ENGINEERING BEHAVIOUR OF CEMENT TREATED SOFT CLAY AT HIGH WATER CONTENT

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ABSTRUCT

The in-situ deep mixing technique has been established as a means to enhance the bearing capacity and reduce settlement into soft ground. This study is concerned with the stress-strain-strength, stiffness, compressibility and expansibility properties of cement stabilized soft clays at high water content. 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 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. In general, stress-strain curves of the treated samples were found to increase abruptly to peak values, then suddenly decrease to low residual values at low clay-water/cement (wc/c ratio) and long curing time. It has been found that the effective cohesion (c^I) and frictional angle (φ^I) of samples increased with increasing cement content (or decreasing wc/c ratio) but c^I increases and φ^I decreases with increasing curing time. Results from consolidation tests showed marked increase in pre-consolidation pressure and reduction in compression index and swell index with increasing cement content and increasing curing time. It is revealed that clay-water/cement ratio (wc/c) is the prime parameter for fine grained soil improvement.

Keywords: *Soft clays, cement stabilization, stress-strain, unconfined compressive strength, compressibility*

1. INTRODUCTION

Various regions of Bangladesh with deep deposits of soft clays at high water content causes special problems associated with engineering design and construction since they have low strength and high compressibility. Thus, suitable ground improvement techniques are needed for deep excavation projects in these soft clays for suitability and deformation control. 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 (Siddiquej et al., 2002). 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 (Nagaraj et al., 1998; Miura et al., 2001). The behavior of the group column type DMM improved ground has been investigated by (Hashizume et al., 1998) and (Probaha et al., 2000). The increase in strength with time of surrounding clay adjacent to soil-cement columns was experimentally and numerically studied by (Nagaraj et al., 1998; Miura et al., 2001).

Investigations by (Nagaraj et al., 1998) and (Miura et al., 2001) concentrated on the basic aspects involved in the strength development of high water content clays with cementing agents. (Hashizume et al., 1998) and (Kamaluddin et al., 2002) 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. Therefore, there is a need to study the engineering behavior of cemented soft clays of Bangladesh at high water content and use them to explain some aspects of the observed engineering behavior for deep mixing method in a well-controlled laboratory condition first, before extending it to the field condition.

This study presents stress-strain-strength and compressibility characteristics of cement stabilized soft clays at high water contents so that the state of water contents will simulate the condition realized in deep mixing method. Attempts have also been made to identify the critical factors governing the engineering behavior of cement treated clays, which 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 engineering behavior.

2. EXPERIMENTAL INVESTIGATION

2.1 Soil Sample

Clay sample was collected from KUET campus at a depth of 5 ft from the existing ground level with disturbed and undisturbed state. Its index properties are presented in Table 1. Portland composite 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 cement slurry was prepared with the required amount of cement with water. The mixing of the hardening agent and the clay was done until the mixture was uniformly mixed, the mixing done within 10 minutes. Such a uniform paste was transferred to a cylindrical mould 75 mm diameter x 100 mm height and 44 mm diameter x 120 mm height. Cylindrical moulds of 75 mm diameter x 100 mm height were used for the preparation of samples for direct shear and consolidation tests and 44 mm diameter x 120 mm height were used for the preparation of samples for unconfined compression tests. After 48 hours the cylindrical samples were dismantled. All the cylindrical samples were wrapped in thick polythene bags and these were stored in room temperature until the lapse of different planned curing times. Then the sample was trimmed to the size required for the specific tests to be conducted, i.e., to 6o mm diameter x 25.4 mm high for the shear tests and to 63.5 mm diameter x 25.4 mm high samples for the consolidation tests.

2.3 Parameters

Clay-water cement ratio, w c/c, 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 w c/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 study.

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, logσ_v') relationship of clay-cement mixtures at wc/c ratios of 15, 10 and 7.5 after 2 and 4 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 logσ_v' (Horpibulsuk et al,. 2000).

The clay-cement mixtures were made up from four conditions of initial clay-water content (w_i): 120%, 150%, 200% and 250% with the clay. The (e, logσ_v') is 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.

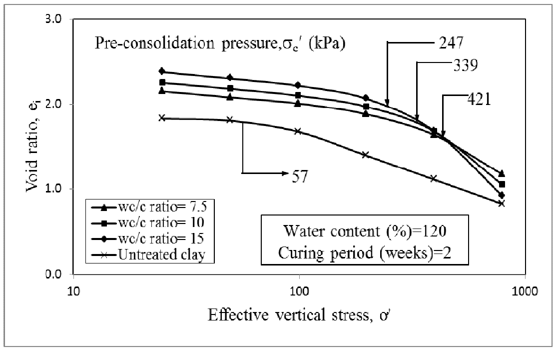

Figure1: Effect of wc/c ratio on e - logσ_v' 2 weeks of curing

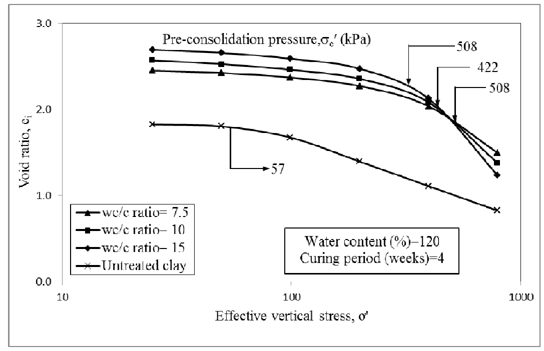

Figure2: Effect of wc/c ratio on e - logσ_v' 4 weeks of curing

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 breakup of cementation bond, which is similar to the behavior of naturally cemented 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. Comparing the effect for variables wc/c, curing time and water content on improvement of compressibility properties, the role of wc/c has prompter, initiative and more effective.

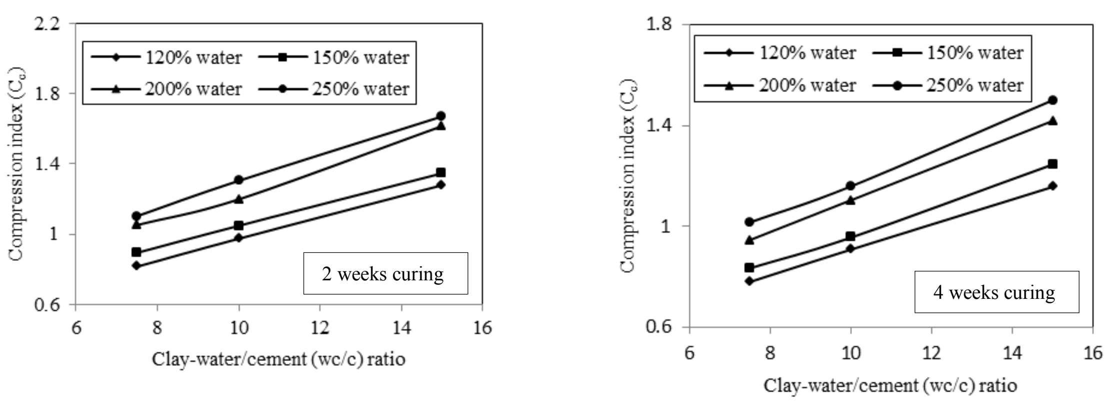

Figure 3: Effect of clay-water/cement (wc/c) ratio on compression index

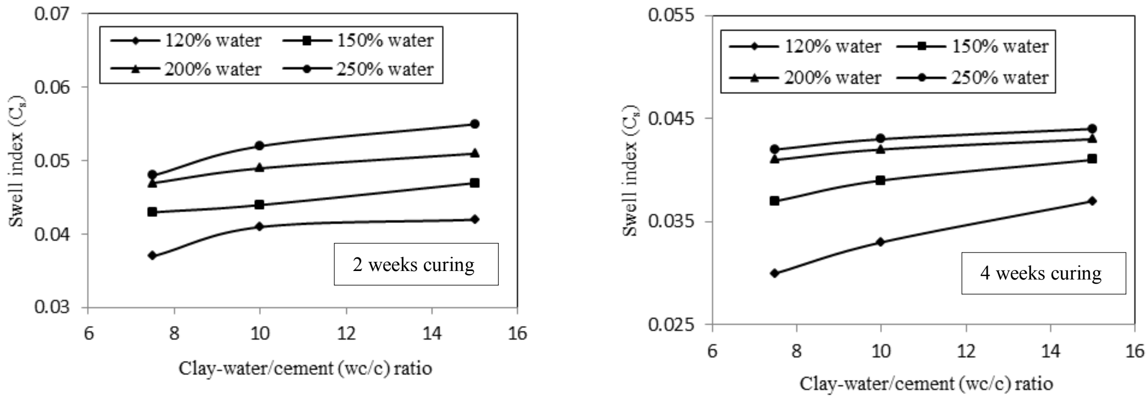

Figure 4: Effect of clay-water/ cement (wc/c) ratio on swell index

Table 1**:** Physical and index properties of the untreated clay sample

Property Name	**Value**	**Property Name**	**Value**
Initial moisture content w (%)	38	Liquidity Index, LI	0.49
Liquid limit, LL (%)	55	Sand % (4.75-0.075mm)	15
Plastic limit, PL (%)	21	Silt % (0.075-0.002mm)	60
Plasticity index, PI	34	Clay % (<0.002->0.001mm)	25
Specific Gravity	2.77	USCS	CH

Table 2**:** Compressibility Parameters for Cement Stabilized Clays

Curing (weeks)	**wc (%)**	**wc/c Ratio**	**σ_y' (Kpa)**	**C_c**	**C_s**
2	120	7.5	421	0.815	0.037
		10	339	0.974	0.041
		15	247	1.279	0.042
	150	7.5	412	0.894	0.043
		10	348	1.048	0.044
		15	241	1.347	0.047
	200	7.5	402	1.052	0.047
		10	334	1.199	0.049
		15	235	1.616	0.051
	250	7.5	394	1.103	0.048
		10	329	1.304	0.052
		15	229	1.671	0.055
4	120	7.5	508	0.78	0.03
		10	422	0.908	0.033
		15	315	1.157	0.037
	150	7.5	501	0.834	0.037
		10	415	0.956	0.039
		15	309	1.246	0.041
	200	7.5	498	0.946	0.041
		10	410	1.104	0.042
		15	312	1.419	0.043
	250	7.5	492	1.016	0.042
		10	414	1.159	0.043
		15	310	1.501	0.044
Untreated clay			57	0.803	0.162

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

Admixture	w_i (%)	wc/c Ratio	Curing Time	
			2 w	4 w
Cement	120	7.5	259.952	383.592
		10	194.461	243.026
		15	129.053	147.185
	150	7.5	259.525	369.911
		10	189.452	236.156
		15	122.184	140.214
	200	7.5	254.480	356.379
		10	186.154	226.237
		15	114.356	126.647
	250	7.5	248.315	352.283
		10	181.294	225.549
		15	109.722	126.142
Untreated clay			76.374	

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

Parameters	w_i (%)	wc/c ratio	Curing time	
			2 w	4 w
c' in Kpa	120	7.5	111	124
		10	104	113
		15	101	111
	150	7.5	109	120
		10	102	114
		15	95	107
	200	7.5	106	116
		10	98	110
		15	85	95
	250	7.5	102	113
		10	95	104
		15	82	97
φ' in degree	120	7.5	45.34	44.83
		10	44.27	42.76
		15	41.08	40.29
	150	7.5	41.73	39.04
		10	39.86	38.83
		15	38.69	37.19
	200	7.5	40.40	38.94
		10	39.39	37.31
		15	38.09	35.33
	250	7.5	39.35	37.45
		10	38.62	33.22
		15	36.20	31.13
c'	Untreated clays		21.33	
φ'	Untreated clays		15	

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 2 and 4 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 clay sample having the same clay-water/cement ratio are shown Figs. 5.1 and 5.2 for 2 and 4 weeks curing respectively. It reveals that the higher curing time, the higher strength and the lower strain. Shear types of failures were observed. 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. Fig. 6 shows that the lower the wc/c, the greater the enhancement of the cementation bond strength inducing higher strength. Fig. 5.1 and 5.2 show 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.

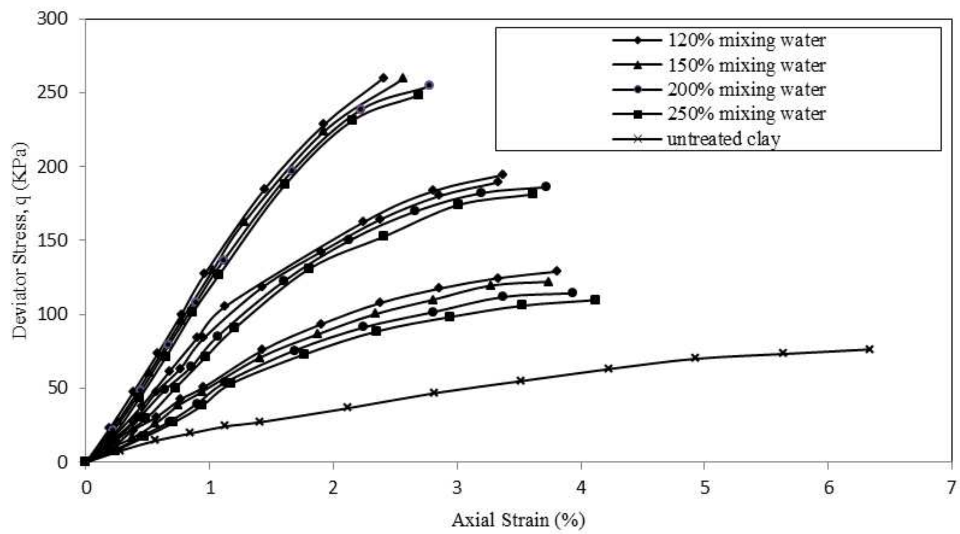

Figure 5.1**:** Stress-strain variations of clay at different wc/c for curing 2 week

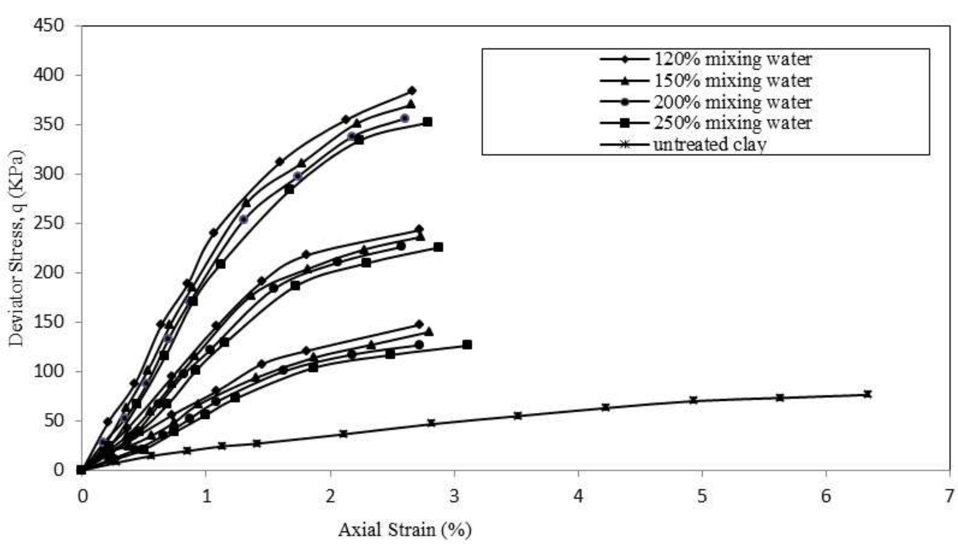

Figure 5.2**:** Stress-strain variations of clay at different wc/c for curing 4 week

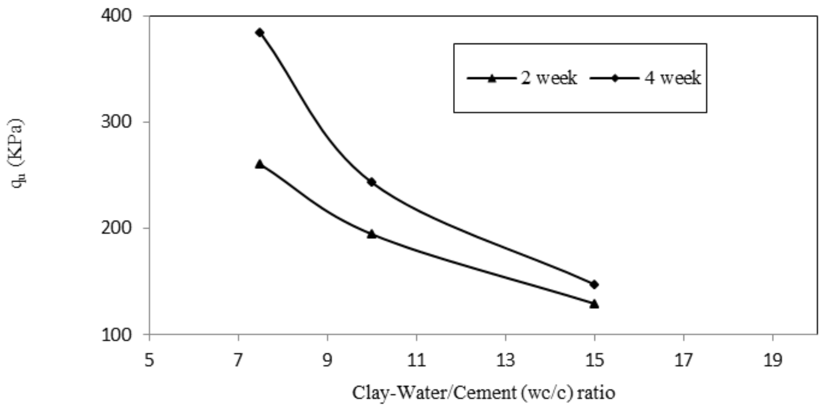

Figure 6**:** Strength variations with wc/c for stabilized clay

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 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 wi = 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 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.

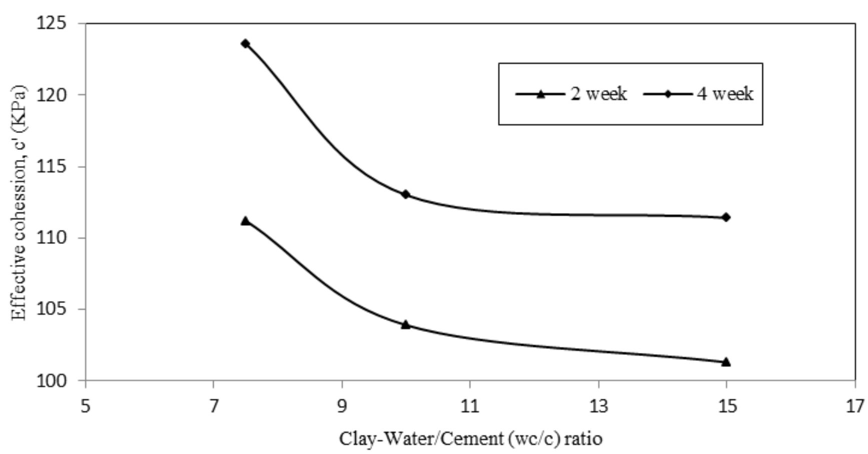

Figure 7**:** Effective cohesion variations with wc/c of stabilized clays for curing 2 and 4 weeks

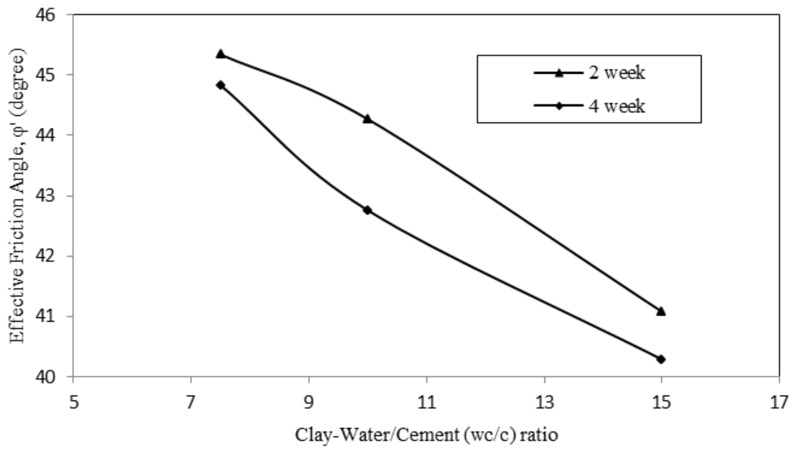

Figure 8**:** Effective friction angle variations with wc/c of stabilized clays for curing 2 and 4 weeks

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 (Chew et al,. 2004). 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 (Nagaraj et al., 1998; Miura et al., 2001).

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 cementing agents can be considered to 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.

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. 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.

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 (Yamadera et al,. 1997) 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 (Yamadera et al,. 1997) 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 the soft clay 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 (Nagaraj et al., 1998; Miura et al., 2001).

6. ANALYSIS OF COMPRESSION BEHAVIOR IN 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 consolidation. However, the resistance to plastic deformation is governed by the fabric (Nagaraj et al., 1998; Miura et al., 2001).

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 and wc/c. 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 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. 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 play a dominant role in the engineering behavior depending upon the effective cell pressure condition and level of cement content.

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 (Chew et al,. 2004). 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.

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.

8. CONCLUSIONS

Stress-strain, strength, compressibility and expansibility behavior of untreated and cement treated soft clays at high water content were investigated by performing unconfined compression tests, consolidation test and direct shear test. The major findings and conclusions can be summarized as follows:

i. Shear types of failure were observed in the unconfined compression tests. It has been found from unconfined compression test results that the amount cement content and curing markedly affect the value of q_u. Values of q_u increased with increasing curing time and increasing cement content (lowering wc/c ratio). Significant increase in strength development index with cement content and curing time has also been found.

ii. It has been found that both the effective cohesion ($c^ı$) and effective angle of internal friction ($\varphi^ı$) of treated samples increased with increasing cement content but $c^ı$ increases and $\varphi^ı$ decreases with increasing plasticity index. At a particular curing time and wc/c ratio, $c^ı$ and $\varphi^ı$ of samples was found to decrease with increasing mixing water content.

iii. At higher stress beyond the pre consolidation pressure, the e-log$\sigma^ı$ curves of the treated clays shift at higher void ratio than those of the untreated clays having the same consolidation pressure. This shifting is almost parallel with the virgin consolidation line of the untreated clay and this behavior is more significant with higher cement content and longer curing period.

iv. The significant increase in pre consolidation pressure, reduction in compression index (C_c) and swell index (C_s) have been observed with increasing cement content and increasing curing time. The swelling behavior of treated clays has been found to be very stiff in very low C_s. At a particular wc/c ratio and curing time, values of C_c and C_s increase significantly with the increase of mixing water content.

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