Prediction of Compressibility Characteristics of In-situ Cohesive Soil using Reconstituted Sample

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ABSTRACT
Collecting undisturbed soil samples are essential in determining the compressibility of cohesive soils. The challenges of collecting good quality soil samples at significant depths has been well documented in the literature. However, reconstituted samples can be prepared using disturbed samples which can provide an insight on the compressibility nature of this cohesive soil. Limited research has been carried out focusing on preparation of reconstituted soil cakes in the laboratory which could simulate in-situ stress conditions. A modified oedometer mould has been developed to prepare the reconstituted soil cakes for this purpose. Soil slurries were prepared mixing natural clay powder specimens thoroughly with fixed portions of sand or bentonite clay (as an admixture) and water (near liquid limit). A number of test specimens with varying liquid limits were prepared. The prepared soil slurry samples were placed in the modified oedometer mould and consolidated applying varying effective stresses. The soil cakes prepared were used as consolidation test specimens for one dimensional consolidation tests. A number of consolidation tests were performed as per ASTM D2435/D2435M-11. The consolidation behavior and parameters obtained from these test results were compared to the undisturbed samples as well as established relationships from the literature.

RÉSUMÉ
Le prélèvement d'échantillons de sol non perturbés est essentiel pour déterminer la compressibilité des sols cohérents. Les difficultés rencontrées pour collecter des échantillons de sol de bonne qualité à des profondeurs significatives ont été bien documentées dans la littérature. Toutefois, les échantillons reconstitués peuvent être préparés à partir d'échantillons perturbés, ce qui permet de mieux comprendre la nature de compressibilité de ce sol cohérent. Des recherches limitées ont été menées sur la préparation en laboratoire de tourteaux reconstitués qui pourraient simuler des conditions de stress in situ. Un moule oedométrique modifié a été mis au point pour préparer les tourteaux reconstitués à cette fin. Les boues de sol ont été préparées en mélangeant soigneusement les échantillons de poudre d'argile naturelle avec des portions fixes de sable ou d'argile bentonite (en mélange) et d'eau (près de la limite de liquidité). Un certain nombre de spécimens d'essai avec des limites de liquidités variables ont été préparés. Les échantillons de boue de sol préparés ont été placés dans le moule à oedomètre modifié et consolidés en appliquant diverses contraintes effectives. Les tourteaux préparés ont été utilisés comme éprouvettes de consolidation pour des essais de consolidation unidimensionnels. Un certain nombre d'essais de consolidation ont été effectués selon les normes ASTM D2435/D2435M-11. Le comportement de consolidation et les paramètres obtenus à partir des résultats de ces tests ont été comparés aux échantillons non perturbés ainsi qu'aux relations établies dans la littérature.

1. INTRODUCTION

The performance of foundations constructed over compressible clay soils may experience excessive settlements when not properly designed. In order to support the design process, it is critical that the compressibility properties of the clay material be well known. Therefore, undisturbed (UD) soil samples should be collected from field and tested in the laboratory to obtain the appropriate consolidation parameters (i.e. compression index, swell index, preconsolidation pressure etc.). Collecting and transporting UD soil samples can be challenging, costly and depending the soil sensitivity, samples are often subjected to varying degrees of disturbance during transportation and extraction.

To overcome these problems, the concept of a reconstituted (RC) soil sample was introduced in the past to simulate the behavior of a normally consolidated clay sample. RC samples were used to assess the influence of soil structure on mechanical behaviour of natural sedimentary clays (e.g. in Nagaraj & Srinivasa Murthy, 1986; Burland, 1990; Hong & Tsuchida, 1999; Liu & Carter, 1999; Chandler, 2000; Cotecchia & Chandler, 2000).

The quality of a RC soil sample is greatly influenced by the method of sample preparation and size of the mould used to prepare soil samples (i.e. the mould diameter). A number of studies were recently completed (e.g. Cerato & Lutenegger, 2004; Yin & Miao, 2015; Shi & Herle 2015), where advanced setups for the preparation of RC soil samples are discussed. However, the equipment used is prohibitively expensive for typical geotechnical studies.

The present study introduces a simplified sample preparation method, which can be successfully used to prepare good quality RC clay samples. UD clay samples were first collected from various sites and 1-D consolidation tests were completed using UD samples. The clay samples were then reused to prepare RC samples as well as modified clay (MC) samples using the simplified sample preparation method. To obtain a wide range of compression indices, various amounts of admixtures were added with the in-situ clay to prepare the MC samples. Consolidation tests were then completed on both RC and MC samples. The compressive characteristics of these samples are discussed and compared to the behaviour of UD samples, as well as well-known established relationships. Note that the effect of sample disturbance were not considered in the present study.

2. EXPERIMENTAL SETUP

As per ASTM D2435/D2435M-11, the minimum diameter and height of a mould required to carry out a consolidation test are 50 mm and 12 mm, respectively. A modified mould has been fabricated for this study. The diameter and height of the new mould are 63.5 mm and 125 mm respectively (63.5 mm being a common ring diameter for consolidation moulds). Soil cakes have been prepared applying incremental vertical loads with a lever arm. Vertical effective stresses ranging from 6.5 kPa to 800 kPa have been applied maintaining a loading ratio of 1:10. Schematic diagram of modified oedometric consolidation apparatus is as shown in Figure 1.

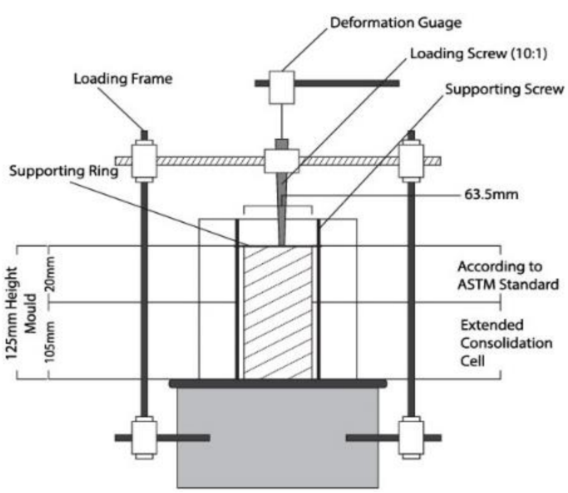

Figure 1. Schematic diagram of modified consolidation apparatus

3. SAMPLE PREPARATION

Both undisturbed (UD) and disturbed (D) samples were collected from five selected locations based on the distinctive soil types. Clays collected from Dhaka (Mirpur) and Mowna had red colour, samples collected from Narayanganj, Barisal had grey colour and clays from Dhaka (Airport) were brown. Wash boring methodology was used to extract the Shelby tube (undisturbed) samples. Table 1 shows the summary of the physical properties (in-situ) of the soil samples collected from several locations. It is noted that clays of Bangladesh predominantly consisted of illitic or chloritic minerals (Islam et al., 2002).

The natural undisturbed clay are designated in Table 1 as A 100 (UD), B 100 (UD), D 100 (UD), M 100 (UD) and N 100 (UD). Initial letter designates location, the following numeric indicates percentage of in-situ materials and two letters in the parenthesis gives the states of the soil sample, such as undisturbed (UD), disturbed (D). For example, A 100 (UD) represents the sample was collected from Dhaka (Airport), contains 100 percent (by weight) in-situ soil in an undisturbed condition. (100% in-situ soil refers to an in-situ soil 100% by weight. If it is less than 100% then remaining percent contains the portion of admixture (i.e. bentonite, sand) mixed to prepare 100% by weight as modified clay; e.g. DB60:40 refers to 60% of in-situ soil and the rest 40% of bentonite (see Table 1)).

3.1 Reconstituted Natural Clay (RC)

The in-situ soil samples (mentioned in Table 1) were naturally dried, ground and sieved through 425 µm sieve to prepare soil powders before using it to prepare reconstituted sample. The RC clay sample used in this study contained 93% to 98% fines passing through 75 µm sieve. The specific gravity (G_s) of the samples ranged from 2.64 to 2.69. A total number of fifteen (15) Atterberg limit tests (three tests for samples collected from each of the 5 locations), were conducted. Natural moisture contents were also determined. The results obtained from the tests provided LL ranging from 34% to 45% and natural moisture content varying from 21% to 34%. The reconstituted natural clays are described as A 100 (RC), B 100 (RC), D 100 (RC), M 100 (RC) and N 100 (RC). As explained earlier, sample A 100 (RC) represents the sample was collected from Dhaka Airport, containing 100 percent (by weight) in-situ soil in reconstituted condition.

3.2 Reconstituted Modified Clays

Modified clay samples were prepared by mixing the Dhaka (Mirpur) natural clay powder with different portions of admixtures (bentonite or sand) to obtain a wide range of liquid limits (as shown in Table 1).

Sands consisted of a particle specific gravity (G_s) ranging from 2.66 to 2.69 and 7 percent passing by weight 75 µm sieve were mixed to reduce the liquid limits of natural clay powder. Fineness modulus (FM) of sand was 1.29.The value of D_{10}, D_{30} and D_{60} was 0.1427 mm, 0.2435 mm and 0.3830 mm, respectively. The proportion of sand used to produce the modified clay are presented in Table 1 and designated as DS75:25 and DS60:40. (DS75:25 and DS60:40 represents 75% and 60% of Dhaka (Mirpur) natural clay mixed with 25% and 40% of sand respectively. A total number of six (6) Atterberg limit tests (3 tests for each mixtures), were conducted.

Bentonite clay was also used as an admixture to increase the liquid limit of natural clay powder. G_s of bentonite clay ranged from 2.62 to 2.67 and LL from 480% to 500% respectively.

Table 1. Physical properties of soil

Sample ID	Soil Type	Soil Site Location	Natural Moisture Content	LL	PL
Natural Clays					
A100(UD)	Madhupur Tract (Brown Clay)	Dhaka(Airport)	21 – 29	38 - 42	25 - 29
B100(UD)	Brahmaputra & Gangetic Alluvium (Grey Clay)	Barisal	28 – 32	35 - 42	24 - 32
N100(UD)		Narayanganj	26 – 34	34 - 44	23 - 31
D100(UD)	Madhupur Tract (Red Clay)	Dhaka (Mirpur)	19 – 26	39 - 45	28 - 31
M100(UD)		Mowna	22 – 28	37 - 48	26 - 30
Modified Clays					
D100:0	100% D100	D100(D)	-	39 - 45	28 - 31
DB60:40	60% D100 + 40% Bentonite	D100(D)	-	190 - 200	50 - 60
DB70:30	70% D100 + 30% Bentonite	D100(D)	-	140 - 150	42 - 52
DB80:20	80% D100 + 20% Bentonite	D100(D)	-	110 - 120	45 - 38
DB90:10	90% D100 + 10% Bentonite	D100(D)	-	70 - 80	30 - 38
DS75:25	75% D100 +25% Sand	D100(D)	-	30 - 35	22 - 26
DS60:40	60% D100 + 40% Sand	D100(D)	-	24 - 28	15 - 19

The proportion of bentonite used to produce the modified clay are presented in Table 1 as DB60:40, DB70:30, DB80:20 and DB90:10. DB60:40 represents Dhaka (Mirpur) natural clay of 60% and B for bentonite of 40% mixture. DB70:30, DB80:20 and DB90:10 can be described similarly. A total number of twelve (12) Atterberg limit tests (3 tests for each mixtures) were also conducted.

4. TEST METHODOLOGY

Reconstituted natural and modified clays as described in previous section, having an initial water content equal to their respective liquid limits, were used to prepare the reconstituted samples. According to Head (1992), a low vertical stress should be applied to prepare the reconstituted test samples with a high initial moisture content. This would prevent the soil from squeezing through the space between the confining ring and the porous disk. Table 2 shows the test scheme used in this study. In the 1st step, soil samples (soil cake) were prepared applying vertical stress of 6.5, 12.5, 25, 50, 100, 200, 300, 400, 500, 600, 700 and 800 kPa using the modified test apparatus described above.

In the 2nd step, soil cakes prepared from 1st step were consolidated to assess the behavior of reconstituted natural and modified clays. The loading steps were kept at 25, 50, 100, 200, 400, 800 and 1600 kPa respectively. Undisturbed clay samples (see Table 1) were also consolidated using 25 to 1600 kPa of vertical pressure (i.e. the sample IDs A100 (UD), B100 (UD), D100 (UD), M100 (UD) and N100 (UD)).

Thirty-six (36) consolidation (oedometer) tests were completed. Fifteen (15) tests were conducted on undisturbed soil. The remaining eleven (11) tests were conducted on soil cakes of reconstituted natural and modified clays. To ensure the reproducibility of test results of reconstituted soil, several repetition tests were also carried out.

Table 2. Test scheme used in this study

Types of Compression Test		Sample ID	
1st Step	2nd Step	A100(RC)	DB60:40
Slurry compressed at 6.5 – 800 kPa	Test Specimen (Soil cake) compressed at 25-1600 kPa	B100(RC)	DB70:30
		N100(RC)	DB80:20
		D100(RC)	DB90:10
		M100(RC)	DS75:25
		-	DS60:40

5. TEST RESULTS

5.1 Void Ratio-Effective Vertical Stress Relation for Undisturbed and Reconstituted Natural Clays

The results obtained from oedometer tests on undisturbed and reconstituted natural clays are illustrated as void ratio vs effective vertical stress (p) (e–log p) curves on Figure 2 (a-e). The results indicate that each type of undisturbed and reconstituted natural clay soil samples shows similar trend under the same effective vertical stress. It should be noted that, vertical pressure applied during reconstituted soil preparation was such that it yielded similar void ratio similar to undisturbed samples.

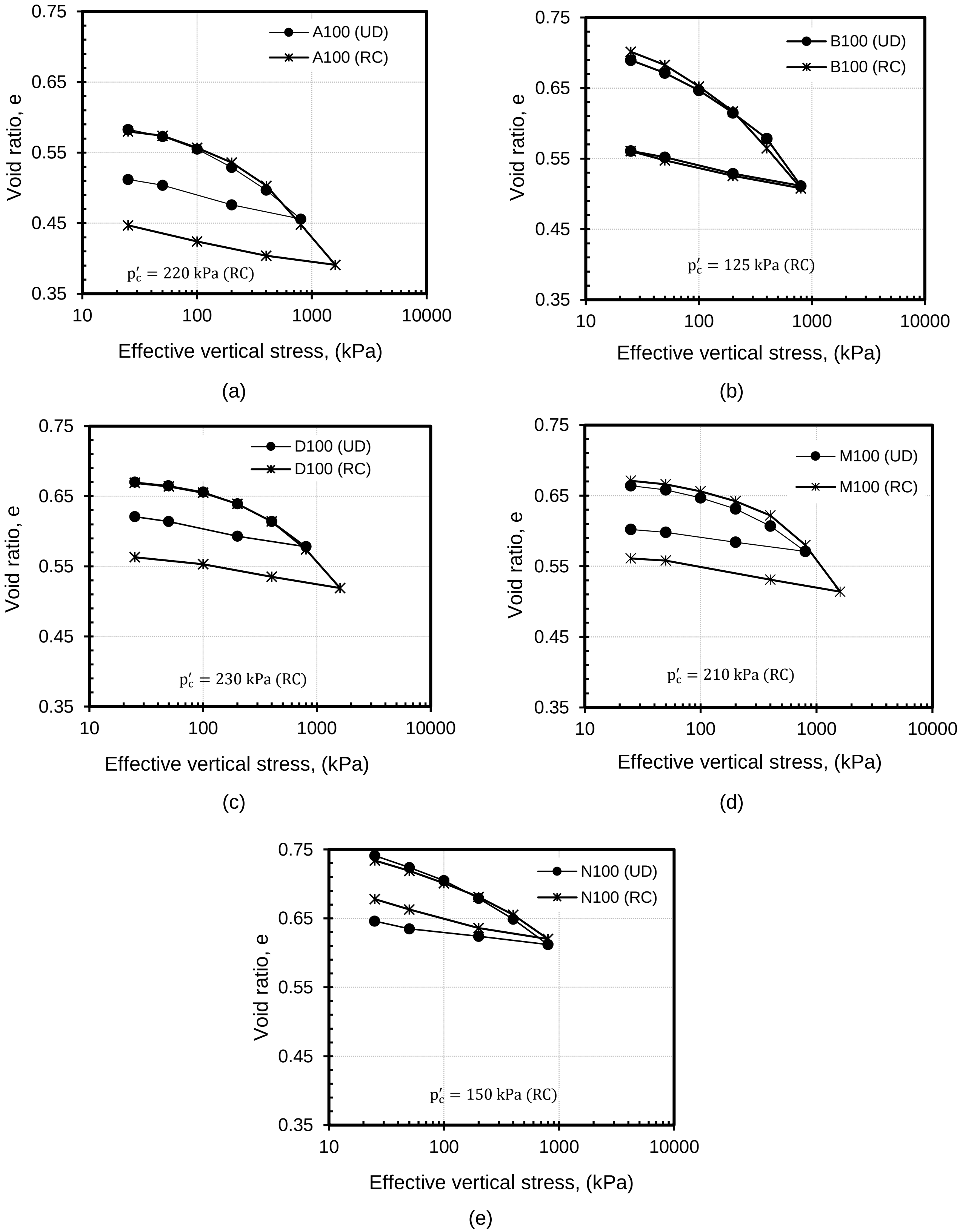

Figure 2. Comparison of void ratio against effective vertical stress for undisturbed and reconstituted natural clay soil samples.

Preconsolidation pressures and compression indices for UD samples were estimated from the plot and are presented in Table 3. Compression index of reconstituted clay samples were also estimated. Values of compression index were similar for undisturbed and reconstituted natural clays (Table 4). Preconsolidation pressure of reconstituted clays were also within the range of undisturbed clays (Figure 2).

Table 3: Estimated compression index (C_c) and preconsolidation pressure (p'_C) of Undisturbed Soil

Sample ID	Sample Depth (m)	C_c	p'_C (kPa)
A100(UD)	25.0 – 33.0	0.181 – 0.124	150 - 250
B100(UD)	3.0 – 5.0	0.171 – 0.218	110 - 180
D100(UD)	6.5 –10.5	0.100 – 0.165	160 - 220
M100(UD)	4.0 – 9.0	0.100 – 0.141	150 - 210
N100(UD)	6.0 – 9.0	0.093 – 0.118	110 - 190

Table 4. Comparison of C_c between UD and RC clays

Sample ID	C_c (UD)	C_c (RC)
A100	0.118	0.147
B100	0.175	0.185
D100	0.101	0.108
M100	0.241	0.240
N100	0.111	0.101

5.2 Liquid Limit and Compression Index

Many researchers have proposed empirical relationships between the compression index and the soil index properties such as liquid limit, plastic limit, and natural moisture content. These parameters can be measured reasonably accurately in traditional geotechnical laboratories. Therefore, it may be also useful to estimate the compression index using empirical relationships. A summary of a select few relationships is stated in Table 5.

Figure 3 shows $e - \log p$ plots for Dhaka (Mirpur) clay mixed with sand and bentonite at various proportions. Compression indices was estimated from Figure 3 and plotted against liquid limits of the modified soil sample as shown on Figure 4. The results presented in Figure 4 show a good agreement with the empirical correlations proposed by Skempton 1944, Cozzolino 1961, Terzaghi & Peck 1967 and Azzouz et al 1976.

5.3 Moisture Content and Compression Index

Figure 5 presents the variation of compression indices against the moisture content of the modified soil samples of Dhaka (Mirpur) clay. A linear relationship between compression index and moisture content at lower moisture content (up to a maximum value of 30%) is obtained. This agrees well with the findings of Azzouz et al. (1976). At higher moisture contents, the relationship between moisture contents and compression indices are nonlinear and the trend agrees well with the findings of Peck and Reed (1954).

Table 5. Correlations for compression index, C_c

Ser	Equation	Applicability	Reference
Compression Index (C_c) vs Liquid Limit (LL)			
1	$C_c = 0.007(LL - 7)$	Remolded Clays	Skempton (1944)
2	$C_c = 0.0046(LL - 9)$	Brazillian Clays	Cozzolino (1961)
3	$C_c = 0.009(LL - 10)$	Normally Consolidated Clay	Terzaghi & Peck (1967)
4	$C_c = 0.006(LL - 9)$	All Clays	Azzouz et al. (1976)
Compression Index (C_c) vs Moisture Content (w)			
5	$C_c = 0.000176w^2 + 0.005w - 0.135$	Chicago Clays	Peck & Reed (1954)
6	$C_c = 0.01(w - 5)$	All Clays	Azzouz et al. (1976)
Compression Index (C_c) vs Initial Void Ratio (e_0)			
7	$C_c = 1.15 (e_0 - 0.35)$	All clays	Nishida (1956)
8	$C_c = 0.43 (e_0 - 0.25)$	Brazillian Clays	Cozzolino (1961)
9	$C_c = 0.75 (e_0 - 0.50)$	Low Plasticity Soil	Sowers (1970)

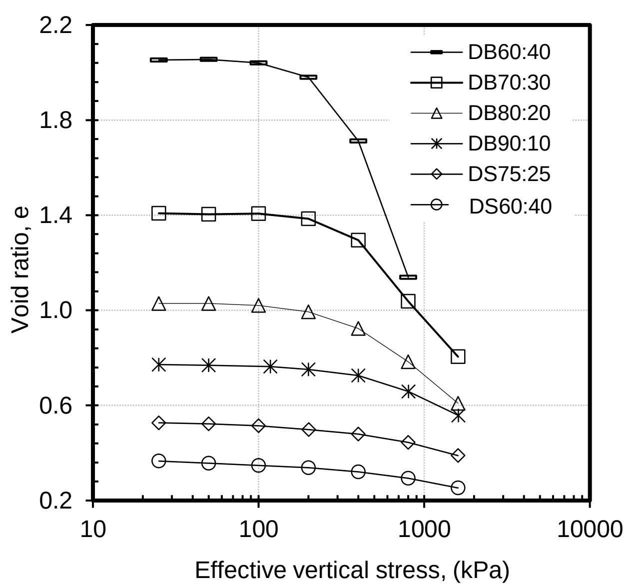

Figure 3. Change in void ratio with effective vertical stresses of Dhaka (Mirpur) clay for different proportions of sand and bentonite

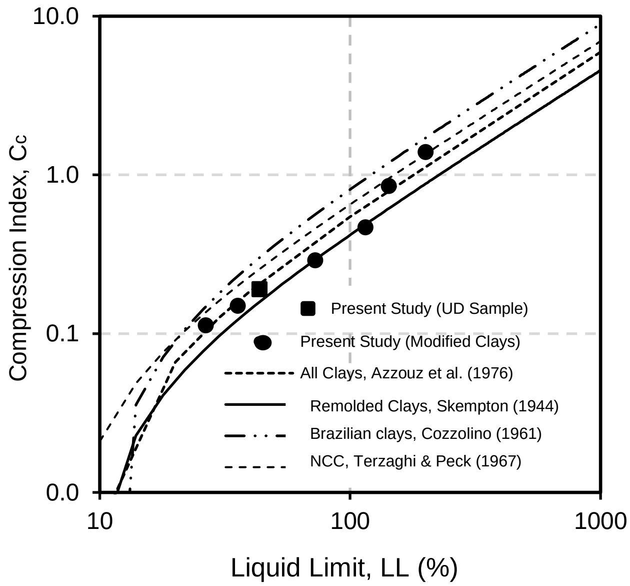

Figure 4. Compression index and liquid limit relationship for Dhaka (Mirpur) clay with different proportions of sand and bentonite

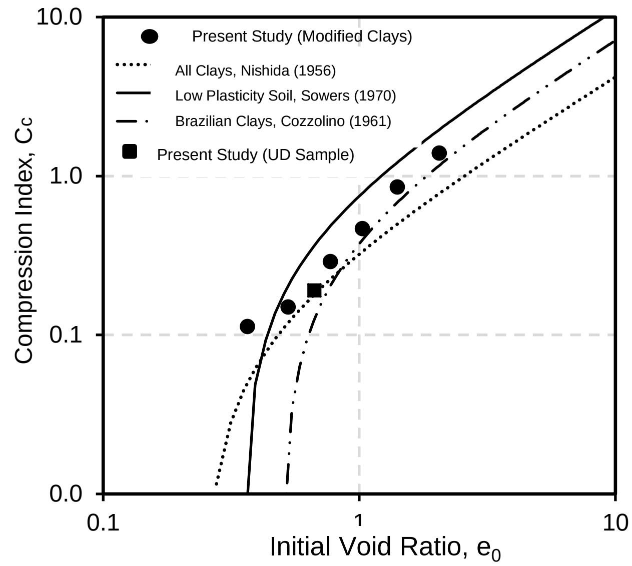

Figure 6. Compression index and initial void ratio relationship for Dhaka (Mirpur) clay with different proportions of sand and bentonite

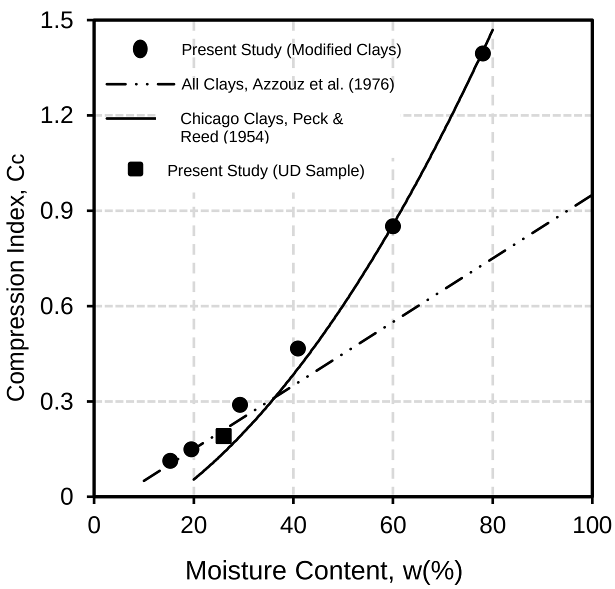

Figure 5. Compression index and moisture content relationship for Dhaka (Mirpur) clay with different proportions of sand and bentonite

5.4 Initial Void Ratio and Compression Index

Figure 6 shows the variation of compression indices with initial void ratio. The results remains within the range suggested by Nishida (1956), Cozzolino (1961) and Sowers (1970).

5.5 Proposed Correlations Equation

Based on the findings of the present study, the following relationships between liquid limit, moisture content and void ratio with compression index are proposed and presented in equations 1 to 4.

$$C_c = 0.004\,(LL + 2.6) \qquad 20 \leq LL \leq 110 \quad [1]$$

$$C_c = 0.0107(LL - 67.8) \quad 110 \leq LL \leq 200 \quad [2]$$

$$C_c = 0.0002w^2 + 0.0026w + 0.0255 \quad [3]$$

$$C_c = 0.8\,(e_0 - 0.35) \quad [4]$$

6. CONCLUSIONS

In order to reproduce the in-situ undisturbed state of a reconstituted sample in the laboratory, an appropriate sample preparation technique is necessary. The procedure proposed in this study used a modified oedometer mould, which not only addresses the effective loading stage, but also prepares the sample specimen without additional trimming. Moreover, the prepared soil samples successfully simulated the compressibility nature of the soils in an undisturbed state. The relations presented in equations 1-4 are based on a limited number of data. It is noted that the findings reported in this study are part of an ongoing extensive research program focusing on the Characterization of Reconstituted Clay.

7. ACKNOWLEDGEMENTS

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