Compressibility behaviour of remoulded, fine-grained soils and correlation with index properties

A. Sridharan and H.B. Nagaraj

Abstract: Correlating engineering properties with index properties has assumed greater significance in the recent past in the field of geotechnical engineering. Although attempts have been made in the past to correlate compressibility with various index properties individually, all the properties affecting compressibility behaviour have not been considered together in any single study to examine which index property of the soil correlates best with compressibility behaviour, especially within a set of test results. In the present study, 10 soils covering a sufficiently wide range of liquid limit, plastic limit, and shrinkage limit were selected and conventional consolidation tests were carried out starting with their initial water contents almost equal to their respective liquid limits. The compressibility behaviour is vastly different for pairs of soils having nearly the same liquid limit, but different plasticity characteristics. The relationship between void ratio and consolidation pressure is more closely related to the shrinkage index (shrinkage index = liquid limit – shrinkage limit) than to the plasticity index. Wide variations are seen with the liquid limit. For the soils investigated, the compression index relates better with the shrinkage index than with the plasticity index or liquid limit.

Key words: Atterberg limits, classification, clays, compressibility, laboratory tests.

Résumé : La corrélation des propriétés pour fin de conception avec les propriétés d'indices a pris une signification accrue récemment dans le domaine de la géotechnique. Alors que des tentatives ont été faites dans le passé pour corréler la compressibilité avec différents indices pris individuellement, on n'a jamais considéré globalement toutes les propriétés dans une étude donnée pour examiner quelle propriété d'indice présente la meilleure corrélation avec le comportement en compressibilité particulièrement à l'intérieur d'un ensemble de résultats d'essais. Dans la présente étude, dix sols couvrant une plage suffisamment large de limites de liquidité, de plasticité et de gonflement ont été sélectionnés, et des essais de consolidation conventionnels ont été réalisés en partant de leurs teneurs en eau initiales quasiment égales à leurs limites de liquidité respectives. On trouve que le comportement en compressibilité est extrêmement différent pour des paires de sols ayant quasiment la même limite de liquidité, mais différentes caractéristiques de plasticité. On trouve que les courbes d'indice de vide-pression suivent mieux l'indice de gonflement (indice de gonflement = limite de liquidité – limite de gonflement) que l'indice de plasticité. De grandes variations ont été observées avec la limite de liquidité. On voit que pour les sols étudiés, l'indice de compression offre une meilleure corrélation avec l'indice de gonflement qu'avec l'indice de plasticité ou la limite de liquidité.

Mots clés : limites d'Atterberg, classification, argiles, compressibilité, essais de laboratoire.

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Introduction

Compressibility of soils is an important engineering consideration. The oedometer test is used to determine the compressibility characteristics of soils which are typically described using the compression index, C_c, and the coefficient of consolidation, c_v. The compression index is used to predict how much settlement will take place, and the coefficient of consolidation is a rate parameter used to predict how long it will take for a given amount of compression to take place. However, oedometer testing requires undisturbed samples and is quite time-consuming and expensive. For this reason, researchers in the past have correlated compressibility characteristics with index properties. The first well-known correlation was presented by Skempton (1944), who gave the following correlation for the compressibility of remoulded soils with liquid limit, w_L:

$$[1] \quad C_c = 0.007(w_L - 10)$$

Other subsequent correlations are presented in Table 1, which shows that different researchers have used various parameters, including liquid limit (w_L), natural moisture content (w_n), initial in situ void ratio (e_o), dry unit weight (γ_d), plasticity index (I_P), and void ratio at liquid limit (e_L). The availability of so many equations suggests that none are completely satisfactory to generalize and correlate compressibility with the index or other properties.

Nagaraj and Srinivasa Murthy (1983) extended Skempton's compressibility equation (eq. [1]) using the void ratio at liquid limit (e_L) to give a generalized equation for compressibility

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Table 1. Compression index equations.

Equation	Applicability	Reference
$C_c = 0.007(w_L - 10)$	Remoulded clays	Skempton 1944
$C_c = 0.0046(w_L - 9)$	Brazilian clays	Cozzolino 1961
$C_c = 0.009(w_L - 10)$	Normally consolidated clays	Terzaghi and Peck 1967
$C_c = 0.006(w_L - 9)$	All clays with $w_L < 100\%$	Azzouz et al. 1976
$C_{c10} = 0.009(w_L - 8)$	Osaka Bay clay	Tsuchida 1991
$C_{c10} = 0.009w_L$	Tokyo Bay clay	Tsuchida 1991
$C_c = 0.01(w_n - 5)$	All clays	Azzouz et al. 1976
$C_c = 0.01w_n$	All clays	Koppula 1981
$C_c = 0.01(w_n - 7.549)$	All clays	Herrero 1983
$C_c = 0.0115w_n$	Organic silt and clays	Bowles 1989
$C_c = 1.15(e - e_o)$	All clays	Nishida 1956
$C_c = 0.29(e_o - 0.27)$	Inorganic soils	Hough 1957
$C_c = 0.35(e_o - 0.5)$	Organic soils	Hough 1957
$C_c = 0.246 + 0.43(e_o - 0.25)$	Motley clays from Sao Paulo, Brazil	Cozzolino 1961
$C_c = 1.21 + 1.055(e_o - 1.87)$	Lowlands of Santos, Brazil	Cozzolino 1961
$C_c = 0.75(e_o - 0.50)$	Soils with low plasticity	Sowers 1970
$C_c = 0.208e_o + 0.0083$	Chicago clays	Bowles 1989
$C_c = 0.156e_o + 0.0107$	All clays	Bowles 1989
$C_c = 0.2e^{1.6}$	Naturally sedimented young soils	Shorten 1995
$C_c = 0.5(\gamma_w/\gamma_d)^{2.4}$	All soil types	Herrero 1980
$C_c = 0.185[G_s(\gamma_w/\gamma_d)2 - 0.144]$	All soil types	Herrero 1983
$C_c = 0.5I_PG_s$	All remoulded, normally consolidated clays	Wroth and Wood 1978
$C_c = 0.329[0.027(w - w_p) + 0.0133I_P(1.192 + \mathrm{ACT}^{-1})]$	All remoulded, normally consolidated clays	Carrier 1985
$C_c = 0.2237e_L$	All remoulded, normally consolidated clays	Nagaraj and Srinivasa Murthy 1983
$C_c = 0.2343e_L$	All remoulded, normally consolidated clays	Nagaraj and Srinivasa Murthy 1986
$C_c = 0.274e_L$	Clay – sand mixes	Nagaraj et al. 1995

Note: ACT, activity; C_c, compression index; C_{c10}, compression index when consolidation pressure p = 10 kg/cm^2; e, void ratio at a specific pressure; e_L, void ratio at liquid limit; e_o, initial or in situ void ratio; G_s, specific gravity; I_P, plasticity index; w_L, liquid limit; w_n, natural water content; w, water content of the remoulded soil considered; w_p, plastic limit; γ_d, dry unit weight of soil at which C_c is required; γ_w, unit weight of water.

of saturated, normally consolidated, uncemented soils of the form

$$[2] \qquad \frac{e}{e_L} = a - b \log_{10} \sigma'_v$$

where a and b are constants that vary slightly with the test conditions and the number of data considered, σ'_v is the effective consolidation pressure, and e is the void ratio of the soil at an effective consolidation pressure of σ'_v.

Soils with the same liquid limit may have different plastic limits and shrinkage limits, thereby exhibiting different shrinkage or volume-change behaviour. As a consequence, the soils are bound to exhibit different compressibility behaviour even though the liquid limit is the same. This aspect has not been given due consideration in the past except in the work of Wroth and Wood (1978). Any attempt to correlate compressibility characteristics with liquid limit alone will be limited because the plasticity and volume-change properties would not be considered, viz., plastic limit and shrinkage limit.

It has already been stated in the literature (Yong and Warkentin 1966; Perloff and Baron 1976; Sridharan and Rao 1971; Sridharan and Prakash 1998) that capillary forces initiate the shrinkage process. The capillary forces depend upon the pore size: the smaller the pore size, the higher the capillary forces. As evaporation continues, the radius of the meniscus developed in the water in every pore where there is an air–water interface continues to decrease and the menisci retreat into the soil mass until the shear stresses induced by the capillary stresses are equalized by the shear strength mobilized due to interparticle friction, entanglement, and cohesion at the particle level. Thus, the shrinkage limit test is similar to a consolidation test with the difference being that capillary stresses induce the shrinkage. Hence, the void ratio at the shrinkage limit can be taken as a limiting void ratio beyond which compression will be significantly less. Thus, the idea that the shrinkage limit can be an important index test deserves examination,

Table 2. Index properties of remoulded natural soils used in the present study.

Soil No.	Soil type	G_s	w_L (%)	w_P (%)	w_s (%)	I_P (%)	I_S (%)	Grain-size distribution: Sand (%)	Silt (%)	Clay (%)	Mineralogy	C_c
1	Red earth 1	2.70	37.0	18.0	14.7	19.0	22.3	35.5	38.5	26.0	Kaolinite, montmorillonite, muscovite, quartz	0.23
2	Silty soil	2.65	39.0	29.5	27.4	9.5	11.6	36.5	58.5	5.0	Illite, quartz	0.20
3	Kaolinite 1	2.65	48.0	35.6	39.0	12.4	9.0	16.0	74.5	9.5	Kaolinite, quartz	0.24
4	Red earth 2	2.70	48.0	23.2	15.5	26.7	32.9	8.0	57.0	35.0	Kaolinite, montmorillonite, muscovite, quartz	0.40
5	Kaolinite 2	2.64	55.0	31.4	33.1	23.6	21.9	1.0	67.0	32.0	Kaolinite, quartz	0.30
6	Cochin clay (oven dried)	2.61	56.4	38.1	21.0	18.3	35.4	18.0	64.5	17.5	Illite	0.37
7	Brown soil 1	2.66	58.5	32.1	13.5	26.4	45.0	19.5	42.5	35.0	Montmorillonite, kaolinite, muscovite, quartz	0.43
8	Kaolinite 3	2.65	58.7	45.2	46.4	13.5	12.3	0.0	88.5	11.5	Kaolinite, quartz	0.25
9	Illitic soil	2.58	73.4	51.9	39.0	21.5	34.4	0.9	71.6	27.5	Illite, kaolinite, quartz	0.42
10	BC soil	2.70	73.5	35.6	11.9	37.9	61.6	13.0	35.5	51.5	Montmorillonite, quartz	0.62

especially when volume changes are involved. The range of void ratio change from the liquid limit state to the state of lowest void ratio is represented by the difference between the liquid limit and the shrinkage limit, termed the shrinkage index (I_S). This has been considered for correlation in the present investigation.

Methodology

A large amount of data is available regarding compressibility characteristics and index properties, and work has been done to correlate and generalize compressibility behaviour, mainly with liquid limit as a generalizing parameter. Most of these correlations are based on the available compressibility data from the literature and therefore experimental procedures and sample conditions varied to some extent. The laboratory program reported herein has been designed to minimize this problem.

Ten soils including a number of natural soils and commercially available kaolinite covering a wide range of liquid limits ($37 < w_L < 74$) were selected for the present study and have been tested for their physical properties as per standards with the results reported in Table 2.

The specific gravity of the soils used was determined using a pycnometer (stoppered bottle with a capacity of 50 mL) as specified by British Standard BS 1377 (British Standards Institution 1990). The specific gravity values are an average of two tests; individual determinations differed from the mean by less than 0.01. The liquid limit of soils was determined by cone penetrometer method as specified by British Standard BS 1377. The liquid limit tests were carried out to secure a minimum of five points for plotting the flow curve. The consistency of the soil specimens was adjusted such that the fall cone penetration ranged between 15 and 25 mm. The plastic limit of clay specimens was determined by rolling thread method as outlined in the British Standard BS 1377. Shrinkage limit of the soil specimens was determined as per BS 1377. While placing the wet soil at their liquid limit water contents into the shrinkage dish, care was taken to expel entrapped air. Cracking during fast drying was prevented by first allowing the soil to air-dry under controlled conditions and then oven-drying to a constant mass. The shrinkage limits reported are the average of three determinations, and the variation between individual determinations was <0.5%.

Grain-size analysis was done as per British Standard BS 1377 (British Standards Institution 1990) by wet sieving 100 g of dry soil using a 75 μm sieve. The portion retained on the 75 μm sieve was oven-dried and sieved through 300, 212, and 150 μm sieves. The soil passing through 75 μm was collected carefully and air-dried, and the grain-size distribution analysis was performed by the hydrometer method. The results are presented in Table 2. Figures 1*a* and 1*b* give the grain-size distribution of the soils used in the present investigation.

The mineralogical analysis of the soils was performed using an X-ray diffractometer and Cu–kα radiation. The principal clay minerals present in the soils are given in Table 2.

One-dimensional consolidation tests

The soils were tested in standard fixed-ring consolidometers using brass rings, 60 mm in diameter and 20 mm high. The inside of the rings was lubricated with silicone grease to minimize side friction between the ring and the soil specimen. The consolidation tests were conducted in a room maintained at a uniform temperature of 20°C.

Taking into consideration initial moisture content, which is an important parameter controlling compressibility, the soil specimens were remoulded to their respective liquid limit water contents. The initial water content was set equal to the liquid limit water content, primarily because it is the extreme limiting water content above which the soil will begin to flow. These soil specimens were

Fig. 1. Grain-size distribution of soils used in the present investigation: (*a*) soils 1–6, and (*b*) soils 7–10.

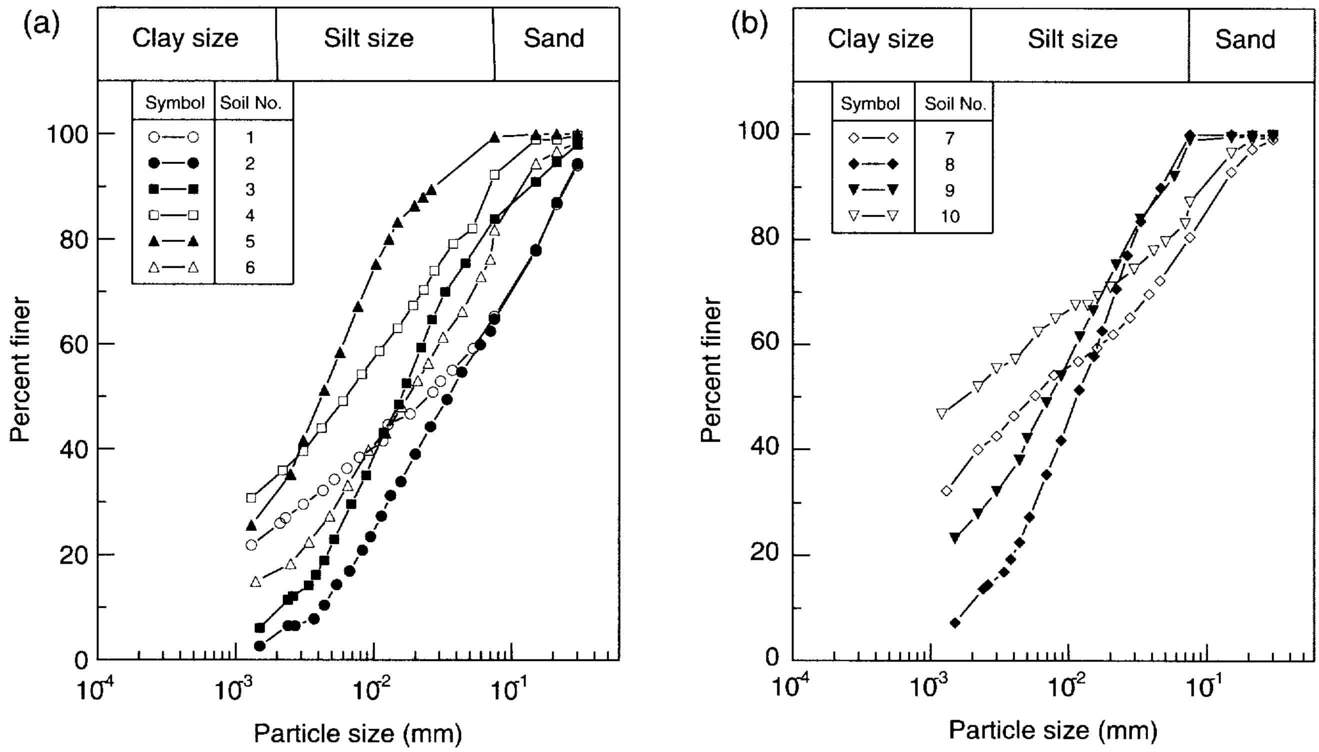
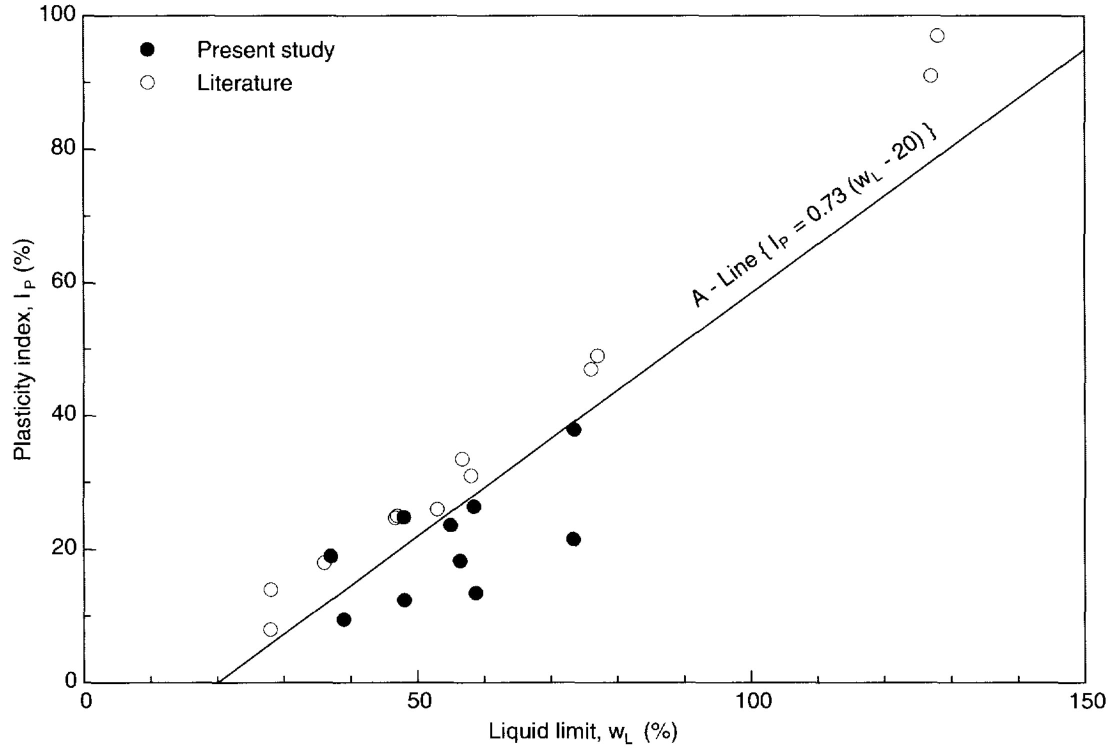


Table 3. Index properties of remoulded natural soils from the literature.

Soil No.	Soil type	w_L (%)	w_P (%)	w_S (%)	I_P (%)	I_S (%)	G_s	C_c	Reference
L1	Glacial silty clay	28.0	20.0	—	8.0	—	2.72	0.13	Leonards and Ramiah 1959
L2	Boulder clay	28.0	14.0	—	14.0	—	2.69	0.13	Skempton 1944
L3	Sandy delta mud (Ton v)	36.0	18.0	—	18.0	—	2.71	0.25	Skempton 1944
L4	Weiner Tegel	46.7	22.0	—	24.7	—	2.76	0.31	Burland 1990
L5	Vienna clay	47.0	22.0	—	25.0	—	2.76	0.31	Hvorslev 1960
L6	Oxford clay	53.0	27.0	—	26.0	—	2.57	0.30	Skempton 1944
L7	Black cotton soil	57.0	23.0	15.5	34.0	41.5	—	0.34	Ranganatham 1961
L8	Residual clay	58.0	27.0	—	31.0	—	2.74	0.36	Leonards and Ramiah 1959
L9	Gosport clay	76.0	29.0	—	47.0	—	2.67	0.46	Skempton 1944
L10	London clay	77.0	28.0	—	49.0	—	2.71	0.49	Skempton 1944
L11	Kleinbelt Ton	127.0	36.0	—	91.0	—	2.77	0.94	Burland 1990
L12	Argile plastique	128.0	31.0	—	97.0	—	2.58	0.81	Burland 1990

hand remoulded in the consolidation rings to a thickness of 20 mm, taking care to prevent any air entrapment in the specimens. Filter papers were positioned on the top and bottom of the soil specimen to prevent particles from being forced into the pores of the porous stones placed on both sides of the specimen. The porous stones were kept in distilled water for sufficient time to reach saturation, and were used in damp conditions to avoid absorption of water from the sample. Each ring with the sample prepared as described above was placed in a consolidation cell and screwed tightly to the close-fitting metal jacket on top of the cell. The cell was then mounted and positioned on a loading frame with a vertical deflection dial gauge properly adjusted and fixed in position to give a proper dial reading under application of load. The cell was inundated with distilled water and a nominal load of 6.25 kPa was applied. Care was taken to replenish any evaporated water.

Fig. 2. Soils used in this study plotted on the plasticity chart.



After equilibrium was attained, as indicated by the nearly constant readings on the dial gauge, conventional oedometer tests were carried out. A load-increment ratio of unity was adopted and each load maintained until near equilibrium had been attained. Each specimen was loaded to a maximum of 800 kPa and later unloaded with a load-decrement ratio of unity.

Results and discussion

For verification of the present experimental investigation, and the general applicability of the proposed correlation, soils with varying index properties and different geological origin were also selected from the literature (Table 3). The plasticity of the soils used in the present investigation and those selected from the literature is shown in Fig. 2.

Figures 3*a*–3*g* present the plot of void ratio – consolidation pressure curves of soils having nearly the same liquid limit but different plasticity and shrinkage indices. These figures clearly demonstrate that, even though the liquid limits of the soil sets are nearly the same, the magnitude of compression is vastly different. Soils with a higher plasticity index (I_P) or shrinkage index (I_S) undergo more compression than those with a lower plasticity index or shrinkage index. For all soils tested in the present study, the magnitude of compression follows well with shrinkage index. Even though the magnitude of compression follows well with plasticity index for most of the soils, there is an exception to this trend in Fig. 3*d*, wherein it can be observed that, even though soil 5 has a higher plasticity index than soil 6, the compression of soil 5 is less than that of soil 6, with their liquid limits being nearly the same. For other soils both plasticity index and shrinkage index relate well with the magnitude of compression. For the soils selected from literature, the magnitude of compression relates well with the plasticity index in Figs. 3*a* and 3*b*. In Figs. 3*c*–3*g* for soils from the literature, the magnitude of compression does not follow that well with the plasticity index. Because shrinkage limit data were not available in the literature for these soils (except for soil L7), it was not possible to determine the relationship between the magnitude of compression of normally consolidated soils and the shrinkage index. For soil L7 from the literature, both plasticity index (I_P = 34) and shrinkage index (I_S = 41.5) are available. Comparing soil L7 with soil 7 of the present study (wherein the liquid limit is nearly the same), L7 should have compressed more if the plasticity index is the controlling index property. On the contrary, the shrinkage index of soil 7 is greater than that of soil L7 and the final compression for soil 7 is greater than that for soil L7. Thus the compression behaviour is better represented by the shrinkage index. It is very evident from the present work and from the literature that the magnitude of compression of soils is not the same for all soils with the same liquid limit. This variation in the compressibility behaviour is accounted for in the variation of the plasticity or shrinkage properties of the soils. Further, compression follows very well with the shrinkage index and reasonably well with the plasticity index. Figure 4 shows a typical void ratio versus log σ'_v curve for soils 9 and 10 from this study which have nearly the same liquid limit but

Fig. 3. Void ratio versus effective vertical consolidation pressure of soil sets of liquid limit approximately (*a*) 28, (*b*) 37, (*c*) 47, (*d*) 55, (*e*) 58, (*f*) 75, and (*g*) 128%. w_i, initial water content at which consolidation test was started.

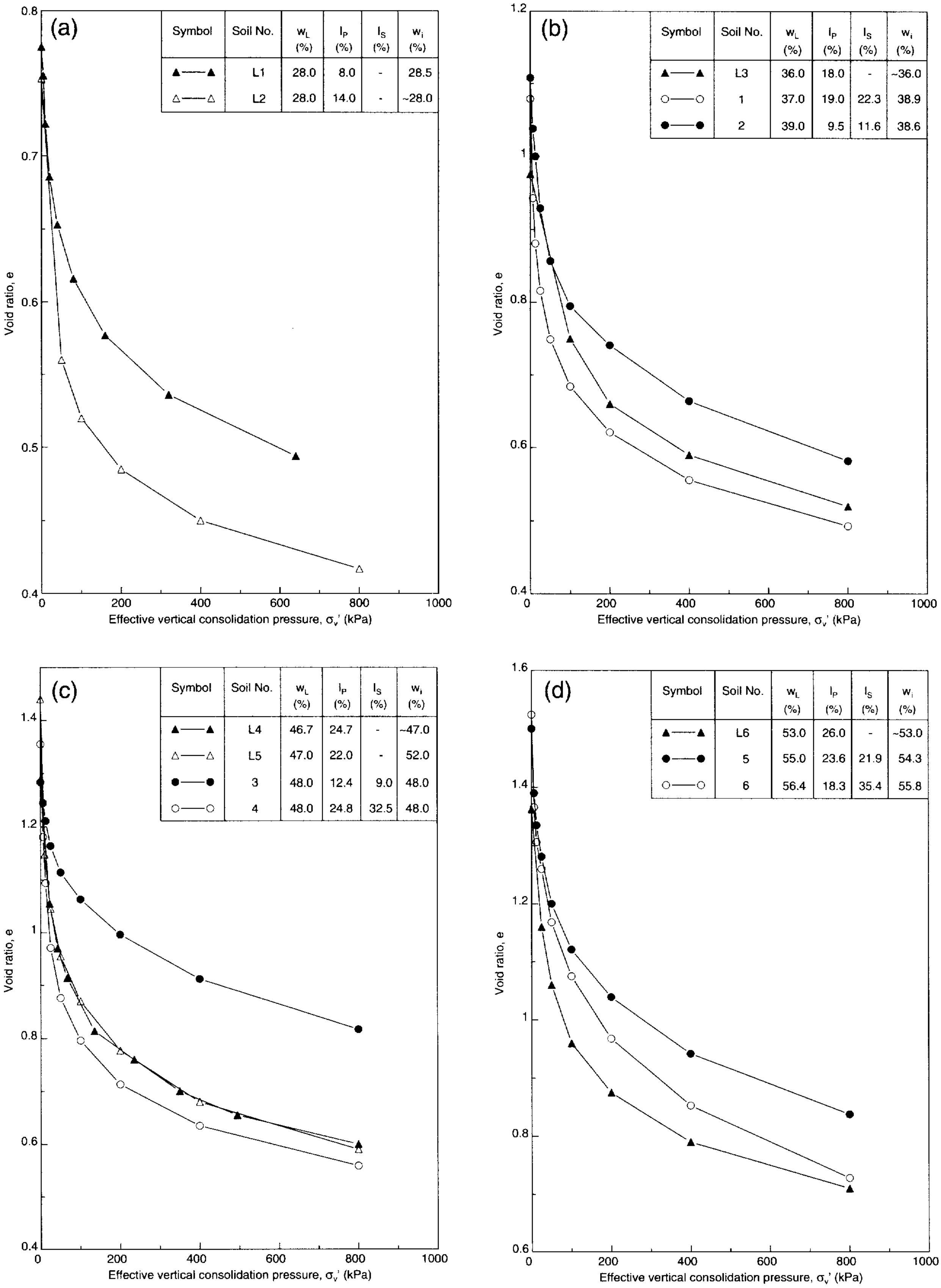


Fig. 3 (*concluded*).

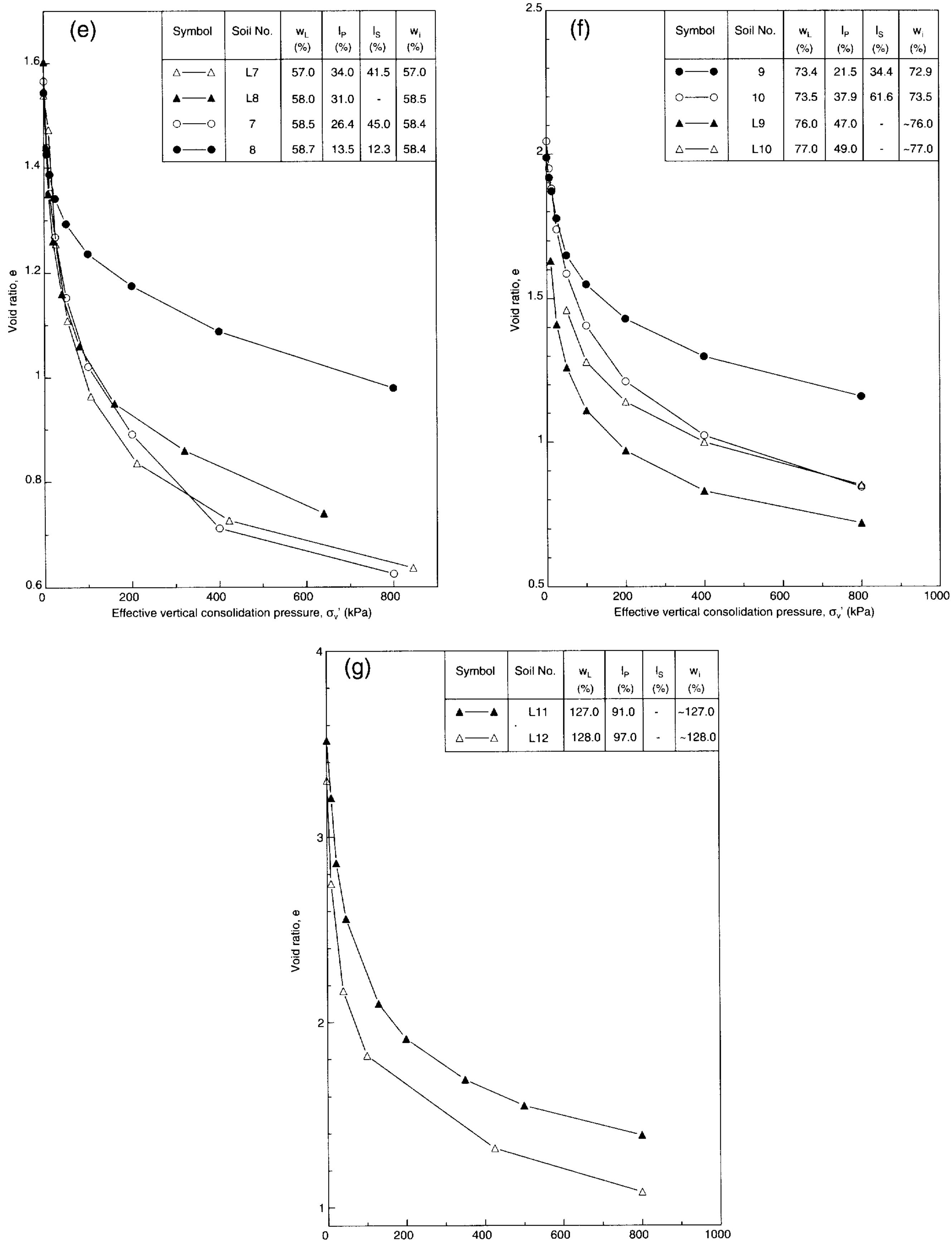


Fig. 4. Void ratio versus the logarithm of effective vertical consolidation pressure for soils 9 and 10 of the present study which have nearly the same liquid limit.

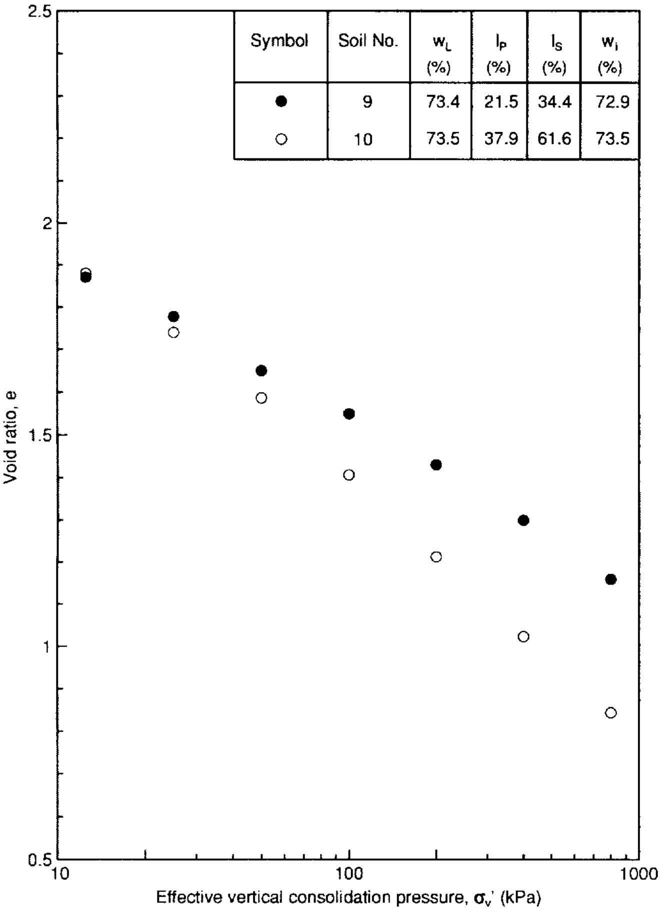
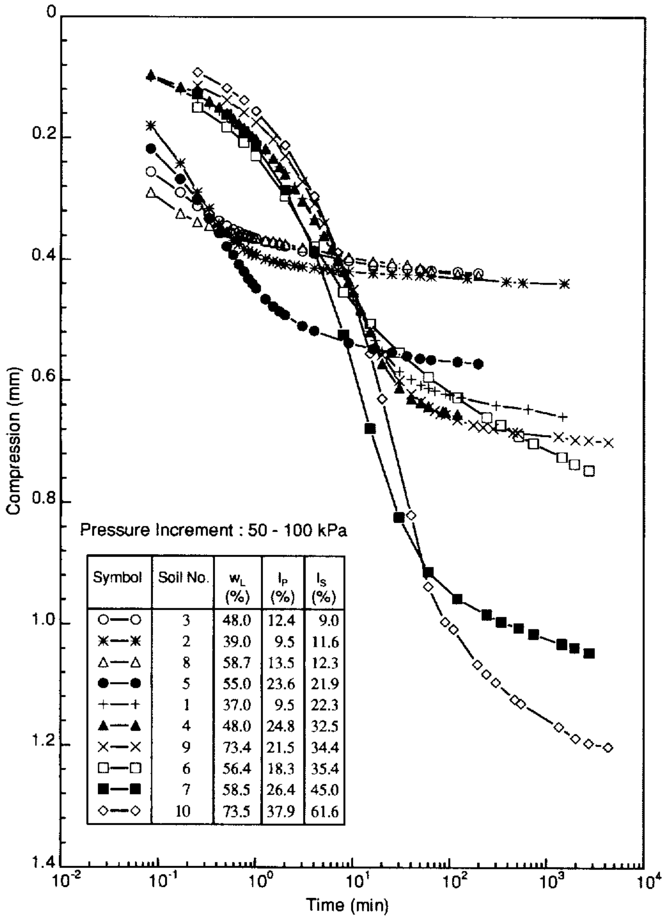


Fig. 5. Time–compression curves of soils with different plasticity characteristics used in the present study.



different plasticity characteristics; a marked difference in compression behaviour is clearly visible in the figure.

Figure 5 shows a typical time–compression plot of soils tested in the present study for a pressure increment of 50–100 kPa. From the figure, it is evident that the time–compression behaviour follows the order of shrinkage index and also plasticity index in general, with the exception of soil 6, but it definitely does not follow liquid limit. At all liquid limits, soils with a lower shrinkage index or plasticity index have more immediate compression and less total–final compression and reach the end of primary compression earlier than soils with higher shrinkage index or plasticity index. Figure 5 shows that, although soils 3 and 4 have the same liquid limit of 48.0%, soil 3 has a lower shrinkage index and plasticity index, undergoes compression more quickly, and attains the end of primary compression earlier. Furthermore, soil 4 undergoes more compression for any pressure increment than soil 3. Thus it is clear that both the amount and rate of compression of normally consolidated soils vary with shrinkage index or plasticity index.

Figure 6 shows the cumulative change in void ratio at any effective vertical pressure with log σ'_v for different soils studied in this investigation (the cumulative change in void ratio at any effective vertical pressure is defined as the void ratio at liquid limit water content minus the void ratio at any required effective vertical pressure). The curves in Fig. 6 are positioned in the order of their shrinkage index. Figures 7*a*–7*c* show that cumulative change in void ratio at a pressure of 800 kPa correlates well with both shrinkage index and plasticity index, although the correlation is better with shrinkage index. The correlation with liquid limit is poor.

The compression index, C_c, which is a widely used parameter in the literature to relate the compression of soils, is shown to relate well with the shrinkage index (Fig. 8*c*) as

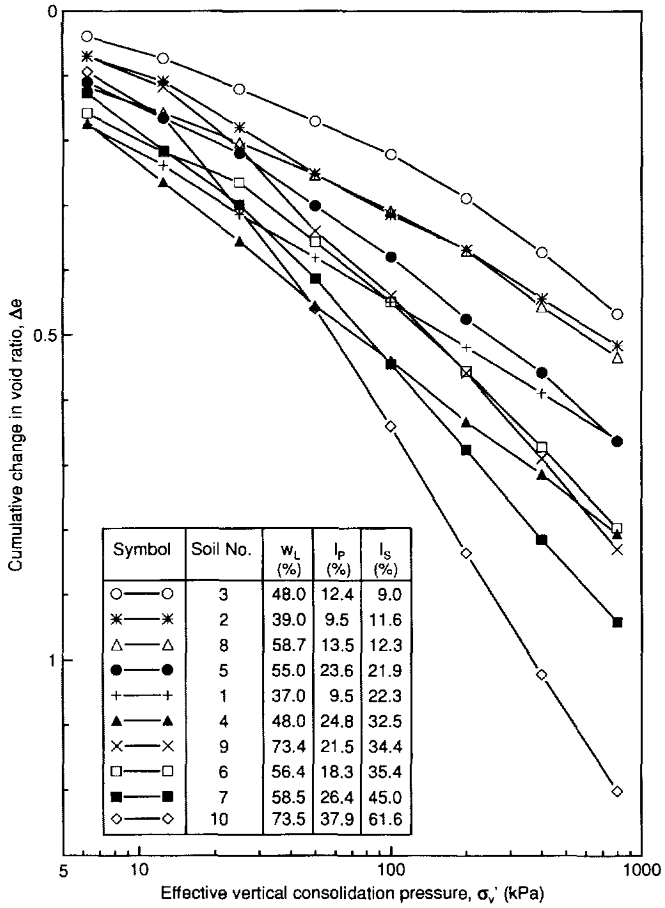
$$[3] \qquad C_c = 0.007(I_S + 18)$$

with a correlation coefficient $r = 0.96$ as compared with $r = 0.78$ for the liquid limit (Fig. 8*a*) and $r = 0.91$ for the plasticity index (Fig. 8*b*). For the soils tested here, the compression index was calculated in the pressure range 100–800 kPa.

In an empirical study, Carrier (1985) indicated that the compression index is directly related to the plasticity index. Wroth and Wood (1978), using critical-state concepts, derived an empirical relation between C_c and index properties as

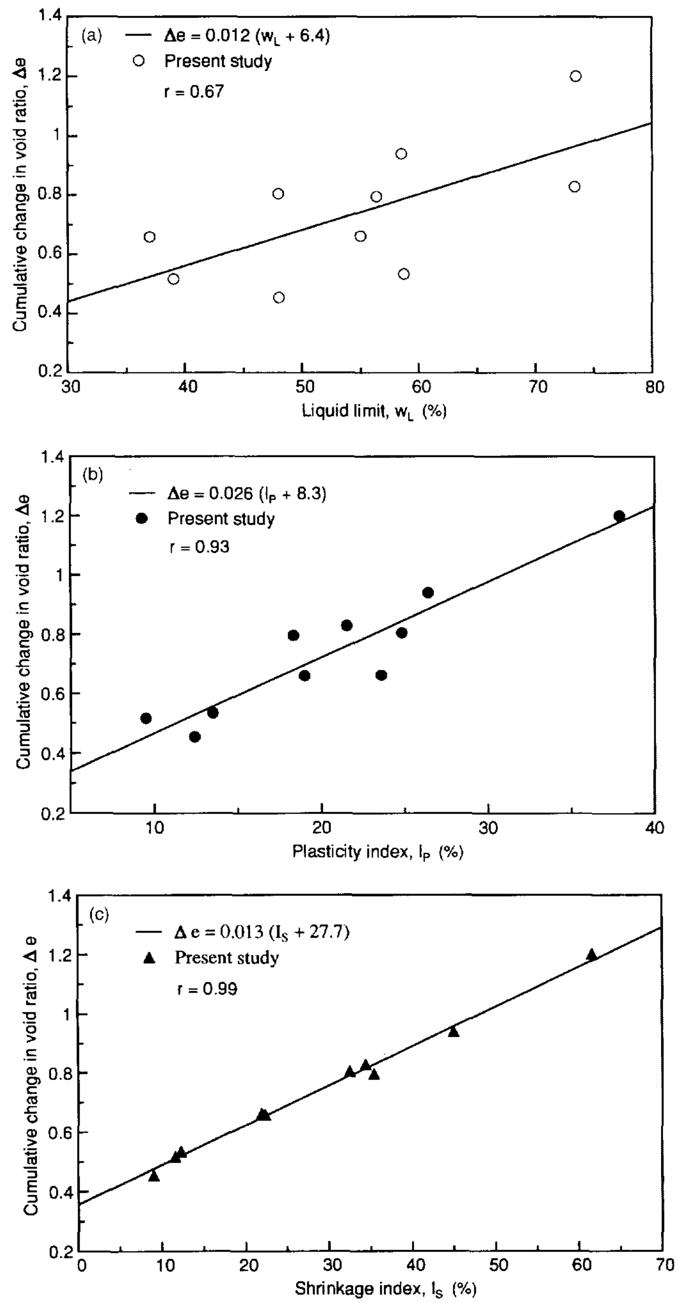
$$[4] \qquad C_c = 1.35 I_P$$

Fig. 6. Cumulative change in void ratio (void ratio at the liquid limit water content minus void ratio at any effective vertical pressure under consideration) versus effective vertical consolidation pressure for soils with different plasticity characteristics.



Symbol	Soil No.	w_L (%)	I_P (%)	I_S (%)
○—○	3	48.0	12.4	9.0
✳—✳	2	39.0	9.5	11.6
△—△	8	58.7	13.5	12.3
●—●	5	55.0	23.6	21.9
+—+	1	37.0	9.5	22.3
▲—▲	4	48.0	24.8	32.5
×—×	9	73.4	21.5	34.4
□—□	6	56.4	18.3	35.4
■—■	7	58.5	26.4	45.0
◇—◇	10	73.5	37.9	61.6

Fig. 7. Relationship between cumulative change in void ratio (void ratio at the liquid limit water content minus void ratio at an effective vertical pressure of 800 kPa) and (*a*) liquid limit, (*b*) plasticity index, and (*c*) shrinkage index.



Wroth and Wood found that C_c depends only on the plasticity index. But the present investigation indicates that the shrinkage index has a better correlation with the compression index than with the liquid limit or plasticity index.

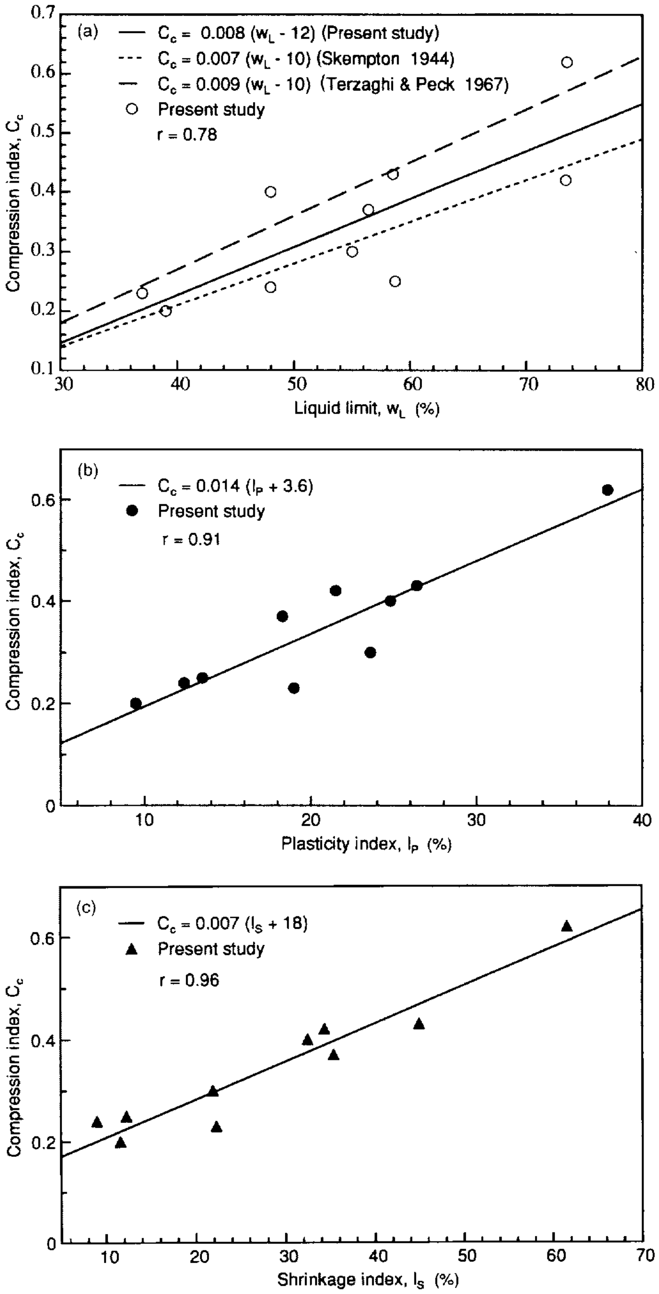
Conclusions

The following conclusions are made from careful experimental investigations carried out on 10 different soils of different plasticity characteristics. The magnitude of compression of the soils has a good correlation with the shrinkage index, i.e., $I_S = w_L - w_S$, where w_S is the shrinkage limit. The compression index, C_c, also has a good correlation with the shrinkage index as follows:

$$C_c = 0.007(I_S + 18)$$

The newly proposed correlation considers the two extreme limits of water content of a soil, viz., liquid limit and shrinkage limit. In this study it has been shown that the numerous correlations between compressibility and liquid limit are limited because they do not fully consider the plasticity characteristics. A soil with a lower shrinkage index compresses less than a soil with a higher shrinkage index, even though their liquid limits are about the same. In other words, a soil with a lower shrinkage limit compresses more than a soil with a higher shrinkage limit, even though their liquid limits are nearly the same. Further, soils with the same liquid limit but different shrinkage indices will have different time – compression behaviour. Soils with lower shrinkage indices compress faster.

Fig. 8. Relationship between compression index and (*a*) liquid limit, (*b*) plasticity index, and (*c*) shrinkage index.



The results also indicate that, in the absence of the shrinkage index, the plasticity index can be used to predict the compressibility characteristics with a better correlation coefficient than the liquid limit.

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