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SOME GEOTECHNICAL STUDIES ON BANGLADESH SOILS : A SUMMARY OF PAPERS BETWEEN 1957 - 96

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ABSTRACT: The paper has presented a brief inventory of the geotechnical studies conducted on soils of different regions/areas of Bangladesh by the author and his colleages since 1957 to 1996. The summary has included general information about stratifications, grain size characteristics; natural water content, liquid limit and plasticity index; sensitivity and liquidity index; specific gravity, in-situ dry density, initial void ratio, unconfined compressive strength, cohesion, angle of internal friction, compression index, compression ratio-natural water content relation, preconsolidation, overconsolidation ratio, and coeff. of consolidation; compaction characteristics with time of initially uncompacted earth embankment, and hand compactors for earth embankment; estimation of field permeability of sand beds from simple laboratory tests; and California bearing ratio (CBR) characteristics and ground improvement by mechanical and chemical stabilization, for Bangladesh soils. Some empirical relations for compression index connecting liquid limit, initial void ratio, natural water content and normalized zero-air-void-curve (ZAVC) slope of local silts and clays have also been presented.

KEYWORDS: Bangladesh soils, geotechnical investigation, strata characteristics, shear strength, compression index equations, compression ratio, permeability estimation, hand compactors, California bearing ratio, ground improvement.

INTRODUCTION

It is fairly well agreed upon (Jumikis, 1962) that the modern discipline of 'Soil Mechanics' often called ' Geotechnique' or 'Geotechnics', began in 1925 with the publication of the book 'Erdbaumechanik' (Terzaghi, 1925). Karl Terzaghi (1883-1963) is popularly known as founder of modern soil mechanics, as his works and the works of many persons whom he guided have helped to develop the new science in different countries. This science has excercised a great influence on foundation engineering practice all over the world and has provided new techniques for selecting the appropriate types of foundation under a given set of conditions and for predicting the future behaviour of the completed structures.

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From 1952 to 1984 extensive geotechnical investigations were done by the writer and his colleagues for the various irrigation, water development, flood control and power development projects of the country. The studies were done in Hydraulic Research Laboratory (HRL) set up in 1948 under Irrigation Department of the then Govt. of East Bengal and in River Research Instiitute (RRI) set up in 1978 (merging the existing HRL) under Bangladesh Water Development Board (BWDB).

The writer and his colleagues in the Geotechnical and Material Laboratory of Development Design Consultants Ltd. (DDC) in Dhaka also conducted systematic geotechnical studies on soils of the country since 1986 to date. Using the geotechnical data of these studies Serajuddin and in co-authorship with his associates wrote a good number of papers on various geotechnical aspects of soils of different areas of Bangladesh from 1957 to 1996 as shown in the reference. This paper is a summary of the salient findings of those papers.

GEOLOGY

Most of Bangladesh is an extremely flat delta which consists of a large alluvial basin floored primarily with Quaternary sediments deposited by the Ganges and Brahamaputra rivers and their numerous associated streams and distributaries (Morgan and McIntire, 1959). The three major physiographic units namely Hill formations of Sylhet in the north-east and of Chittagong Hill Tracts in the south-east, Uplifted Pleistocene Terraces, and Recent flood-plain and piedmont alluvium, which occupies roughly seventy percent of the total land area of Bangladesh, are shown on Fig.1. (Hunt, 1976.) The recent floodplain deposits are again differentiated into meander flood-plain deposits, estuarine and tidal flood plain deposits, depending on the environmental conditions that existed at the time of deposition.

The Quaternary sediments of the country have different characteristics, ranging from piedmont deposits near the northern and eastern borders of the country to swamp and deltaic deposits in southern districts near the southern sea-shore. The major locations of the older alluvial deposits are on the north of the Ganges-Padma river system. Barind Tract, Madhupur Tract, and Lalmai Hills are the major areas of such deposits. They are not subject to normal seasonal flooding.

SOME PHYSICAL AND GEOTECHNICAL PROPERTIES

Colours

Colours of the soils usually range from light gray to dark gray and (often) black, from light brown to brown or tan, or reddish, and occasionally a combination of them. Light gray to dark gray soils are

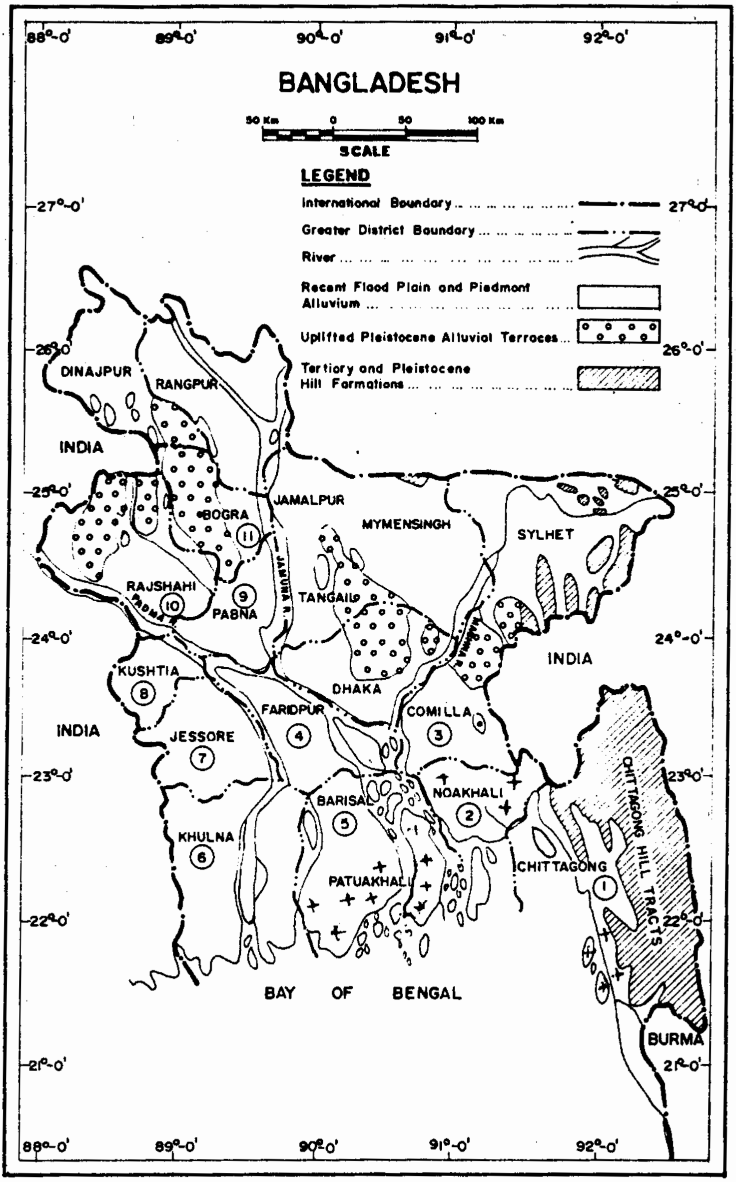


Fig 1. Map of Bangladesh Showing Three Major Physiographic Units and Greater Districts

more frequently obtained than those of other colours. Soils with bluish and greenish colours were also encountered sometimes.

Stratifications and Grain Size Characteristics

. Bangladesh soils have been grouped into four zones in this paper consisting of the old districts as below:

North-West Zone: Dinajpur, Rangpur, Bogra, Rajshahi and Pabna.

North-East Zone: Mymensingh, Sylhet, and Dhaka.

South-West Zone: Kushtia, Jessore, Faridpur, Khulna and Barisal.

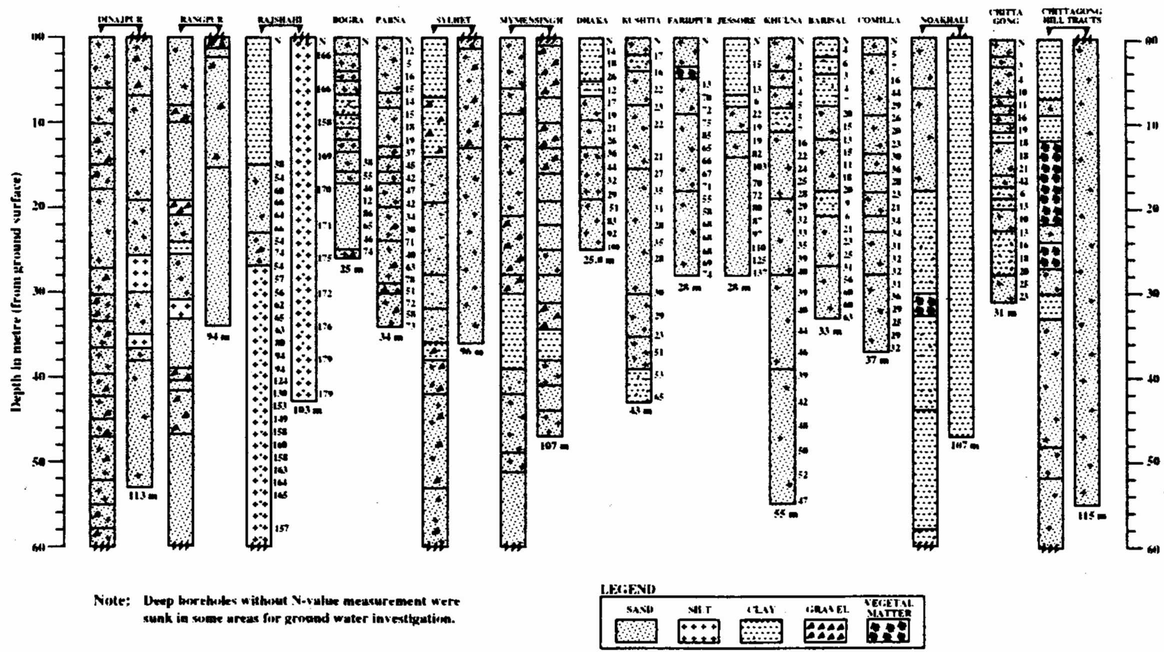
South-East Zone: Comilla, Noakhali, Chittagong and Chittagong Hill Tracts.

Field exploration logs confirmed by detailed laboratory classification and identification tests on the sub-surface soils indicate that soil profiles are generally highly stratified and discontinuous horizontally within short distances. It is difficult to connect the soils strata between the bore-holes of a site although the general grains characteristics and plasticity properties of the soil at the site appear to have similarity, differing only in combination of soil fractions and in depths of occurrence in different boreholes. Fig. 2 gives an approximate general idea of the nature of soil formations, thicknesses of stratifications, and grain size compositions. The borehole log presents the soil profile of the particular hole at the site and it is not a generalised one for the district or the area (Serajuddin, 1976b). These profiles are randomly selected from many subsurface soil investigation reports of different areas of the country.

Soil formations of Bangladesh consist predominantly of medium to fine sands, silts and clays and a wide variety of combination of these soil fractions. Fine sands and silts and a combination of the two in varying proportions are quite frequently encountered. Coarse sand and fine gravels appear to exist only in the limited areas, mainly along the northern borders in the greater districts of Dinajpur, Rangpur, Mymensingh and Sylhet and they occur in varying proportions with other soil fractions namely sand and silt (Serajuddin, 1967b.) When a detailed comparative study is made of the occurrence of different types of soils in different explored areas, the following general trends appear to exist. All soil classifications in this paper are made according to Unified Soil Classification System (USCS).

In the North-West Zone, gravelly sand (along northern borders), sand and silt and a combination of them appear to be predominant soil types and clay is less frequently encountered. Organic clays and organic silts are rarely encountered.

In the North-East Zone, silts and clays occasionally with organic matters are found along with other soil types such as gravelly sand, coarse, medium and fine sand in varying combinations.



Note: Deep boreholes without N-value measurement were sunk in some areas for ground water investigation.

Fig 2. Some Typical Soil Profiles of Different Greater Districts

In the South-West Zone, gravel is almost non-existent; medium to fine sand, fine sand, silts and clays are mainly encountered in varying combinations. Organic matters in the form of peat, semidecomposed and decomposed vegetable matters are frequently encountered mixed with soils in varying and appreciable quantities in many places of greater Khulna district in particular and other districts occasionally at some places of the zone.

In the South-East Zone, medium to fine sand, fine sand, silt and clay mixed with varying amounts of other soil components generally exist. Fine sand and silt and a combination of the two appear to be more frequently encountered than clay, particularly in the upper layers; Chittagong Hill Tracts have formations of silt-stones, and shales along with sand, silt and clay.

Natural Water Content, Liquid Limit and Plasticity Index

When liquid limits (W_L) of cohesive fine-grained soils of the four zones of Bangladesh are plotted on Casagrande plasticity chart (Fig.3) against the corresponding plasticity indexes (I_P), most points plot above the A-line [$I_P=0.73\ (W_L-20)$]. These index properties for some fine-grained soils of recent formations of the south-west coastal region of the country plot very closely on both sides of the A-line of the plasticity chart and many of them plotting below A-line contain considerable amounts of peat and organic matter. Clays containing organic matters are available in other zones occasionally. Although plastic silts are comparatively less than the plastic clays, non-plastic silts are abundantly found in the different test zones. The natural water contents of cohesive inorganic fine-grained soils mostly occur in the range of about 20 to 50 percent . The soils containing organic matters may have occasionally much higher values. Natural water contents of the great majority of plastic silts and clays of the country are generally lower than and closer to their liquid limits, thereby indicating that the layers from where the samples were taken, were probably normally consolidated, and laboratory consolidation tests data of the locations confirmed the probable conclusions in most cases (Serajuddin and Ahmed, 1967).

Studies on soils of Bangladesh coastal embankment project area covering about 1.34 million hectares of tide lands of greater Khulna, Barisal, Noakhali and Chittagong districts indicate that soft silt-clay, peat and loose fine sand-silt formations are predominantly existent in this project area, and plastic materials are found to be characterised by high moisture content; liquid limits are in the range of about 25 to

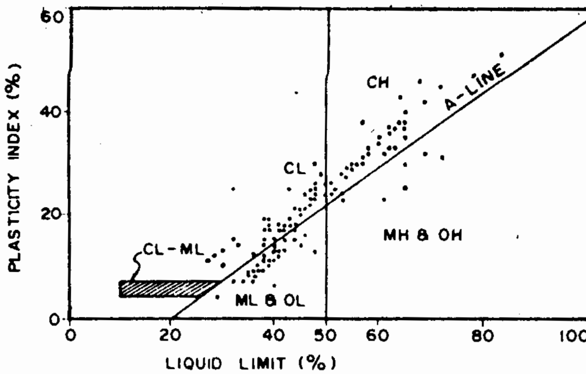


Fig 3. Position of Bangladesh Silt and Clay Soils on A. Casagrande Chart

about 125 percent and plasticity index in the range of about 2 to about 96 percent but a great majority of the plastic materials are in the medium to high plasticity range. Natural moisture content as low as about 10 percent and as high as about 140 percent were obtained in the coastal cohesive soils but those of the majority of the cohesive soils were found in the range of about 25 to 50 percent, liquid limit of the majority samples were in the range of about 25 to 95 percent and their plasticity index in the range of about 7 to 55 percent. Liquid limit below natural moisture content was obtained in some cases and liquid limit very close to but slightly above the natural moisture content was obtained in many samples and undisturbed tube samples of such plastic silts and clays were very soft, had very little or negligible unconfined compressive strengths and unconfined compressive test specimens in vertical position were found to settle under their own weight (Serajuddin, 1964, 1969.)

Sensitivity and Liquidity Index

Table 1 shows some typical values of sensitivity and liquidity index of clays and plastic silts of some areas of the country and Fig. 4 shows the liquidity index vs sensitivity relation of these soils (Serajuddin and Islam - 1982) . Most soils included in Table 1 and Fig. 4 appear to have sensitivity less than about 4.

Shear Strength

It is difficult to make any exact generalisation of the shear strength values of soils existing in wide variety of combinations of mineral grains, grain shape, grain size, and manner of packing.

Table 1. Approximate Range of Some Typical Values of Sensitivity and Liquidity Index of Clays and Plastic Silts of Some Areas of the Districts.

Name of District	Rang of Values	
	Sensitivity	Liquidity Index
Mymensingh	1.31 - 2.66	0.15 - 0.53
Sylhet	1.04 - 5.26	0.17 -1.01
Dhaka	1.20 - 2.33	0.03 - 1.16
Jessore	1.00 - 1.80	0.34 - 1.19
Faridpur	1.10 - 4.00	0.00 - 1.42
Patuakhali	1.67 - 2.20	0.41 - 1.42
Khulna	1.25 - 4.51	0.523-1.39
Chittagong	1.10 - 3.22	0.24 -1.266

Approximate ranges of some typical values of unconfined compressive strength (q_u), cohesion (C) and angle of internal friction (ϕ) for some typical cohesive/semicohesive inorganic fine-grained soils are summarised in Table 2 along with some other soil test parameters (Serajuddin, 1957, 1964, 1967b, 1969; Serajuddin and Ahmed, 1967, 1981 & 1982 and Serajuddin et al, 1985).

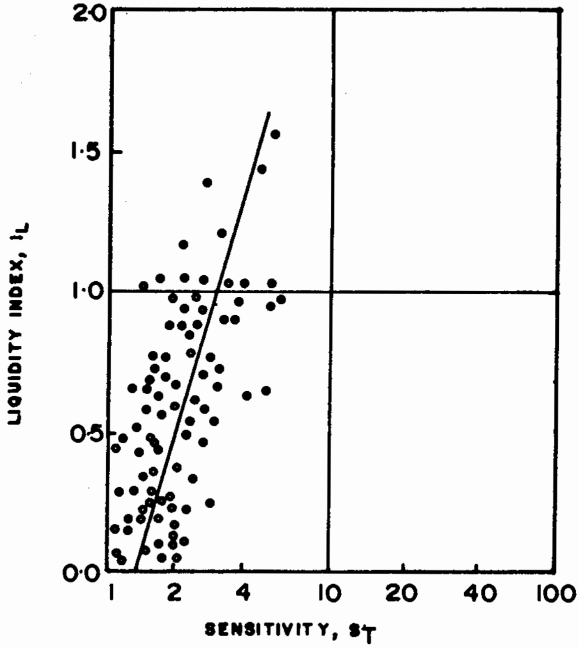


Fig 4. Liquidity Index versus Sensitivity

Table 2. Approximate Range of Some Typical Values of Soil Test Parameters for Cohesive/Semi-cohesive Inorganic Fine-Grained Soils of Bangladesh

Sl. No.	Explored zone	Average sample depth (m)	Soil Classification by unified system	Specific gravity	Natural water content (%)	In-situ dry density (g/m^3)	Initial void ratio	Unconfied compressive strength (kg/cm^2)	Cohesion (kg/cm^2)	Angle of internal friction (degree)	Compression index C_c	Coefficient of consolidation, C_v ($\times 10^{-3}$ cm^2/sec)
1	North-West Zone	3.5-11.0	CL, ML CH, MH CL-CH	2.60-2.70	19-52	1.08-1.72	0.558-1.420	0.06-1.94	0.08-0.91	7-34	0.100-0.640	0.2-110
2	North-East Zone	3.5-8.0	CL,ML,CH	2.67-2.71	20-46	1.17-1.77	0.511-1.290	0.20-1.46	0.14-0.98	1-34	0.090-0.288	0.21-92
3	South-West Zone	3.5-9.5	CL,ML,CH	2.62-2.79	24-47	1.15-1.56	0.706-1.320	0.02-1.66	0.03-4.43	2-35	0.080-0.520	0.55-32
4	South-Eest Zone	5.0-12.5	CL,ML,CH	2.62-2.69	24-54	1.09-1.60	0.711-1.463	0.31-1.49	0.006-0.68	2-39	0.145-0.564	0.50-38

An extensive sub-soil investigation by static cone penetration test *(SCPT) was done in 1960's in* the coastal embankment project area of the country along with collection of undisturbed cohesive silt and clay soils in Shelby tube by drill hole method adjacent to location of SCPT. A comparative study between static cone resistance (q_c) and actual q_u determined on the undisturbed cohesive silt/clay soil of the same layer has indicated that average value of q_u of the cohesive soils of the coastal areas of Bangladesh is about 0.50 kg/cm² corresponding to a static cone resistance value of q_c equal to 10 kg/cm², which means a reduction factor of 20 to estimate q_u from q_c, and a reduction factor 40 to estimate cohesion (C) from q_c are required (Serajuddin, 1969)

From a study (Serajuddin and Chowdhury, 1996) by plotting several hundred test results of q_u of clays and plastic silts of the country against N-values of the clay/silt layers measured by locally manufactured standard penetration test equipment and local procedure of pulling and releasing the drop weight by a crew of labourers has indicated that q_u of saturated cohesive silt and clay layer can be estimated by using the relation $q_u = f\,N$ (kPa) and the values of f (the proportionality) for cohesive soil layers of Uplifted Pleistocene deposits can be taken as below :

i) f = 16 for reddish, brown or tan coloured Uplifted Pleistocene silt and clay deposits (Madhupur clay residuum) of medium to high plasticity of Dhaka Metropolitan City areas and Tangail district.

ii) f = 14 for reddish brown or tan coloured Uplifted Pleistocene silt and clay deposits (Barind clay residuum) of medium to high plasticity of greater Rajshahi district.

Again, based only on the plasticity characteristics of the cohesive silt and clay deposits occurring in different areas of Bangladesh, the following values of k are suggested to estimate q_u of saturated cohesive silt and clay layers from N-values of the layers :

i) f=16 for clays and silts of high plasticity with $W_L \geq 51\%$

ii) f=15 for clays and silts of medium plasticity with W_L = 36-50%

iii) f = 13 for clays and silts of low plasticity with $W_L \leq 35\%$

Consolidation Characteristics

Compression Index and Coeff. of Consolidation

Primary consolidation settlement analyses are appropriate for all saturated or nearly saturated, fine-grained soil deposits having coeff. of permeability (k) on the order of 10^{-6} m/s or less (Bowles, 1982.) Consolidation test data for Bangladesh fine-grained soils for estimation of primary consolidation settlement are plenty and are summarised in Table 2 (Serajuddin, 1957, 1964, 1967a, 1967b, 1969, 1987; Serajuddin and Ahmed, 1967, 1982; Serajuddin et al, 1985). It has been found that values of compression index (Cc) of Bangladesh plastic silts and clays lie approximately between 0.10 and 0.70 but a great majority of them lie within the range of about 0.10 to 0.40.

Preconsolidation

Analysis of consolidation test parameters including computed existing overburden pressure (P_o) and estimated maximum preconsolidation pressure (P_c) indicated that the silt and clay soils strata were predominantly normally consolidated. But slightly to moderately overconsolidated clay and silt layers in various locations of the country were also encountered as shown in Table 3 (Serajuddin, 1964, 1965, 1967a, 1967b and 1969; Serajuddin and Ahmed, 1967).

Empirical Relations for Compression Index

The compression index (C_c) of compressible clays and silts has some empirical relations with liquid limit (W_L) initial void ratio (e_o) and natural water content (W_N). Serajuddin and Ahmed(1967) connected C_c with W_L and e_o of a large number of undisturbed plastic silt and clay soil samples of different areas of Bangladesh and obtained the following empirical equations :

$$C_c = 0.0078\,(W_L - 14\%) \quad (1)$$

$$C_c = 0.44\,(e_o - 0.30) \quad (2)$$

A general survey by Serajuddin (1964 and 1969) of the engineering aspects of soils of Bangladesh coastal embankment project area has suggested the following two relationships for C_c with e_o and W_N for fine-grained soil of the project area:

$$C_c = 0.50\,(e_o - 0.50) \quad (3)$$

$$C_c = 0.0135\,(W_N - 20\%) \quad (4)$$

Another correlation study (Serajuddin and Ahmed, 1982) with additional test data from cohesive fine-grained soils occurring within about 7 m from the ground surface of the different areas of the country suggested the relationship:

$$C_c = 0.47\,(e_o - 0.46) \quad (5)$$

with a correlation coefficient of 0.77

Table 3. Approximate Range of Preconsolidation Values of Some Foundation Clays and Silts of Bangladesh

Brief Description of site	NMC (%)	LL (%)	PI (%)	Preconsolidation Pressure, P_c (kg/cm^2)		P_o (kg/cm^2)	P_c - P_o (kg/cm^2)		OCR (P_c/P_o)	
				CM	SM		CM	SM	CM	SM
Rajshahi around Kaliganghat and Amnura	15-18	47-51	20-29	2.2-2.3	-	0.225-0.229	1.974-2.07	-	9.75-10.0	-
Kushtia around Alamdanga and Pabna-Kushtia Ganges river bed Char	27-31	35-84	10-44	1.09-3.39	1.28-4.37	0.67-2.47	0-1.86	0-2.84	1.00-2.22	1.00-2.86
Faridpur around Golabaria, Baliakandi and Amdanga	32-47	NP and 45-47	NP and 20-47	1.42-2.51	1.81-3.28	0.35-0.66	1.07-1.90	1.25-2.67	2.89-4.11	2.89-5.38
Jessore	48-52	64-68	35-36	0.98-3.39	1.09-2.74	0.85-1.42	0.13-1.97	0.24-1.32	1.15-2.39	1.28-1.74
Khulna around Kalabashukhali, Hankura, Kewratola, Pachuria and Hasanpur	32-53	35-60	11-29	0.98-1.75	0.98-1.20	0.36-1.00	0.43-1.235	0.43-0.65	1.75-4.38	1.78-2.18
Dhaka around DND project area	25-34	36-41	20-22	1.31-1.64	1.31-1.53	0.42-0.63	0.89-1.01	0.89-0.90	2.60-3.36	2.43-3.36
Comilla around Motlab	29-37	35-39	7-11	2	-	0.265-0.297	1.703-1.735	-	6.73-7.52	-
Sylhet around Juri	37	46	20	0.67	1.09	0.39	0.28	0.70	1.72	2.8
Chittagong around Patenga and Dohazari	27-52	NP and 36-47	NP and 13-20	1.01-4.92	-	0.449-1.14	0.26-4.25	-	1.23-7.34	-

NMC = Natural Moisture Content
LL = Liquid Limit
PI = Plasticity Index
OCR = Over Consolidation Ratio

CM = Casagrande Method (Serajuddin, 1967a)
SM = Schmertman Method (Serajuddin, 1967a)
P_c = Estimated Maximum Pre-consolidation Pressure
P_o = Computed Present Overburden Pressure

Serajuddin (1987) made a study of the applicability of "universal compression index equation" of Herrero (1980, 1983a, 1983b) to Bangladesh plastic silts and clays and derived by regression method twelve compression index equations (Eqs. 7 to 18) for Bangladesh fine-grained soils, as shown in Table 4.

In these equations normalized zero-air-voids-curve (ZAVC) slope, initial void ratio, e_o, and natural water content, W_N, were used as variables to derive the regression equations for estimation of compression index, C_c, using power, linear, logarithmic and exponential regressions.

The normalized zero-air-voids-curve (ZAVC) slope was equal to

$$[G_s (\gamma_w/\gamma_d)^2] = [G_s ([1+e_o]/G_s)^2] \qquad (6)$$

where, G_s = specific gravity
γ_w = unit weight of water
γ_d = dry density of soil
e_o = initial void ratio

Table 4. Compression Index Equations for Bangladesh Fine-Grained Soils

Variables	Type of Regression	Compression Index Equations	Coeff. of Correlation (r)	Eq. No.
Normalized ZAVC Slope	Power	$0.1446 [G_s ([1+e_o]/G_s)^2]^{1.4522}$	0.82	(7)
-do-	Linear	$0.2765[G_s([1+e_o]/G_s)^2-0.5171]$	0.85	(8)
-do-	Logarithmic	$0.3860[\ln G_s([1+e_o]/G_s)^2+0.3174]$	0.82	(9)
-do-	Exponential	$0.0553e^{1.014\, G_s ([1+e_o]/G_s)^2}$	0.83	(10)
Initial Void Ratio	Power	$0.2625e_o^{1.3678}$	0.81	(11)
-do-	Linear	$0.4049 (e_o - 0.3216)$	0.85	(12)
-do-	Logarithmic	$0.3584 (\ln e_o + 0.7829)$	0.79	(13)
-do-	Exponential	$0.0568e^{1.5063e_o}$	0.83	(14)
Natural Water Content	Power	$0.0030W_N^{1.2497}$	0.78	(15)
-do-	Linear	$0.0102 (W_N - 9.15)$	0.79	(16)
-do-	Logarithmic	$0.3265 (\ln W_N - 2.721)$	0.76	(17)
-do-	Exponential	$0.0648\, e^{0.328W_N}$	0.89	(18)

The above comparative study has indicated that for the types of inorganic silt and clay soils which generally exist in different areas of Bangladesh, the equations 8, 12 and 18, and also the equations developed earlier, using Bangladesh soils data would give more dependable estimated values of C_c than the similar equations developed on the basis of geotechnical data of other countries and regions of the world.

Compression Ratio and Natural Water Content Relationship

The compression S of a confined stratum of normally loaded ordinary cohesive silt/clay can be estimated from the relation

$$S = H \frac{Cc}{1+eo} \log_{10} \frac{Po+DP}{Po} \qquad (19)$$

where $[C_c/(1 + e_o)]$ is termed compression ratio, H is the thickness of the bed of cohesive silt/clay under a pressure P_o and ΔP is the dfference of pressure for an increase of the pressure from P_o to $P_o + \Delta P$.

The linear graphical relation as established for this paper by the writer between compression ratio and natural water content for Bangladesh inorganic cohesive silts and clays selected at random from the available consolidation test data of 1954 to 1984 representing different geographical and geological regions of the country is shown on Fig. 5(a). The linear relation for the same obtained by Serajuddin and Ahmed (1967) for Bangladesh cohesive soils is shown on Fig. 5(b). The relation obtained by Fadum (mentioned by Terzaghi and Peck, 1948) for soils of other countries is also shown on Fig. 5(b).

Permeability

Influence of Fines on Permeability of Sand Beds and Estimation of Permeability from Simple Laboratory Soil Tests

A reasonably accurate estimate of the coefficient of permeability of the ground is frequently required in civil engineering problems which involve flow of water. Published formulas of several authors correlating the permeability of beds of granular materials with their geometrical properties apprear to be restricted in their application to clean sands and are unlikely to be suitable for fine and medium to fine sands mixed with trace to appreciable quantities of nonplastic silts which occur predominantly in different areas of Bangladesh. An investigation was, therefore, undertaken by Serajuddin (1970) and Serajuddin and Islam (1985) to find permeability of different sands containing various proportions of nonplastic fines (particles smaller than 0.075 mm) at different degree of packing and to compare the laboratory measured permeability values with size, shape, uniformity, porosity, amount of silts present and in-situ measured permeability so that the test results can be used to make an approximate estimate of field permeability of sand beds containing silts. The influence of nonplastic silts in reducing the permeability of sand beds has been demonstrated in Tables 5(a) and 5(b). These tables can be used to estimate the permeability of sand beds having grading and approximate porosity similar or close to the grading and porosity of sands of these tables. Serajuddin (1970) studied on fine and medium to fine sands containing zero to 25 percent nonplastic fines. Serajuddin and Islam (1985) studied on idealised coarse to medium to fine sands containing zero to 25 percent nonplastic fines.

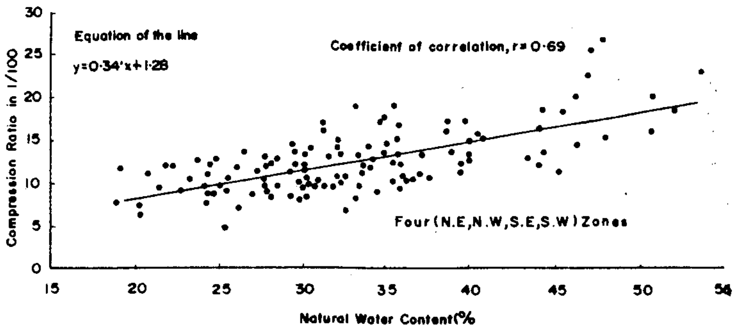


Fig 5. (a) Compression Ratio versus Natural Water Content

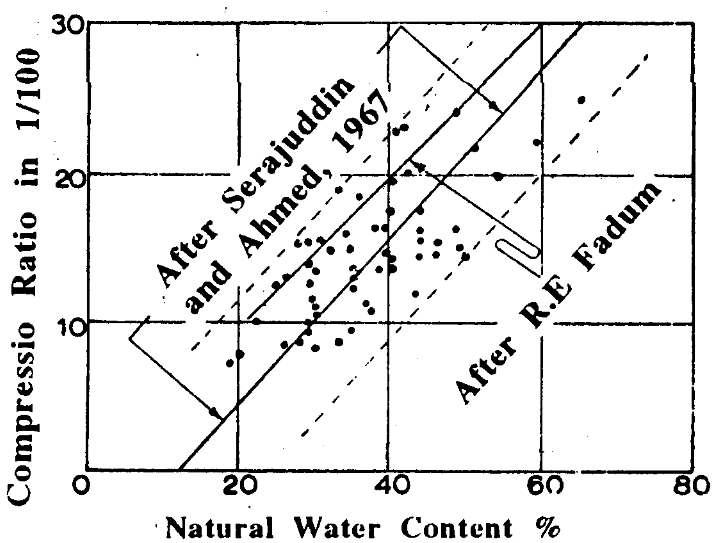


Fig 5. (b) Compression Ratio versus Natural Water Content

Table 5. Co-efficient of Laboratory Measured Permeability, k_{20} for (a) Selected Aquifer Sands in Natural Gradings and (b) Laboratory Mixed Sands in Predetermined Proportions of Various Sand Fractions and Non-plastic Fines.

(a) Aquifer Sands

Sample No.	Granular Composition: % finer than the diameter (mm)				D_{10} (mm)	Coeff. of Permeability k_{20} (cm/secx10^{-4}) at the indicated porosity (%)			
	4.75	2.0	0.425	0.075		33.3	37.5	41.17	44.44
5	-	-	99	5	0.100	5	8	13	-
6	-	98	95	10	0.075	2	4	8	-
7	-	98	60	10	0.075	5.5	8.5	14	23
9	78	76	44	2	0.200	32	45	60	-
10	-	98	78	2	0.150	17	33	60	-
11	87	77	50	0	0.250	90	200	-	-
12	-	-	98	8	0.076	-	-	4.4	-
13	90	88	72	8	0.100	6	12	20	-
14	98	92	70	8	0.100	17	28	42	-
15	98	97	58	8	0.100	8	14	20	34
16	-	-	97	25	0.030	-	5.5	7.5	10
17	-	100	90	8	0.100	-	4.2	10	25
19	-	100	70	8	0.090	18	24	30	-

(b) Laboratory mixed sands

						30	35	40	45
1	-	100	0	0	0.440	-	225	330	500
2	-	100	25	0	0.180	-	125	190	300
3	-	100	50	0	0.120	60	78	100	130
4	-	100	75	0	0.130	68	95	140	200
5	-	100	55	5	0.100	28	44	-	-
6	-	100	57	10	0.074	13	23	40	70
7	-	100	63	15	0.043	10	18	31	-
8	-	100	74	19	0.035	4.5	9	20	-
9	-	100	65	25	0.024	1.5	3	6	-
10	-	100	100	2	0.010	48	59	70	85
11	-	100	100	4	0.081	13	23	40	70
12	-	100	100	10	0.081	8	13	20	-
13	-	100	100	15	0.058	-	7.5	14	25
14	-	100	100	20	0.025	3	5.5	10	-
15	-	100	100	25	0.022	-	1.5	3	5.7
16	-	100	50	9	0.120	20	40	77	-
17	-	100	75	10	0.074	9.5	17	29	50

Compaction

General Compaction Characteristics

In earth construction like dams, embankments, retaining walls, highways, and airfields, it is desirable to have high compaction (a) to decrease future settlements (b) to increase shear strength (c) to decrease permeability and (d) to decrease erosion of slopes.

Laboratory compaction tests are done (a) to determine optimum moisture content (OMC) which is to be used when compacting the soil in the field, and (b) to ascertain the degree of denseness in the field which can be expected from compaction at the optimum moisture content under a certain compactive effort (light or heavy).

In Table 6 are shown the range of average values of maximum dry density (MDD) and optimum moisture content (OMC) achieved by standard and modified Proctor compaction test in the laboratory on about one thousand various types of soils of the different zones. These samples were collected from soils occurring within about 2 to 3 m depths from the ground surface of the various investigated areas of the greater districts of Chittagong, Noakhali, Comilla, Faridpur, Barisal, Khulna, Jessore, Kushtia, Pabna, Rajshahi, Bogra, Dhaka and Mymensing of Fig. 1.

Compaction of Earth Embankments through Natural Process

The earth embankments were and are constructed from time to time by head basket placing of earths engaging labourers in different areas of the country in connection with control of floods, training of rivers, irrigation of lands, protection of coastal areas from inundation by saline tidal water during high tide and cyclones and construction of different grades of roads and highways. Compaction with modern mechanical equipment could not be made for want of sufficient number of such equipment or for difficulty of movement of such heavy equipment in many areas of the country. There was a strong old belief that the earth embankments so constructed achieved adequate compaction in several years through natural causes of downward percolating rain water and self-weight of the earth of the embankment. Investigations were done in 1960's to physically verify the extent and nature of densification of some selected old and recent earth embankments of the greater districts of Khulna, Barisal and Kushtia. The following conclusions regarding compaction under natural causes were derived from the studies (Rahman et al, 1963 and Serajuddin et al , 1979.)

> For clays, plastic silts, and sandy clays the field compaction of the selected investigated locations of the greater Khulna and Barisal districts varied from about 56 to 89 percent with an average of about 78 percent and for nonplastic silts, silty sands and sandy silts the field compaction varied from about 73 to 97 percent with an average of about 88 percent. The field moisture content varied from about 11 to 44 percent excluding the peaty clays having 70 to 88 percent field moisture content . The percent compaction was calculated with respect to maximum dry density (MDD) achieved by standard Proctor compaction in the laboratory.

Table 6. Approximate Range of Some Typical Values of Laboratory Maximum Dry Density and Optimum Moisture Content for Different Soils of Bangladesh.

Sl. No.	Location	Finer than 75 Micron (%)	Liquid Limit (%)	Plasticity Index (%)	USC Symbol	Maximum Dry Density		Optimum Moisture Content	
						Standard (g/cm3)	Modified (g/cm3)	Standard (%)	Modified (%)
1.	South - East Zone	52 - 99	20 - 40	1 - 21	CL,ML ML- CL	1.60- 1.97	1.72 - 2.09	11 - 22	8 - 16
		23 - 50	- NP -	- NP -	SM	1.85- 1.99	2.01 - 2.07	10 - 12	9 - 11
2.	South - West Zone	53 - 100	24 - 49	2 - 25	CL,ML ML- CL	1.64- 1.84	1.82 - 2.00	14 - 21	10 - 16
		93 - 100	51 - 72	25 - 43	CH,MH	1.51 -1.75	1.72 - 1.90	18 - 24	14 - 18
		25 - 42	- NP -	- NP -	SM	1.53-1.63	1.69 - 1.84	15 - 20	11 - 15
3.	North - West Zone	50 - 100	17 - 49	2 - 30	CL,ML ML-CL	1.42 -1.81	1.90 - 1.96	12 - 26	12 - 23
		78 - 100	51 - 85	24 - 61	CL - CH CH,MH	1.48-1.66	--	17 - 25	--
4.	North - East Zone	67 - 99	28 - 56	2 - 3	CL,ML, CH,MH	1.69- 1.92	1.62 - 2.03	12 - 20	10 - 17
		16 - 65	NP	NP	SM, SM-ML	1.72-1.89	1.80 - 1.99	12 - 16	10 - 14

Note : Standard and Modified compaction data are in most cases for different samples because both standard and modified compaction tests are only occasionally done on the same samples for comparison.

- For the selected investigated locations of the greater Kushtia district the compaction in the earth embankment was in the range of 74 to 84 percent with field moisture contents from 20 to 28 percent for plastic silt-clay soils.

- An increase in density in the surface extending upto a depth of about 1 to 1.25 m occurred due to shrinkage in the plastic silts, sandy clays and clays during dry season which was not lost during the wet period. This increase averaged about 6 percent maximum at the surface and decreased with depth.

- There was an increase in embankment compaction with depth due to the weight of the embankment which caused consolidation. This increase in density was probably about 0.5 percent per foot depth.

- There was no apparent increase in density due to seepage forces of downward percolating rain water.

<u>Hand Compactors</u>

In a study (Serajuddin, 1980) it has been demonstrated that certain types of hand compactors (made of concrete) are useful for sandy soils and clayey soils of our country to achieve compaction in absence of mechanical compaction equipment and in areas where these mechanical equiment can not be transported. The different hand compactors which were studied are shown in Fig. 6. Comparative cost of compaction by these hand compactors are shown in Table 7. The summary of observations about the efficiency of these hand compactors are presented in Table 8

Fine-Grained Soils as Road Construction Materials

<u>California Bearing Ratio</u>

A systematic geotechnical investigation was done on soils occurring within about 2-3m depths in different areas of eleven greater districts of Chittagong, Noakhali, Comilla, Faridpur, Barisal, Khulna, Jessore, Kushtia, Pabna, Rajshahi and Bogra of the south-east, south-west and southern part of north-west geographical regions as shown in Fig. 1. The purpose of the study was to assess suitability of the soils for possible future use as road embankment fills and as subgrade materials. Classification tests and CBR tests under different compaction efforts and moisture conditions were done on a large number of soil samples of the said districts. All these CBR tests data were analysed and evaluated with respect to different ranges of plasticity indices, achieved dry densities, relative compactions

Table 7. Comparative Cost of Hand Compaction

Hand Compactor No.	Sandy Material Man-secs/per cu. ft.	Clayey Material Man-secs/per cu. ft.
1	60	103
2	132	223
3	106	182
4	55	95
5	-	370

Table 8. Summary of Observations for the Hand Compactors

Compactor Number	Sandy Material	Clayey Material
1.	95% standard maximum compaction can be attained only with a 10 cm lift using 6 or 8 passes and at high moisture contents.	90% standard maximum compaction can be attained only with 6 or 8 passes and at a moisture content below 22% and with a 15 cm lift.
2.	95% standard maximum compaction can be attained at all conditions except with only 4 passes.	90% standard maximum compaction can be attained with a 15 cm lift using 6 or 8 passes at moisture content below 22%.
3.	95% standard maximum compaction can be attained at all conditions with a high moisture content except using only 4 passes. 90% standard maximum compaction can be attained at all conditions.	Using 15 cm lift and 8 passes, upto about 87% standard maximum compaction was possible at moisture content of about 22%.
4.	95% standard maximum compaction not possible except very high moisture contents. 90% standard maximum compaction is possible only at high moisture contents.	Estimated that 4, 6 or 8 passes would give about 90% standard maximum compaction at moisture content of about 22% and with a 15 cm lift.
5.	Not tried	Because of smaller base area and higher stress intensity, more than 90% standard maximum compaction can be attained.

calculated on the basis of corresponding modified MDD, and compaction moisture contents. The findings are briefly summarised in Figs. 7 and 8 (Serajuddin and Azmal, 1991). Also soaked CBR values of specimens compacted at equal level of standard and modified compactive effort at moisture contents 2-3 percent wet and dry of respective OMC showing effect of variation of moulding moisture content from respective OMC is presented in Fig.8(a).

Salient observations of the above study on 461 soil samples of the different areas are as under :

- about 91 percent of the tested soil samples of the investigated areas are silty and clayey soils of A-4, A-6 and A-7-6 soil subgroups of AASHTO classification system; A-1 soil subgroup does not exist in the top layers and A-2, A-3, A-5 and A-7-5 occur rarely. Majority of the soil samples are low to medium plastic and have soil particles 51 to 100 percent smaller than 0.075m. The soils generally have high NWC, about 10 to 15 percent above respective modified OMC.

- compactibility of the soils is fair to good, specially when subjected to modified compactive effort.

- standard MDD and OMC of the soils vary from about 1390 to 1970 kg/m3 and about 11 to 27 percent respectively; and modified MDD and OMC of the soils vary from about 1590 to 2100-kg/m3 and about 8 to 23 percent respectively.

- unsoaked CBR values are quite high and on soaking for 4 days under 10 kg surcharge weight, the soaked CBR values become about 33 to 44 percent of the unsoaked CBR values on the average.

- swelling on soaking does not exceed about 2 percent (with a few exceptions).

- at equal level of compactive effort soaked CBR decreases appreciably along with decrease of achieved dry density on variation of moulding moisture even within 2 to 3 percent wet and dry of respective, OMC {Figs. 9 and 10(a)}.

- When the plastic fine-grained soils were compacted to about 95 percent or more of the modified MDD at 2 or 3 percent below or above of the modified OMC, about 15 to 25 percent of the samples then gave soaked CBR values less than 4 percent, about 60 percent gave soaked CBR values of about 4 to 6 percent, about 10 percent gave soaked CBR values of about 6 to 10 percent and about 5 to 15 percent gave soaked CBR values above 10 percent.

- The correlations in Fig. 8(b) between unconfined compressive strength (q_u) and CBR would help to make an estimate of CBR from q_u of similar silty and clayey soils of the country.

- The climatic and hydrological environments are such that subgrade saturation is possible in rainy/flood seasons, and consideration of soaked CBR values for subgrades would be appropriate in pavement design and construction in Bangladesh.

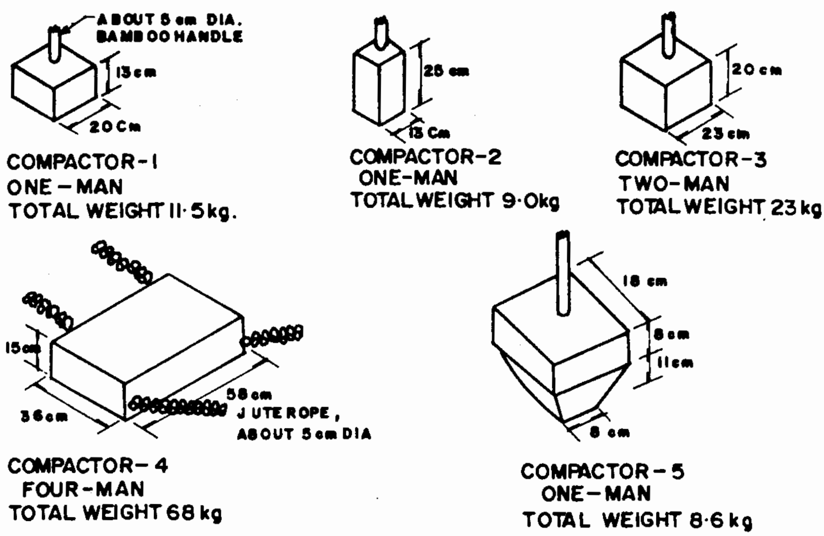


Fig 6. Compactor Details

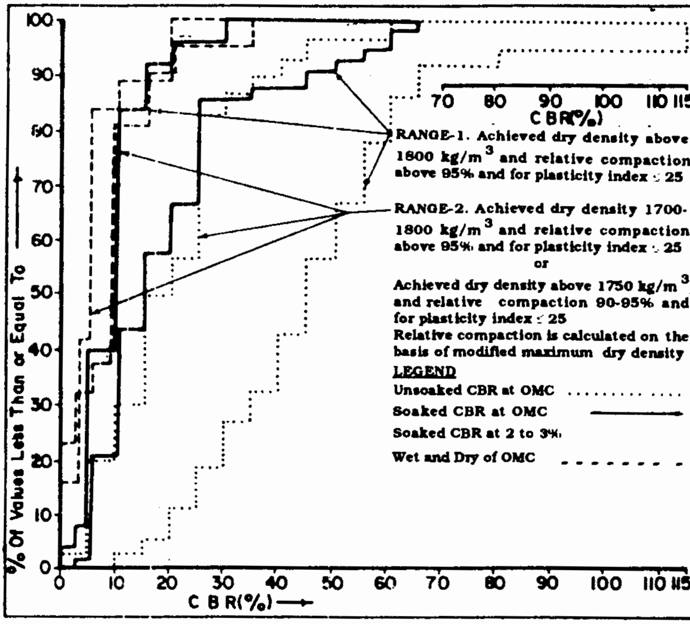


Fig 7. Cumulative Distribution of Unsoaked and Saaked CBR Values of Specimens Compacted at OMC Showing Effect of Soaking; and Soaked CBR Values of Specimens Compacted at Moisture Content 2 to 3% Wet and Dry of OMC Showing Effect of Variation of Moisture Content from OMC, for Range 1 and Range-2

Ground Improvement by Stabilization

Three composite A-4, A-6 and A-7-6 soil samples of the greater districts of Pabna, Bogra and Rajshahi (Fig. 1) with liquid limit and plasticity index from about 28 to 42 percent and 7 to 22 percent respectively and soil fractions finer than 0.075 mm from about 68 to 96 percent were tested for stabilization with different proportion of cement and slaked lime as per British Standards Institution Methods of Test for Stabilized Soils (BS 1924 : 1975). The study indicated that if these types of silty and clayey soils were stabilized with about 7.5 percent cement at modified MDD and OMC, the unconfined compressive strength (q_u) of 17.5 kg/cm2 (250 psi) at 7-day, a minimum value commonly accepted as indicating suitability of stabilized soils for pavement construction (Compendium-8, 1979), would be achieved allowing for the field variation. (Serajuddin and Azmal, 1991).

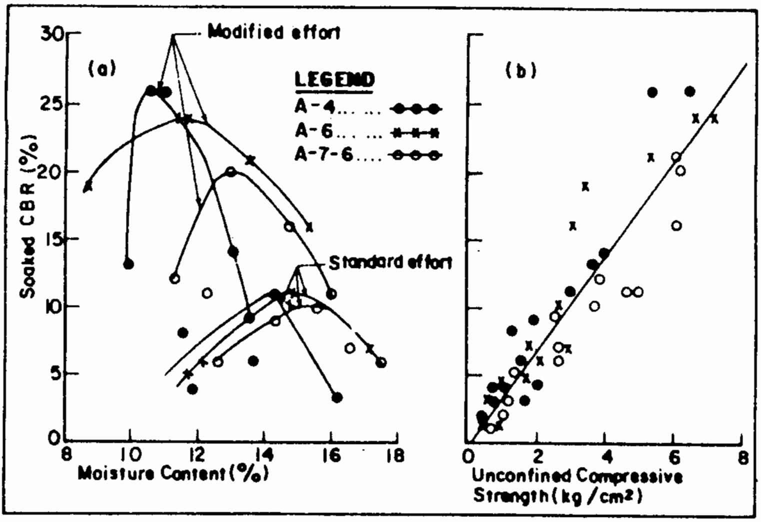


Fig 8. (a) Effect of Variation of Moulding Moisture Content on Soaked CBR at Modified and Standard Compactive Efforts; (b) Correlation Between Soaked CBR and Soaked Unconfined Compressive Strength

Further studies of soil-cement and soil-slaked lime stabilization were made on some selected fine-grained soils of greater districts of Faridpur, Kushtia, Jessore, Khulna (northern area) and Chittagong (Fig. 1) as per BSI Methods of Test for Stabilized Soils (BS 1924 :1975). The studies indicated that a minimum of 7 to 8 percent cement would have to be used to achieve a minimum unconfined compressive strength of 14 kg/cm2 in the field in 7 days at standard maximum dry density of the soil-cement mixtures; and 14 kg/cm2 was considered as the reasonable 7 days unconfined compressive strength required to withstand the weathering effects of the south-east and south-west regions of Bangladesh. Results of soil-slaked lime studies were not encouraging for the types of soils which were low to medium plastic.

Some studies of mechanical stabilization of fine-grained soils (of low soaked CBR values) mixing with different proportions of local fine sands were done. Fine-grained soil and local fine sand mixtures of suitable proportions, sand fraction not exceeding 50 percent and compacted to more than 95 percent of modified MDD with moulding moisture content equal or very close to modified OMC gave soaked CBR values around or above 20 percent. Therefore, the fine-grained soil and local fine sand mixtures at suitable proportions compacted to required density appeared to be quite acceptable as improved subgrade above the compacted subgrade of low CBR of 4 or less than 4 in the road construction as an alternative of soil-cement stabilized improved subgrade. (Serajuddin, 1992, & 1993).

CONCLUSIONS

The paper is expected to give the engineers and engineering profession in Bangladesh dealing with feasibility study, planning, design and construction of civil engineering structures on the soils and of the soils, some basic data on the physical and engineering properties of local soils. In preliminary planning and design work it is useful to have on hand some basic data on local soil conditions before any program of a limited or detailed site investigation is made.

The correlations and empirical equations as developed on Bangladesh soils and presented in this paper should better suit the soils of Bangladesh than those empirical relations developed on the soils of other countries. The correlations should, however, be used as an aid to extend usefulness of soil testings and not as a substitute for proper tests in any case.

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