of a modified soil. Due to the formation of clay clusters, which can hold water caused by the cementation, the plastic limit will increase. As a results, the liquidity index of the clay-cement mixture immediately after mixing with cement increases since the plasticity index is used as the denominator while the clay-water content insignificantly changes in decrease. Fig. 15 shows that the change in liquid limit, plastic limit and plasticity index for cement stabilized C2 clay. The change in the liquid limit due the treatment is insignificant. On the other hand, the plastic limit significantly increases with cement content and curing time. Thus, the decrease in the plasticity index of the mixture is recognized due to the significant increase in the plastic limit of the mixture. The change in water content is minimal. As a result, the liquidity index is increased after adding cement admixture. The similar results were also reported by [1].

5. MICRO-MECHANISTIC EXPLANATION

The compressibility and strength characteristics and microstructure have enabled us to infer that the fabric of soft clay both in un-cemented and induced cemented states. Hence, the role of induced cementation is to weld fabric [13] analyzed the strength data with the water content as limit water content, since they considered that the fabric pattern of all soils at such a state is the same. With the liquid limit of clay as a variable parameter, the previous analysis indicated by [13] that as the water content of the clay increases; the spacing between clusters as well as that between particles increases; hence strength developed for the same cement content decreases. To enhance the strength to the same level, the cement content has to be increased. Definitely, the identification of the fabric pattern is important to identify the possible cementation sites but it is not complete by itself since the structural state (fabric and cementation) cannot be reflected by the parameter water content alone. The experimental observations for three different soft clays in this investigation indicate that it would be advantageous to include the cement content in the same parameter since it would take care of the bonding component of the state represented by water content. Hence, clay-water/cement ratio, wc/c, is an integrated parameter of the structural state of the soft clay in its induced cemented state. It is a convenient parameter to adjust cement content in water to get the same level of strength with the same curing time, which is supported in the investigation of [8].

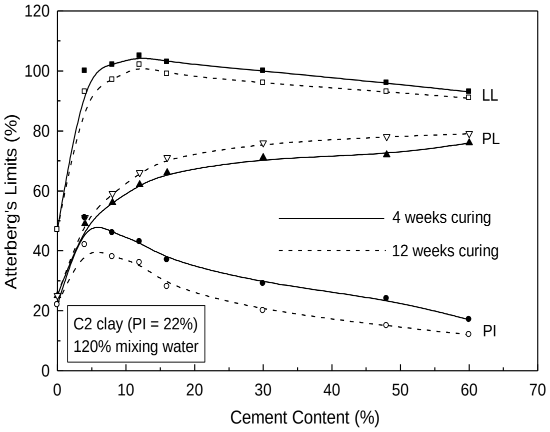


Fig. 15: Effect of cement and curing time on Atterberg's limits for type C2 clay

6. ANALYSIS OF COMPRESSION BEHAVIOR IN K_O-CONSOLIDATION

Figs. 1 and 2 reveal that resistance to compression is markedly enhanced before drastic compression occurs, as vertical pressure increases. This is attributed to the induced cementation bond created by cement. It has been observed that as the clay-water/cement ratio increases, which mean that cement content is decreased, the yield stress reduces. As the curing time increases for the same input condition, the yield stress further increases. Thus, it implies that the yield stress of the stabilized clay increases with increase in curing time and decrease in wc/c as shown in Table 2. It is also revealed that, for Bangladesh clays with four levels of water content i.e., 120%, 150%, 200% and 250%, the yield stress is practically the same as long as the wc/c value is identical; the fabric is not taken into account. The effect of fabric plays a dominant role on the compressibility after the yield state in which the cementation bond is broken down. This is reinforced by results showing that clay-cement mixtures with higher clay-water contents undergo higher settlement at post yield state. This leads to the conclusion that the role of cement admixture is to increase the yield stress in K_o-consolidation, resulting in an increase in the yield surface and failure envelope. However, the resistance to plastic deformation is governed by the fabric [8].

7. ANALYSIS OF STRESS~STRAIN AND STRENGTH CHARACTERISTICS

The test results show that the geotechnical engineering behavior of cement-stabilized clay is dependent upon the clay- water/cement ratio, wc/c and fabric. The role of wc/c is that the lower the wc/c, the greater the yield stress, resulting in enhancement of the yield surface, which means that the failure envelope gets increased; hence, the strength increases. However, the stress ~ strain behavior is governed by the fabric (clay type) and clay-water content. The higher the water content, the greater the spacing between clusters; this leads to a decrease in shear strength and an increase in volumetric strain. With the initial clay-water content at 120% and 150%, the wc/c has a greater influence on the engineering behavior than the fabric. The engineering behavior of the mixtures subjected to low and high effective cell pressures are identical as long as the wc/c is the same, and the clay-cement mixture with lower wc/c develops higher deviator stress. If the initial clay water content is high (viz. 200% to 250%), the wc/c and fabric both play a dominant role in the engineering behavior depending upon the effective cell pressure condition and level of cement content.

The fabric becomes the significant factor for the clay-cement mixtures made up at low wc/c (10 and 7.5) and subjected to high effective cell pressures (200 and 400 kPa). This can be explained by the fact that the engineering behavior is initially governed by the cementation bond, and then the stress paths proceed up to a certain level where the cementation bond is broken down. At this level, the samples at a high initial clay-water content of 200% to 250% exhibit lower shear strength and higher deformation because of the large spacing between clusters. On the other hand at a low effective cell pressure (viz. 50 and 100 kPa), the effective cell pressure is far lower than the yield stress and thus the change of fabric is minimal during shearing. As a consequence, all samples having the same wc/c both made up at low and high clay-water contents exhibit identical deviator stress versus axial strain response [4] and [8].

At higher cement content, the treated specimen becomes much more brittle, with abrupt drops in post-peak stress with strain, which is more akin to the effect of structuration (formation of cementation bond) and destructuration (breaking of cementation bond) processes involved [1]. This is essentially attributed to the cementation bond characteristics. The contribution by the water content of the clay to the stress ~ strain characteristics is far lower than that due to the wc/c thus the cementation bond is the same for mixtures having the same wc/c (Figs. 5 and 12).

When the water content of clay is high and the clay-water/cement ratio is low (e.g. w_i = 200% to 250% and wc/c = 7.5), the strength of the clay-cement mixture is slightly lower than that at a lower clay water content because the spacing between clusters is large, resulting in a reduction in shearing resistance. However, this effect from the fabric is modest when the clay-cement mixtures are made up at low cement content such as at wc/c of 15. The stress ~ strain behavior of the stabilized samples at the same wc/c exhibits identical modulus since the confining pressure equals zero in the unconfined compression test; hence, all samples fail inside the yield surface and the elastic behavior can be recognized according to state boundary surface [7]. From the above results, it can be concluded that the lower the wc/c, the greater the yield stress in K_o-consolidation and failure envelope; however, the characteristics of plastic deformation and stress ~ strain behavior are governed by the fabric.

10. CONCLUSIONS

Based on the test results for the effect of test variables (wc/c, curing time, water content and clay type) on the engineering behavior for improvement of stabilized soft clays, it is evident that the clay-water/cement (wc/c) ratio is the prime parameter for analysis of engineering behavior of cemented soft clays. This parameter is a structural parameter reflecting the influence of both fabric of clay as reflected by its water content and cement content reflecting the level of cementation. At the micro level, it is a combination of fabric and the level of welding of the fabric resulting in the structure of the clay imparting its geotechnical characteristics of the cemented state. The following conclusions can be drawn:

(i) For a given soft clay, the cementation bond strength increases as the clay-water/cement ratio, wc/c decreases. It is demonstrated by the test results of consolidation, the yield stress in K_o-consolidation of samples increases with the decrease in wc/c, and samples having the same wc/c develop practically the same level of yield stress. The stress~strains behavior and strength characteristics in the unconfined compression test are practically the same as long as the wc/c is identical.

(ii) For sample made up at a high wc/c such as 30 and 15, the drained behavior in tri-axial test is governed only by wc/c. The engineering behavior is identical as long as the wc/c is the same, which is strengthened by test results of samples with water contents varying from 120% to 250%.

(iii) Only the wc/c is a parameter governing the engineering behavior of samples made up at a low wc/c (such as 10 and 7.5) and subjected to low effective cell pressure, because all clay-cement mixtures exhibit the same elastic behavior. The same stress ~ strain relationships are realized for all samples having the identical wc/c.

(iv) The fabric has a great influence on the stress~strain behavior for samples made up at a low wc/c and subjected to high effective cell pressures. Their states of stress lie on the state boundary surface where the that samples exhibit elasto-plastic behavior. It is revealed samples having the same wc/c develop practically the same peak deviator stress.

(v) For the improvement of soft clay at a 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 stabilized clays both in compressibility and shear behavior, whereas the effect of fabric can be negligible.

(vi) 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 but low plastic clay undergoes better improvement than medium plastic clay.

REFERENCES

[1] Chew, S.H., Kamruzzaman, A.H.M. and Lee, F.H.: Physicochemical and engineering behavior of cement treated clays, Journal of G. and Geo-E. Engineering, ASCE, pp 696-706, 2004.

[2] Horpibulsuk, S., and Miura, N.: A new method for predicting strength of cement stabilized clays, Coastal Geotechical Engineering in practice, Rotterdam, ISBN 50 5809 1511, 2000.

[3] Horpibulsuk, S., and Miura, N. and Nishsida, K: "Factors influencing field strength of soil-cement column", Proc. of GEC, AIT, Bangkok. Thailand. pp 623-634, 2000.

[4] Horpibulsuk, S., Miura, N. and Nagaraj, T. S.: Analysis and assessment of strength development in cement admixed clays, proc. Int. Conf, on Civil Engg. (ICCE) IIS, India. pp156-163, 2001.

[5] Hashizume, H., Okochi, Y, Dong, J Horii, N, and Toyosawa, Y: Study on the behavior of soft ground improved using Deep Mixing Method. Proc: Int. Conf. on centrifuge 98, pp851-856, 1998.

[6] Kamaluddin, M., Balasubramaniam, A. S. and Bergado, D. T.: Engineering behavior of cement treated Bangkok soft clay, Geotechnical Engineering Journal, 28 (1), pp 89-119, 1997.

[7] Kamaluddin, M. and Buensuceso, B. R.: Lime treated clay: Salient engineering properties and a conceptual model, Soil and Foundations, Vol 42, No. 5, pp 79-89, 2002.

[8] Miura, N., Horpibulsuk, S., and Nagaraj, T.S.: Engineering behavior of cement stabilized clay at high water content. Soils and Foundations, Japan, Vol. 41, No. 5, pp33-45, 2001.

[9] Miura, N., Shen, S. L., Koga, K. and Nakamura, R.: Strength change of the clay in the vicinity of soil-cement column, J. of Geotech. Engrg. JSCE, (569 / 111-43), pp 209-221, 1998.

[10] Nagaraj, T. S., Miura, N. and Yamadera, A.: Induced cementation of soft clays - analysis and assessment, Int. Symp. on Lowland Technology, ILT, Saga University, Japan: pp267-278, 1998.

[11] Probaha, A., Shibuya, S. and Kishida, T.: State of the art in deep mixing technology. Part III: geomaterial characterization, Ground Improvement, Thomas Telford Ltd., Japan: pp91-110, 2000.

[12] Siddique, A., Safiullah A. M. M., and Ansary M. A.: Characteristic features of soft ground engineering in Bangladesh. Proc. of International Symposium, Japan, Vol. 2, pp. pp 231-248, 2002.

[13] Yamadera, A., Nagaraj, T. S. and Miura, N.: Prediction of strength development in cement stabilized marine clay, Proc. Geotech. Engrg. Conf., AIT, Bangkok, pp 56- 65, 1997.