SOILS AND FOUNDATIONS Vol. 32, No. 4, 156-163, Dec. 1992
Japanese Society of Soil Mechanics and Foundation Engineering

PHYSICO-CHEMICAL EFFECT ON COMPRESSIBILITY OF TROPICAL SOILS

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ABSTRACT

The paper examines the role of physico-chemical factors in the consistency limits and compressibility behavior of kaolinitic soils and montmorillonitic soils of residual origin. The liquid limit, equilibrium void ratio at a given load (in the oedometer test) and compression index values of the kaolinitic soils in the remolded state correlate well with the shrinkage limit values, which in turn are a function of the clay fabric. The corresponding engineering properties of the remolded montmorillonitic soils correlate well with the exchangeable sodium content that reflects a soil's potential to develop diffuse ion layer.

Oedometer tests with undisturbed samples highlight the role of clay mineralogy in the engineering behavior of residual soils; on inundation with water under a nominal pressure, the kaolinitic soils exhibit no volume change while the montmorillonitic soils exhibit a notable swell. Oedometer tests with undisturbed samples also showed that besides the physico-chemical factors, the in-situ moisture content, density and degree of saturation have an important bearing on the void ratio sustained by the soils at a given stress level.

Key words: chemical properties, compressibility, mineralogy, residual soils (**IGC**: D5)

INTRODUCTION

Residual soils are products of chemical weathering and their properties are dependent on environmental factors of climate, parent material, topography, drainage, and age (Quarterly Journal of Engineering Geology Report, 1990). Owing to the wide diversity in their conditions of formation, residual soils can differ in the physico-chemical factors of clay mineral type and associated inter-particle forces, amounts of sesquioxides present, type of exchangeable cation and pore electrolyte composition. For example in dry tropical regions with poor rainfall (<305 mm/year) and drainage, montmorillonite rich soils (vertisols) form; in sub-tropical regions with moderate rainfall (305 mm-1270 mm/year) and good drainage, kaolinite rich soils with some amount of 2:1 minerals are formed (ferruginous soils), iron oxide is crystallized as hematite (α-Fe_2O_3) owing to seasonal desiccation and gives the characteristic red color to the soil, gibbsite is usually absent; in hot humid tropics with high rainfall (>1270 mm/year) and good drainage, kaolinite rich

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Manuscript was received for review on March 25, 1991.
Written discussions on this paper should be submitted before July 1, 1993, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

soils containing hydrated (goethite, α-$Fe_2O_3 \cdot H_2O$) or dehydrated (hematite) iron oxides and gibbsite (γ-$Al_2O_3 \cdot 3H_2O$) form (ferrallitic soils) (Townsend 1985, The Quarterly Journal of Engineering Geology Report 1990). The importance of soil physico-chemical factors in the compressibility behavior of tropical soils have not been investigated; several studies are however available highlighting the importance of the above factors in governing the compressibility behavior of pure clays (Bolt 1956; Leonards and Altschaeffl 1964; Mesri and Olson 1971, Sridharan and Venkatappa Rao 1973; Sridharan et al., 1986a). The present study utilizes this knowledge to evaluate the role of the physico-chemical factors in the compressibility behavior of kaolinitic soils (ferruginous soils) and montmorillonitic soils (vertisols) from Karnataka State, India, tested in the remolded saturated as well as undisturbed conditions. It is hoped, that the results of the study will enable a better understanding of the role of physico-chemical factors in the compressibility behavior of residual soils.

MATERIALS AND METHODS

The soils used in the study are mostly from Karnataka State, India (15 out of 17 soils). The soils studied mainly were red soils (ferruginous soils) from Bangalore district (South Karnataka) and black cotton soils (vertisols) from North Karnataka. Sufficient quantity of disturbed soils in the desiccated state were collected from various locations from depths of 1 m to 3 m and were wet sieved to pass a 425 μm (ASTM Standard No. 40) sieve.

A few undisturbed kaolinitic (ferruginous soils from Bangalore district) and montmorillonitic (vertisols from North Karnataka) soil specimens were extracted from depths of 0.5 m to 1.5 m, using 25 mm high and 76 mm diameter stainless steel consolidation rings coated with silicone grease to minimize side friction. The X-ray diffraction analysis of the soils showed kaolinite to be the dominant clay mineral in soils 1 to 8 (red soils from Bangalore district) and montmorillonite to be the principal clay mineral in soils 9 to 17 (majority of the soils are the black cotton soils from North Karnataka).

The exchangeable cation analysis was carried out by displacing the exchangeable cations with ammonium ions on successive treatment of the soil specimens with 1M neutral ammonium acetate solution and estimating the displaced cations by standard methods. Table 1 presents information regarding the specific gravities, grain size distribution and index properties of the soils. The soil specimens were tested in standard fixed ring consolidometers using stainless steel rings 76 mm in diameter and 25 mm height.

The kaolinitic soils Nos. 1 to 8 and the montmorillonitic soils Nos. 9 to 17 were mixed into a soft easily remolded state at moisture contents approximately corresponding to 65% (±5%) of the individual liquid limit values. The moist soil samples were next hand remolded into consolidation rings to a thickness of 18 mm. Using a load increment ratio of unity consolidation tests were performed conventionally, the duration of each load increment being 48 hours. Each soil specimen was loaded to a maximum of 400 kPa and unloaded to the initial pressure of 6.25 kPa.

A few index and oedometer tests were performed with undisturbed kaolinitic and montmorillonitic soil specimens. The undisturbed samples were soaked with water at the initial

Table 1. Some physical properties of soils studied

Soil number	Specific gravity	Grain size distribution, %			Liquid limit %	Plastic limit %	Shrinkage limit %
		Sand	Silt	Clay			
1	2.65	33	42	25	27	15.8	11.0
2	2.61	34	39	27	38	15.3	11.5
3	2.76	12	58	30	74	25	15.7
4	2.68	59	16	25	47	21.5	16.4
5	2.78	40	36	24	47	25.4	16.8
6	2.54	19	60	21	68	35.4	18.0
7	2.78	22	42	36	75	36.3	19.8
8	2.77	11	53	36	75	33.8	20.1
9	2.74	49	20	31	47	25.0	15.9
10	2.76	13	39	48	72	31.4	12.4
11	2.66	54	31	15	47	24.5	15.7
12	2.75	18	32	50	75	32.5	11.1
13	2.77	27	49	24	75	36.6	9.8
14	2.79	8	55	37	84	41.7	11.5
15	2.70	4	65	31	100	45.1	10.9
16	2.79	7	51	42	106	44.1	10.8
17	2.72	33	28	39	124	23.2	12.3

pressure of 6.25 kPa (the insitu normal effective stresses varied over 7 to 24 kPa). Conventional one-dimensional consolidation tests were conducted with the soaked specimens using a load increment ratio of unity, the duration of each load being 48 hours.

RESULTS AND DISCUSSION

Fig. 1 plots plasticity index versus liquid limit for the red (kaolinitic) soils and black cotton (montmorillonitic) soils. The results show that the kaolinitic soils (ferruginous soils) usually plot above the A-line (6 out of 8 points) . The montmorillonitic soils (vertisols) plot close to and on either side of the A-line. Active clays like montmorillonite generally plot well above the A-line. Presumably, the desiccation bonds, formed in the montmorillonitic soils by the action of climatic changes, decreases their effective specific surface area and is responsible for the reduced colloidal activity of the soil specimens. The positions of the red soils from Bangalore district and of the black cotton soils from North Karnataka on the Casagrande's chart, agree well with those established for tropically weathered clays in relation to their clay mineralogical composition (Gidigasu, 1983).

The shrinkage limit of the remolded kaolinitic soils range between 11.0 and 20.0% and those of the montmorillonitic soils between 9.8% and 15.9% (Fig. 2). Interestingly for the same liquid water content of 75% (Table 1) kaolinitic soils (Nos. 7 and 8) have markedly higher shrinkage limits than montmorillonitic soils (Nos. 12 and 13). Another notable comparison is the opposite variations of the liquid limits of kaolinitic and montmorillonitic soils with their respective shrinkage limit values (Fig. 2). The liquid limit of kaolinitic soils in general increases with the shrinkage limit, while the liquid limit of montmorillonitic soils decreases with an increase in shrinkage limit.

In a recent study with remolded ferruginous soils (Sridharan et al., 1988), the importance of the clay fabric in influencing the liquid limit of the remolded residual soils was highlighted. Predominance of strong inter-particle attraction favors a more flocculant fabric and a higher liquid limit for the kaolinitic soil because of greater water entrapment in the soil's open structural units. Comparatively, prevalence of weak interparticle repulsion favors a relatively less random fabric and a lower liquid limit as it encloses smaller void spaces for water entrapment.

The amount of shrinkage upon drying is

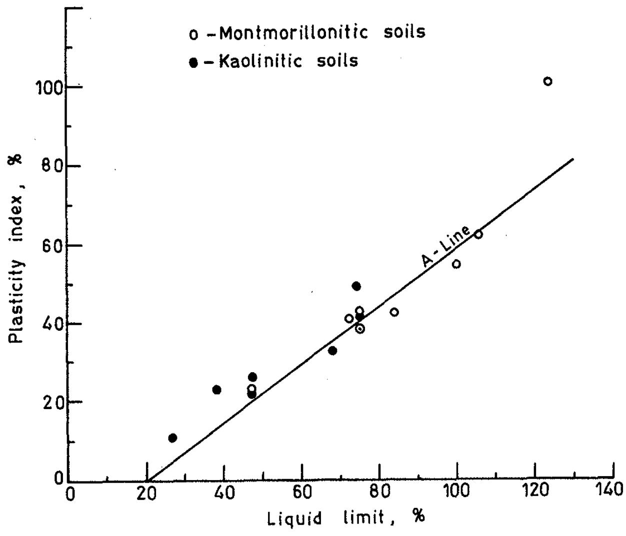


Fig. 1. Plasticity index versus liquid limit for kaolinitic and montmorillonitic soils

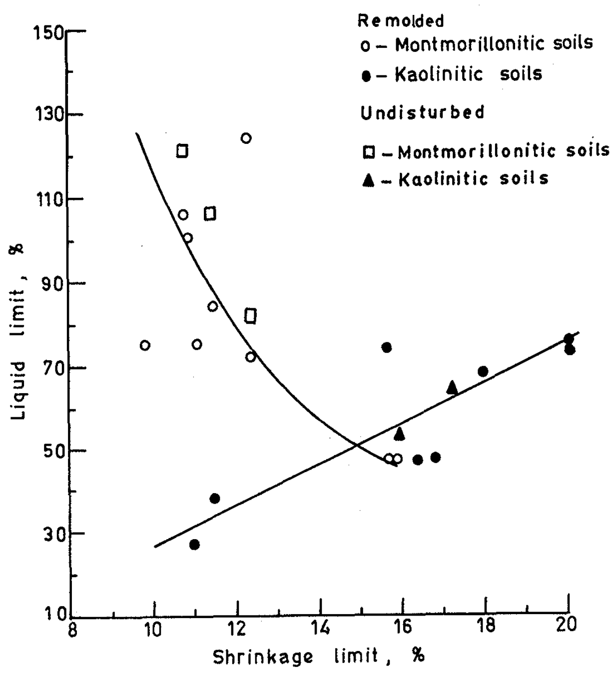


Fig. 2. Variation of liquid limit with shrinkage limit for kaolinitic and montmorillonitic soils

also a function of average particle orientation since experiments have shown that an undisturbed or remolded clay specimen with a more oriented particle arrangement undergoes greater volume reduction upon drying than the same specimen with its particles in a flocculant array (Lambe, 1958). Consequently the increase in liquid limit with shrinkage limit for the remolded kaolinitic soils brings out the influence of the clay fabric on the Atterberg limits of the soils (Sridharan et al., 1988).

With montmorillonitic soils, an increase in liquid limit results from an increase in diffuse ion layer formation (Yong and Warkentin 1975; Sridharan et al., 1986b). Such a situation favours an oriented particle arrangement that provides for a relatively easier movement of particles and particle groups during drying (Mitchell, 1976) explaining the decrease in shrinkage limit with increasing liquid limit for the remolded montmorillonitic soils.

Compressibility Behavior of Kaolinitic Soils

Fig. 3 presents the void ratio-pressure curves for the remolded kaolinitic soils (Nos. 1 to 8). A small preconsolidation like pressure of 25 kPa is observed for the soils owing to their initial remolding water contents being lower than their liquid limit values.

Examination of the void ratio-pressure curves for the remolded kaolinitic soils reveal that with the exception of soil Nos. 3 and 8, all other soils are positioned in their increasing order of shrinkage limits suggesting that a soil with a more random fabric sustains the applied load at a higher equilibrium void ratio.

Table 2 presents the shrinkage limit and compression index data for the remolded and undisturbed kaolinitic soils and shows the C_c values to generally increase with shrinkage limit. Application of consolidation pressure tends to re-orient particles into a parallel array. Presumably the larger compressibility of the higher shrinkage limit (more flocculated) specimen results from greater particle readjustment under the applied load.

Consolidation test curves for the undisturbed kaolinitic soil specimens from Bangalore district are presented in Fig. 4. The soils examined do not undergo any settlement on soaking at the initial pressure of 6.25 kPa, presumably as the intrinsic stresses can sustain

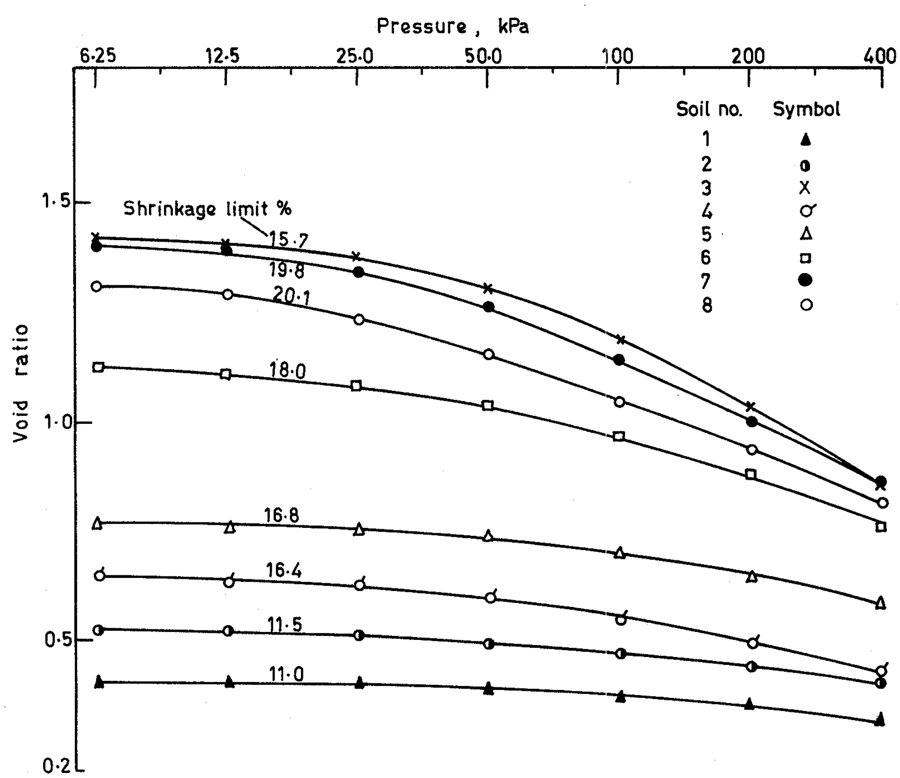


Fig. 3. Void ratio-pressure relationships for remolded kaolinitic soils

Table 2. Compression index data for kaolinitic and montmorillonitic soils

Soil* number	Shrinkage limit (%)	C_c 200–400 kPa	Soil number	Exchangeable sodium meq.100^{-1}	C_c 200–400 kPa
1	11.0	0.13	9	2.34	0.23
2	11.5	0.13	10	3.27	0.50
3	15.7	0.56	11	3.43	0.20
4	16.4	0.21	12	3.72	0.62
5	16.8	0.20	13	5.43	0.57
6	18.0	0.39	14	5.52	0.89
7	19.8	0.45	15	7.15	0.64
8	20.7	0.39	16	8.68	0.93
IIS	15.9	0.27	17	13.32	0.76
MRJ	17.3	0.35	K-1	4.5	0.28
			IH-1	8.2	0.33
			IH-2	8.5	0.38

*Soil numbers 1–8 are remolded kaolinitic soils.
Soil numbers 9–17 are remolded montmorillonitic soils.
Soils IIS and MRJ are undisturbed kaolinitic soils.
Soils K-1, IH-1, IH-2, are undisturbed montmorillonitic soils.

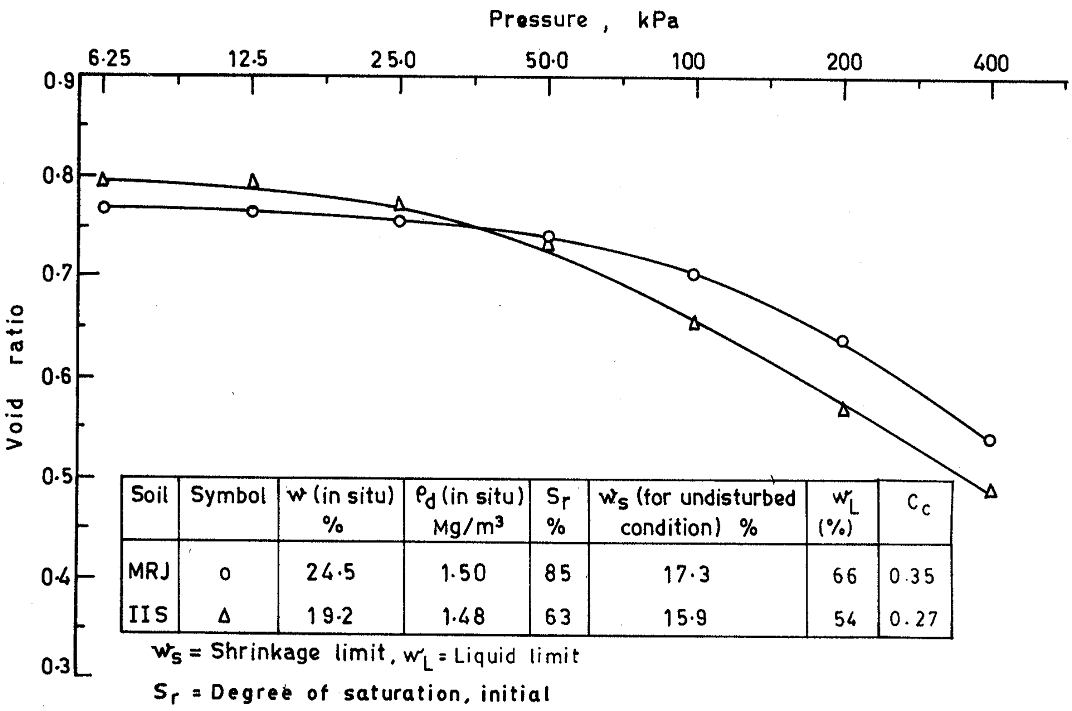


Fig. 4. Void ratio-pressure relationships for undisturbed kaolinitic soils

the small applied pressure on inundation. The consolidation curves exhibit an apparent preconsolidation pressure (Townsend, 1985), ranging from 36 kPa to 50 kPa, which is more than the in-situ stresses (7–24 kPa) and is possibly imparted to the soil by the in-situ soil structure. Consolidation test results also show that the kaolinitic soil with a lesser in-situ dry density and degree of saturation (soil IIS) exhibits a slightly higher in-situ void ratio. On soaking and subsequent loading, the soil specimen (IIS) persists to display higher equilibrium void ratios up to stresses of ≈ 50 kPa, which approximates to its apparent preconsolidation pressure. At higher applied stresses, in the normally consolidated range, the kaolinitic soils are positioned in order of their increasing shrinkage limits (determined for the undisturbed condition), as earlier noted with the remolded specimens.

Compressibility Behavior of Montmorillonitic Soils

Fig. 5 plots the $e-\log p$ curves for the remolded montmorillonitic soils. A small preconsolidation like pressure of ~28 kPa is observed for the soils owing to their initial remolding moisture contents being lower than their liquid limit water contents.

The $e-\log p$ curves of the remolded montmorillonite soils are in general placed in their increasing order of exchangeable sodium contents or decreasing sequence of their shrinkage limits. The equilibrium void ratios sustained by montmorillonite soils at a given pressure, are governed by the physico-chemical repulsion forces arising from interaction of adjacent diffuse double layers (Mesri and Olson 1971; Sridharan and Venkatappa Rao 1973). The exchangeable sodium content of a montmorillonitic soil reflects the soil's potential to develop diffuse ion layer as these monovalent ions readily dissociate from the clay surface in presence of water and appreciably contribute to the diffuse ion layer formation; the other exchangeable cations namely, calcium, magnesium and potassium ions are strongly adsorbed by the clay surface and contribute inappreciably to diffuse ion layer growth (Sridharan et al., 1986b). Understandably then, the remolded montmorillonitic soils with a higher sodium content mobilize greater repulsion forces that enables them to sustain loads at higher equilibrium void ratios. With the exception of Soil No. 17 the other montmorillonitic soils conform to the general pattern of behavior.

Table 2 presents compression index and exchangeable sodium content data for the remolded and undisturbed montmorillonitic soils. An increase in exchangeable sodium content is in general accompanied by an increase in C_c value. Apparently the higher exchangeable sodium content, causes a greater expansion of the diffuse double layer leading to enhanced compressibility of the mont-

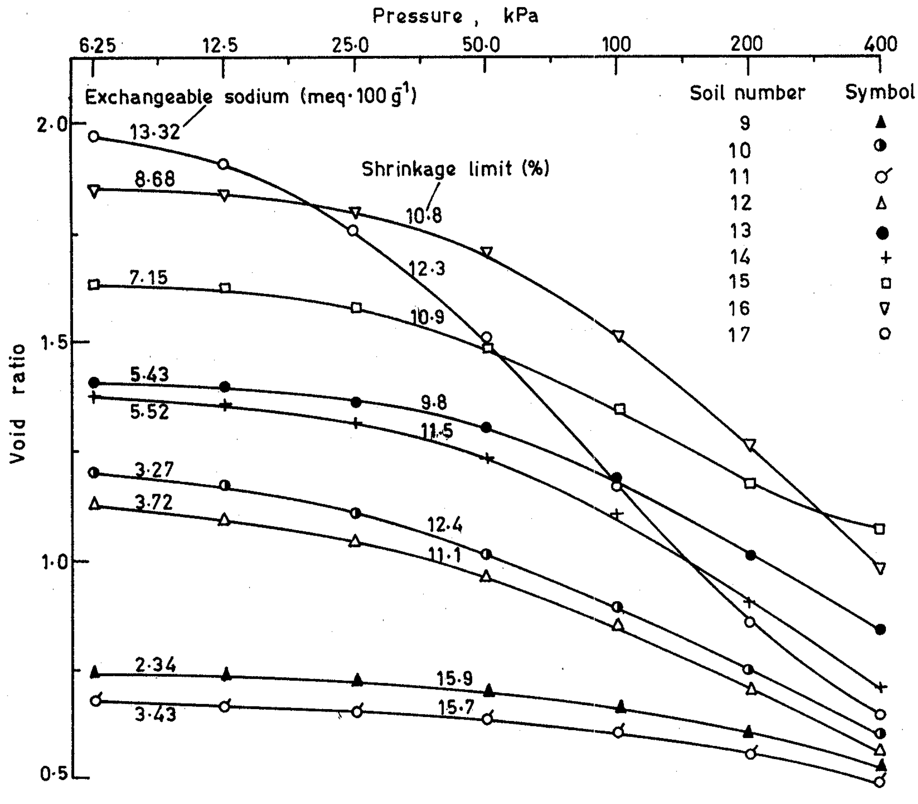
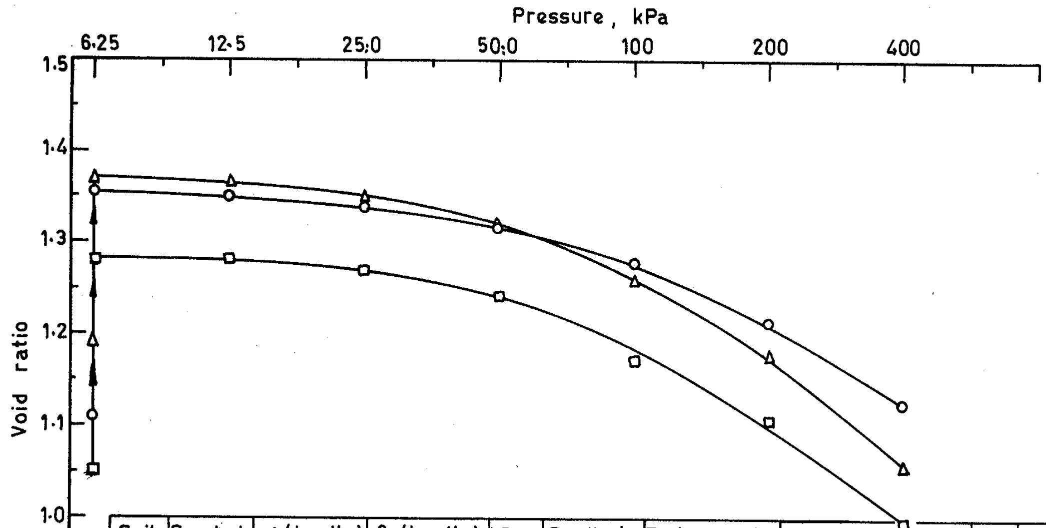


Fig. 5. Void ratio-pressure relationships for remolded montmorillonitic soils



Soil	Symbol	w (in-situ) %	ρ_d (in-situ) Mg/m³	S_r %	Swell at 6.25 kPa (divisions*)	Exchangeable sodium meq·100g⁻¹	w_s (for undisturbed condition) (%)	w_L (%)	C_c
K-1	o	37.8	1.30	93	1092	4.5	12.3	82	0.28
IH-1	□	31.6	1.34	83	1175	8.1	11.4	107	0.33
IH-2	Δ	32.9	1.19	76	818	8.5	10.9	113	0.38

* – 1 division = 0.00254 mm

w = Water content, ρ_d = Dry density, S_r = Degree of saturation, initial
w_s = Shrinkage limit, w_L = Liquid limit

Fig. 6. Void ratio-pressure relationships for undisturbed montmorillonitic soils

morillonitic soil (Sridharan et al., 1986a). The montmorillonitic soils generally exhibit higher range of C_c values than the kaolinitic soils.

A few consolidation tests were performed with undisturbed montmorillonitic soil specimens (vertisols) from North Karnataka (Fig. 6). On inundation with water at the initial pressure of 6.25 kPa, the undisturbed samples swell so that the intrinsic stresses can come into equilibrium with the external pressure; further the magnitude of swelling increases with the in-situ dry density (Fig. 6). On subsequent loading, the placement of the $e-\log p$ curves are observed to be influenced by the in-situ moisture content and density conditions, besides exchangeable sodium considerations. The compression index values of the undisturbed specimens however have a good bearing with exchangeable sodium contents (Fig. 6), similar to that observed for the remolded soils. The remolded montmorillonitic soils exhibit higher C_c values than the undisturbed specimens for similar exchangeable sodium contents (Table 2), presumably owing to the loss of in-situ soil structure on remolding.

CONCLUSIONS

The physico-chemical factors have an important bearing on the index properties and compressibility behavior of the residual soils. The liquid limit, equilibrium void ratio at given load and compression index values of the remolded kaolinitic soils correlate well with the shrinkage limit values which in turn are a function of the clay fabric. The corresponding properties of the montmorillonitic soils correlate well with the exchangeable sodium content which reflects a soil's potential to develop diffuse ion layer.

Oedometer tests with undisturbed samples highlight the role of clay mineralogy in the engineering behavior of residual soils, wherein upon inundation with water under a nominal pressure, the kaolinitic soils exhibit no volume change while the montmorillonitic soils exhibit a notable swell. Results obtained with undisturbed soils also indicate that in addition to the physico-chemical factors, the environmental factors of in-situ moisture content, density and degree of saturation have a significant influence on the void ratios sustained by the specimens at a given stress level.

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