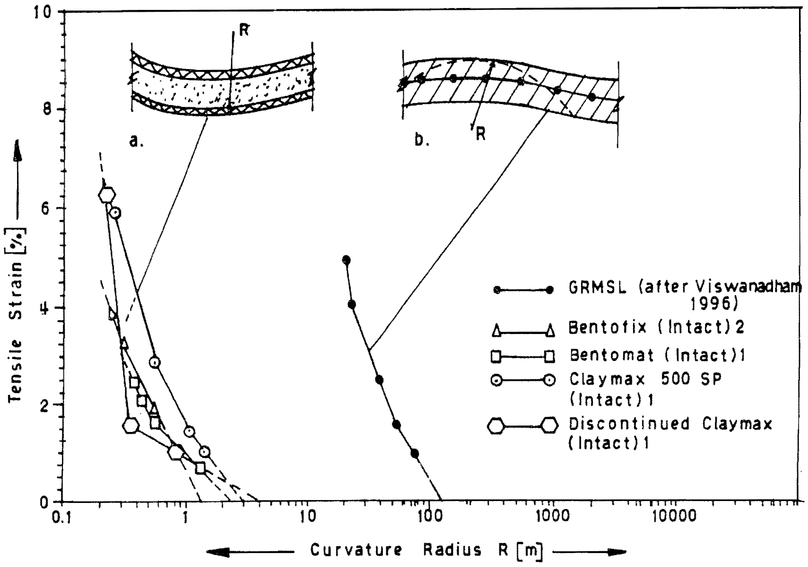

FIG. 17. Variation of Tensile Strain ε with Curvature Radius *R*

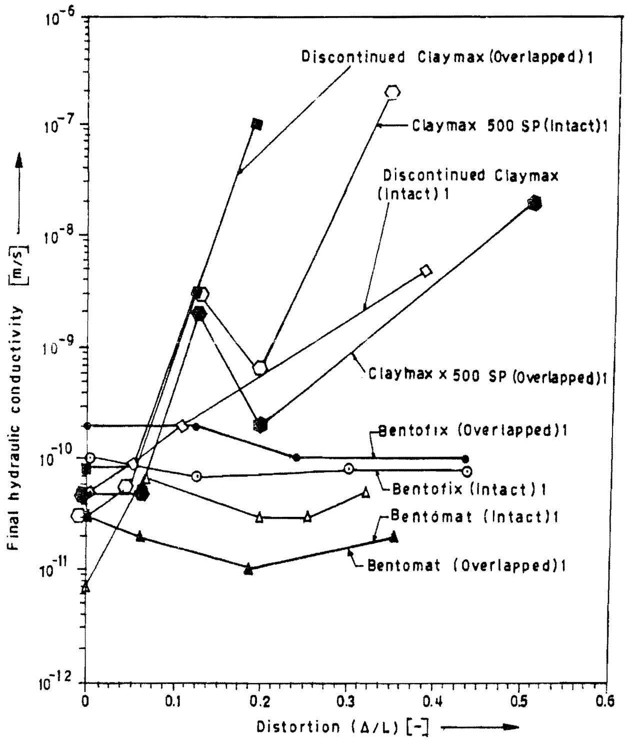

FIG. 18. Variation of Final Hydraulic Conductivity versus Distortion

conclude that the reinforcement of the mineral sealing layer is an alternative solution.

The authors may indicate the manner of computation of tensile strains and the observation of final thickness of the GCL in the central region at the end of each settlement stage. Also, one wonders whether the long duration of testing has not brought in any thixotropic effects on the bentonite.

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Closure by David E. Daniel[8]

The method used to calculate tensile strain was the "tensile strain" curve in Fig. 3. The calculated strains were based on the deflection of the upper surface of the GCL.

The calculation of strain involves assumptions, and it is not surprising that the discussers obtained somewhat different values. In retrospect, perhaps an additional technique (e.g., strain gauges) should have been used.

The test results reported for geogrid reinforced mineral sealing layers (i.e., compacted clay) are very interesting. Further research and development are encouraged.

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SECONDARY COMPRESSION OF PEAT WITH OR WITHOUT SURCHARGING[a]

Discussion by Patrick J. Fox,[5] Associate Member, ASCE, Nina Roy-Chowdhury,[6] Student Member, ASCE, and Tuncer B. Edil,[7] Member, ASCE

The authors have presented the results of an extensive laboratory study on fibrous Middleton peat and concluded that the observed secondary compression behavior is consistent with the C_α/C_c compressibility concept. The discussers also have a familiarity with Middleton peat as a result of investigations conducted at the University of Wisconsin beginning in

[a]May 1997, Vol. 123, No. 5, by G. Mesri, T. D. Stark, M. A. Ajlouni, and C. S. Chen (Paper 11757).

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1988. The objective of this discussion is to comment on the authors' findings and present additional laboratory test results with regard to the applicability of the C_α/C_c concept for peats and clays.

The authors conclude that $C_\alpha/C_c = 0.052$ from Fig. 10, which was constructed by pairing $C_\alpha/(1 + e_o)$ values from the first log cycles of secondary compression with $C_c/(1 + e_o)$ values from the end-of-primary (EOP) $\Delta\varepsilon_v$ versus log σ'_v plots. The values of time (t_p) at the beginning of secondary compression used to obtain these initial $C_\alpha/(1 + e_o)$ values must be considered approximate as most of the authors' tests were conducted without pore pressure measurements. For certain load increments, such as Figs. 7(a and g), the $\Delta\varepsilon_v$ versus log t plots show little or no inflection, and the graphical constructions used to estimate t_p may be inaccurate. In addition, the small scatter of data points in Fig. 10 may result from the exclusion of $C_\alpha/(1 + e_o)$ values from subsequent log cycles. Fox et al. (1992) found that including such values tends to worsen the correlation between C_α and C_c for Middleton peat.

The authors suggest that biodegradation of some peat specimens during secondary compression was responsible for C_α increasing with time in the compression range where C_c decreases with increasing effective stress ($\sigma'_v \geq 2\sigma'_p$). The discussers have performed additional oedometer tests to investigate this possibility. Two specimens (diameter = 63.5 mm; height = 25.4 mm) were cut from a block sample of Middleton peat. Specimen N1 was placed in a polished brass fixed-ring oedometer and incrementally loaded with dead weights to σ_v = 198 kPa using a load increment ratio (LIR) = 1. Pore pressure measurements were taken at the base of the specimen. Successive loads were applied at the end of consolidation (99% excess pore pressure dissipation) such that no secondary compression occurred between load increments. The final vertical stress (σ_v = 198 kPa) was permitted to remain on the specimen for 148 days. Specimen N2 was subjected to 2 Mrad of gamma radiation (over a 9 h period) prior to testing to minimize biodegradation during secondary compression. This level of radiation exposure is considered sufficient to kill bacteria and fungi within the specimen (Skipper et al. 1996; Trevors 1996). To prevent subsequent contamination, the N2 specimen was placed in a sterilized bass oedometer cell, inundated with sterile water, and covered to avoid direct contact with air. N2 was then tested identically to specimen N1.

Fig. 15 shows the EOP e versus log σ'_v plots for specimens N1 and N2 along with one additional EOP test (T11) conducted on Middleton peat as part of a study presented by Edil et al. (1991). Consistent with the authors' findings, C_c decreases with increasing σ'_v at σ'_v = 198 kPa. The e versus log t plots for N1 and N2 at σ_v = 198 kPa are shown in Fig. 16. Secondary compression for specimen N1 shows C_α increasing with time (from 0.36 to 0.74) and then decreasing at the end of the test (to 0.51). Specimen N2, which was irradiated, shows a markedly different secondary compression behavior. In this case, C_α remains essentially consistent with time at 0.34. Using $C_c = 5.7$ from T11 at σ_v = 198 kPa, the value for C_α/C_c for N2 is 0.059, which is in reasonable agreement with the authors' measured value for Middleton peat. These tests support the authors' hypothesis that biodegradation increases C_α during secondary compression.

To further test the effect of sample sterilization on long-term secondary compression, three additional oedometer tests with pore pressure measurements were conducted on an inorganic Canadian clay. Laval sampler specimens of clay taken at a depth of 8.5 m from the L'Assumption site were provided courtesy of S. Leroueil. The clay has liquid limit = 78, plastic limit = 27, average natural water content = 57%, and loss on ignition [ASTM D 2974 ("Standard" 1996)] = 4%. Test C1 was performed as a standard incremental loading EOP test with a reduced LIR near the preconsolidation pressure. Test C2 was performed with load increments applied at EOP using LIR = 1 until σ_v = 594 kPa. The last load increment remained on the specimen for 147 days. Test C3 was performed identically to C2 except that the clay specimen was irradiated prior to testing using the same procedure as for specimen N2. The

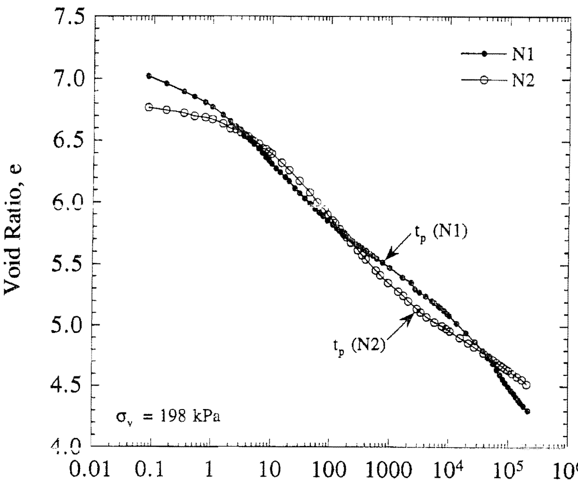

FIG. 16. Plots of e versus log t for N1 and N2 at σ_v = 198 kPa

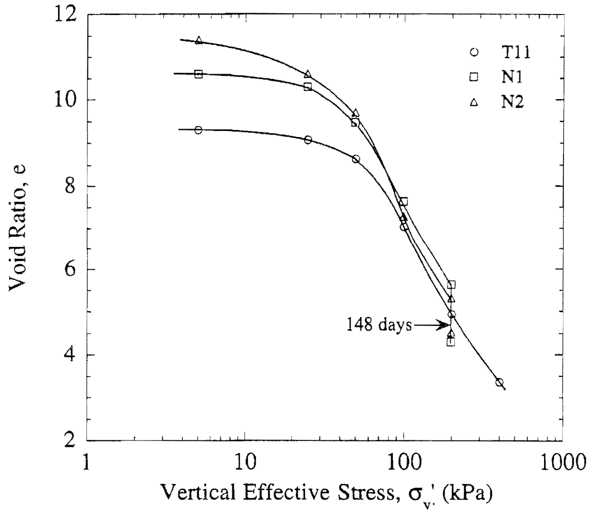

FIG. 15. EOP e versus log σ'_v Plots for N1, N2, and T11

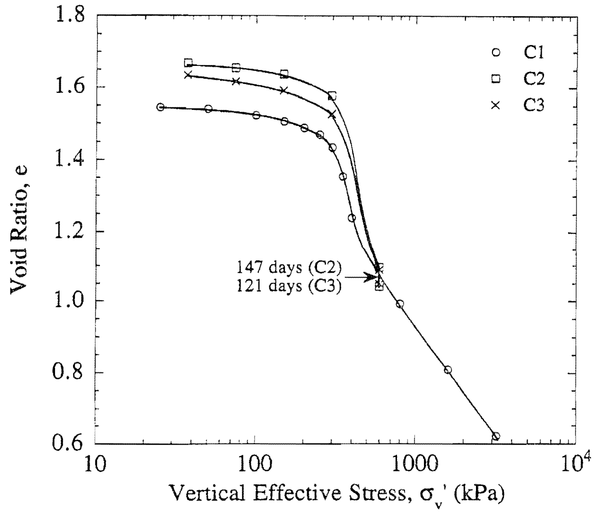

FIG. 17. EOP e versus log σ'_v Plots for C1, C2, and C3

last load increment for test C3 (σ_v = 594 kPa) remained on the specimen for 121 days.

Fig. 17 shows the EOP e versus log σ'_v plots for tests C1, C2, and C3. The final stress level for tests C2 and C3 is in the normally consolidated range and, at σ'_v = 594 kPa, C_c decreases slightly with increasing σ'_v. Fig. 18 shows e versus log t for C2 at σ_v = 594 kPa. After EOP, C_α is initially constant at 0.015 and then begins to increase with time. The corresponding values of C_α/C_c range from 0.021 to 0.070 for the load increment, which is inconsistent with the C_α/C_c concept. The plot of e versus log t for C3 at σ_v = 594 kPa is shown in Fig. 19. Similar to the results for Middleton peat, secondary compression of the irradiated specimen (C3) is significantly different from that of the nonirradiated specimen (C2). For C3, C_α has a constant value of 0.017, which is nearly the same as the initial C_α value for C2 (0.015). Using C_c = 0.73 from test C1 at σ'_v = 594 kPa, the value of C_α/C_c is 0.023. Although this C_α/C_c value falls below the generally observed range of 0.04 ± 0.01 for inorganic soft clays (Mesri and Castro 1987), the secondary compression behavior of specimen C3 is consistent with the C_α/C_c concept.

This limited study demonstrates that irradiating a specimen of clay or peat prior to testing may decrease the rate of secondary compression observed in a long-term oedometer test. For the EOP tests conducted, secondary compression of the irradiated specimens was essentially linear in log time and was consistent with the C_α/C_c compressibility concept. Conversely, C_α generally increased with time for the nonirradiated specimens and was inconsistent with the C_α/C_c compressibility concept. Although gamma radiation may have caused other changes in the soil specimens that were not taken into account, and accepting that biodegradation rates were not actually measured in this study, the tests suggest that biodegradation of organic matter may have an important influence on long-term secondary compression in the laboratory. Assuming that biodegradation is negligible over typical engineering time scales for most saturated soils in the subsurface, these findings may call into question the results of previous laboratory studies of long-term creep (one-dimensional or otherwise) for clays and peats. Additional research is warranted on this issue.

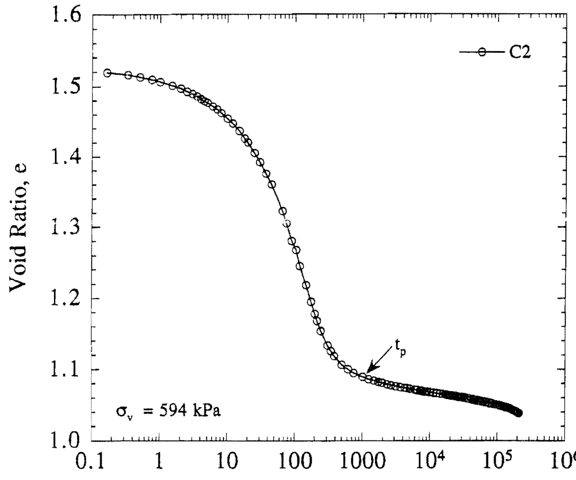

FIG. 18. Plot of e versus log t for C2 at σ_v = 594 kPa

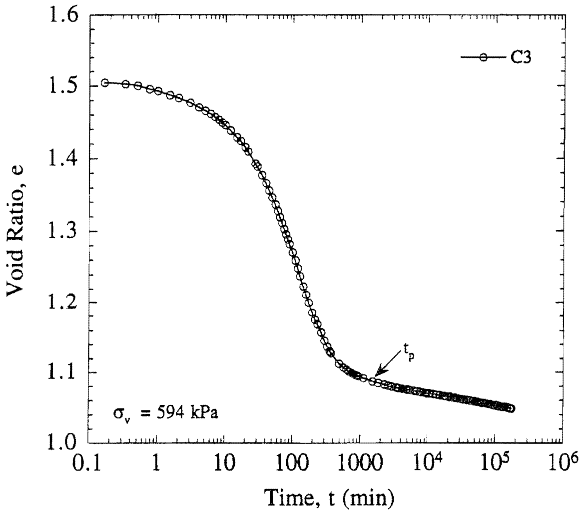

FIG. 19. Plot of e versus log t for C3 at σ_v = 594 kPa

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Discussion by Eulalio Juárez-Badillo,[8] Fellow, ASCE

The discusser is happy to have read this important paper with basic experimental data on the secondary compression of peat. The discusser was especially happy to apply to these experimental data the general equations already provided by the principle of natural proportionality (Juárez-Badillo 1985b) to describe the mechanical behavior of geomaterials.

Figs. 20 and 21 are the same as the authors' Figs. 7(f), 8(e), 9(e), and 11 with theoretical points added.

The general compressibility equation provided by the principle of natural proportionality (Juárez-Badillo 1981) is

$$\frac{V}{V_1} = \frac{H}{H_1} = \left(\frac{\sigma'_v}{\sigma'_{v1}}\right)^{-\gamma} \tag{4}$$

where γ = coefficient of compressibility; V = volume; H = thickness; and (σ'_{v1}, V_1) is a known point.

The discusser found for Fig. 11 a value of γ = 0.33. The corresponding equations for the end-of-primary (EOP) curve at $t = t_p$ and for the end-of-secondary (EOS) curve at $t = \infty$, in terms of ε_v, are

$$\varepsilon_{vp} = 1 - 0.67\left(\frac{\sigma'_v}{100}\right)^{-0.33} \tag{5}$$

$$\varepsilon_{v\infty} = 1 - 0.45\left(\frac{\sigma'_v}{100}\right)^{-0.33} \tag{6}$$

Fig. 21 shows the theoretical points for $t = t_p$ and the theoretical curve for $t = \infty$. The relationship of volumes between both curves is

$$\frac{V_\infty}{V_p} = \frac{H_\infty}{H_p} = \frac{1 - \varepsilon_{v\infty}}{1 - \varepsilon_{vp}} = \frac{0.45}{0.67} = 0.67 \tag{7}$$

The traditional coefficient C_c is given by

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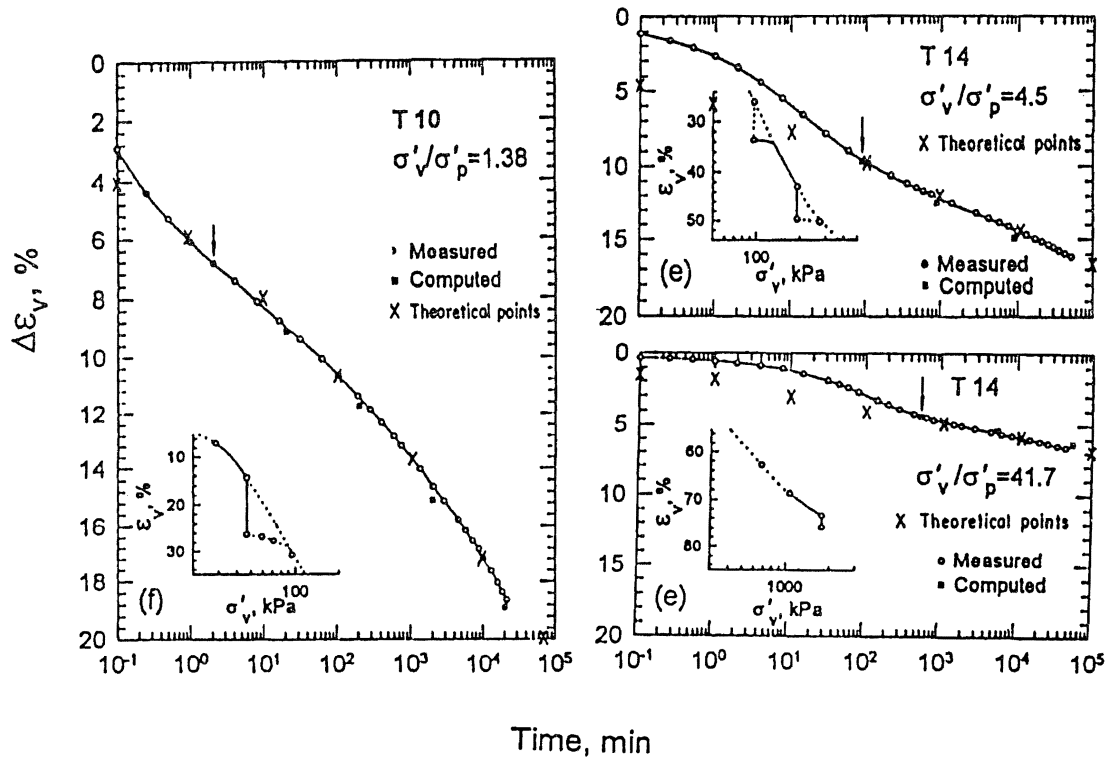

FIG. 20. **Secondary Compression of Middleton Peat**

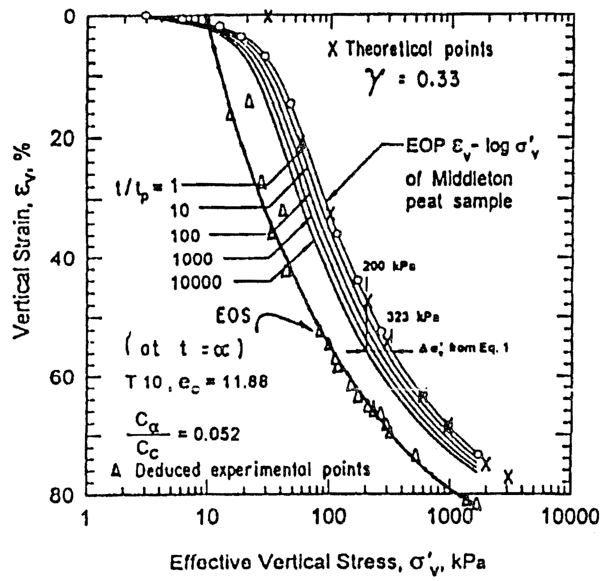

FIG. 21. Secondary Compression of Middleton Peat Predicted by C_α/C_c Concept of Compressibility

$$C_c = 2.3\gamma(1 + e) \quad (8)$$

with values of "8.5 and 2.0" for values of e of 10.2 and 1.6.

The general time volume change equation provided for the principle of natural proportionality (Juárez-Badillo 1985a) reads

$$\Delta H = \frac{(\Delta H)_T}{1 + (t/t^*)^{-\delta}} \quad (9)$$

where ΔH = change in thickness time t; $(\Delta H)_T$ = total change in thickness from $t = 0$ to $t = \infty$; δ = volume fluidity; and t^* = characteristic time at which $\Delta H = (\Delta H)_T/2$.

Important characteristics of (13) are that in a semi-log plot the middle third is practically a straight line with a slope given by

$$\left(\frac{dH}{d \log t}\right)_{t=t^*} = \frac{2.3}{4}\,\delta(\Delta H)_T \quad (10)$$

and this straight line covers a length l in the log scale given by

$$l = \frac{0.6}{\delta} \text{ cycles} \quad (11)$$

Eq. (9) in terms of $\Delta\varepsilon_v$ is

$$\Delta\varepsilon_v = \frac{(\Delta\varepsilon_v)_T}{1 + (t/t^*)^{-\delta}} \quad (12)$$

where $\Delta\varepsilon_v$ takes the place of ΔH in (9) and (10).

The discusser applied (9)–(12) to the totality of Figs. 7, 8, and 9, using Fig. 11 with $\sigma_p' = 34$ kPa.

The values found for $(\Delta\varepsilon_v)_T$, δ, and t^* are contained in Table 2, and Fig. 21 shows the theoretical points for the EOS curve. Due to space limitations, only Fig. 20, corresponding to Figs. 7(f), 8(e), and 9(e), is included. In these three figures may be noted the dilation effect produced by the hydrodynamic effect of primary compression. This points toward a modification of the time scale to be found in the future.

Table 2 shows that for these tests the values of δ and t^* are of the order of $\delta = 0.15$ and $t^* = 10^4$ min. Some dispersion was found, however, only for Fig. 7, that is, at values of σ_v' less than or near the preconsolidation pressure σ_p', and, it appears, only in test T14 where important secondary compression was allowed before application of the new load. These dispersed values are in parentheses in Table 2. The total $(\Delta\varepsilon_v)_T$ is the sum of the primary $(\Delta\varepsilon_v)_p$ plus the secondary $(\Delta\varepsilon_v)_s$ between the EOP and the EOS curves.

Finally, the application of (9), (10), and (11) in practice is contained in Juárez-Badillo (1997).

TABLE 2. Values of Parameters $(\Delta\varepsilon_v)_T$, δ, and t^* for Middleton Peat

Figure (1)	Test (2)	σ'_v/σ'_p (3)	σ'_v (σ'_p = 34 kPa) (kPa) (4)	$(\Delta\varepsilon_v)_T$ (%) (5)	δ (6)	t^* (min) (7)	$(\Delta\varepsilon_v)_P$ (%) (8)	$(\Delta\varepsilon_v)_s$ (%) (9)
7(a)	T9	0.43	14.6	15	0.20	3×10^5	1.5	13.5
7(b)	(T14)	0.57	19.4	(12)	0.12	3×10^5	2.5	(9.5)
7(c)	T12	0.75	25.5	24	0.16	7×10^5	3.0	21
7(d)	T15	1.0	34.0	30	0.18	5×10^5	3.5	26.5
7(e)	(T14)	1.13	38.4	(24)	0.18	5×10^5	3.5	(20.5)
7(f)	T10	1.38	46.9	34	0.17	1×10^4	7.0	27
7(g)	(T14)	6.5	221	18	(0.30)	7×10^5	1.0	17
8(a)	T14	2.3	78	35	0.14	1×10^4	11	24
8(b)	T18	3.0	102	30	0.14	1×10^4	9	21
8(c)	T11	3.2	109	36	0.14	3×10^3	13	23
8(d)	T13	3.2	109	30	0.15	1×10^4	9	21
8(e)	T14	4.5	153	30	0.14	1.5×10^4	10	20
8(f)	T12	4.6	156	30	0.14	5×10^3	8.5	21.5
8(g)	T2	5.8	197	26	0.17	1×10^4	7.5	18.5
8(h)	T13	7.7	262	22	0.17	5×10^4	6.5	15.5
9(a)	T10	8.0	272	26	0.14	1×10^4	8.5	17.5
9(b)	T17	8.8	299	26	0.14	1×10^4	9	17
9(c)	T11	16.4	558	16	0.15	1×10^4	5	11
9(d)	T9	41.4	1,408	14	0.15	1×10^4	5	9
9(e)	T14	41.7	1,418	13	0.16	3×10^4	4	9
9(f)	T10	52.7	1,792	14	0.14	1×10^4	5	9

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Closure by G. Mesri,[9] T. D. Stark,[10] Members, ASCE, M. A. Ajlouni,[11] Student Member, ASCE, and C. S. Chen[12]

The writers are pleased to learn that Fox, Roy-Chowdhury, and Edil have confirmed experimentally the paper's assessment that biodegradation of peat in some laboratory environments may result in misleading interpretation of secondary compression behavior. The discussers' Middleton peat specimen N2, which was subjected to gamma radiation to minimize biodegradation, displays a secondary compression behavior in accordance with the prediction of the C_α/C_c concept, and the corresponding single C_α/C_c datum point computed by the discussers plots completely within the range of $C_\alpha/(1 + e_o)$ versus $C_c/(1 + e_o)$ data in Fig. 10. The discussers should reconsider their "tertiary creep" concept in light of test N1, which suggests that the laboratory favor termed "tertiary creep" by Fox et al. (1992) may actually represent biodegradation of peat in an uncontrolled laboratory environment.

As can be readily checked by compression and excess pore-water pressure measurements in Figs. 7(d), 8(b), 8(d), and 8(h), the Casagrande empirical construction defines an end of primary consolidation almost identical to that defined by excess pore-water pressure measurements. This has been confirmed by reliable pore-water pressure measurements in numerous one-dimensional consolidation tests on undisturbed specimens of over half a dozen soft clay and silt deposits (Mesri and Feng 1992; Mesri et al. 1994b). However, the value of t_p is not explicitly used to obtain C_α, and a precise definition of t_p is not required for accurate definition of C_α from the first log time cycle of secondary compression after primary consolidation. The comparisons in Figs. 7, 8, and 9 between measured and computed secondary compression, and therefore C_α with time, confirm that the value of C_α/C_c, defined using the first log time cycle of secondary compression together with C_c from EOP e versus log σ'_v, is applicable throughout the secondary compression stage. This behavior had been already established by Mesri and Godlewski (1977) by plotting (C_α/C_c) pairs during secondary compression in C_α versus C_c. The values of C_α were defined from t_p to $10t_p$, $10t_p$ to $100t_p$, and $100t_p$ to $1{,}000t_p$, and the corresponding C_c values were obtained from e versus log σ'_v relations to t_p, $10t_p$, and $100t_p$, respectively.

Unfortunately, without a first-hand knowledge of the discussers' testing procedure and interpretation, the writers cannot evaluate the discussers' two oedometer tests on a sample of an inorganic clay. The writers' experiences with numerous oedometer tests on over two dozen soft clay and silt deposits from throughout the world, including 10 inorganic soft clays from eastern Canada, as well as interpretation of oedometer data on numerous soils published in the literature, do not agree with the wide range of C_α/C_c computed by the discussers for one clay. In fact, a C_α/C_c value of 0.07 is anomalous for the inorganic clay described by the discussers. It must be realized that even the most fundamental principles and laws of soil behavior can be tested or verified only by reliable experiments and careful interpretation.

In summary, the discussers' findings illustrate the adverse effects that an uncontrolled laboratory environment can have on the behavior of organic materials. The results presented in the paper indicate that it is not necessary to irradiate every

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[12]Prof. Engr., Sino Geotechnology, 50 Nanking East RD, Taipei, Taiwan.

clay and peat specimen to obtain reliable subsurface information from laboratory tests.

Juárez-Badillo has successfully applied fundamental equations by the principle of natural proportionality to the compressibility data on Middleton peat. The values of the parameters such as γ, δ, and t^* for the theoretical points in Table 2 and Figs. 20 and 21 were found by fitting the theoretical equations to the laboratory data. Similar successful fittings for clays have been published by Juárez-Badillo (1988a,b). It would be interesting and useful to summarize together and interpret values of these parameters of the theoretical equations for various clays and peats. Then it would be possible to make predictions of field settlement versus time using the equations by the principle of natural proportionality.

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RESILIENT MODULUS OF COHESIVE SOILS[a]

Discussion by Frank Atuahene,[5] Associate Member, ASCE

On (3), which was established by multiple polynomial regression analysis, there is no explanation as to why the intercept parameter is missing. Apart from the coefficient of multiple determination, no other characteristics from the analysis of variance are given. The F value is important in the evaluation of the aptness of fit of the relationship, while the t values of the parameters are essential in evaluating the stability of the parameters.

Eq. (3) indicates that an unstressed soil not subject to any strain has zero resilient modulus. This deduction is incongruent with the definition of resilient modulus. Yet another indication of possible problems with (3) is that $S_{u1.0\%}$ could be zero, which in turn means a zero force can cause a 1% strain. Also from the equation, the soil has a zero resilient modulus with a stress of 806.7 kN/m^2 (117 psi) and a 1% strain. From the definition of resilient modulus as the imposed repeated axial stress divided by the resilient axial strain, and with a selected strain of 0.01, the resilient modulus at 806.7 kN/m^2 (117 psi) should be 80.7 MN/m^2 (11.7 ksi) and not zero. Thus, the regression relationship is not validated because the predictions of the relationship are not in conformity with theoretical and practical expectations.

The method of obtaining field compacted samples raises questions. How old was that pavement from which the compacted subgrade was taken? The coring with the auger may have disturbed the compaction integrity of the sample taken. A sample from a freshly compacted soil in the field that has never been subjected to any pavement overburden or dynamic strains could be a better simulation of field compaction.

Closure by Woojin Lee,[6] N. C. Bohra,[7] A. G. Altschaeffl,[8] and T. D. White[9]

The authors thank the discusser for his interest in the paper.

The discussion focuses on (3) from a mathematical and statistical point of view. Eq. (3) came from a step-wise regression technique applied to parameters from the conventional unconfined compression set. The purpose was to correlate results of complicated resilient modulus testing with results of simple unconfined compression testing. The purpose of the paper was to demonstrate a simple correlation between parameters from the two tests and not to clutter it with statistical details. Lee (1993) provides statistical details involved in development of Eq. (3).

The discusser questions the definition of resilient modulus (M_R) from a mathematical point of view. M_R is a ratio of stress and strain (see p. 131 of the paper), which has been correlated with the stress associated with 1.0% strain ($S_{u1.0\%}$) in the unconfined compression test. If there is no applied stress, then there is no associated strain; modulus is undefined, and not equal to zero as suggested by the discusser. In addition it is correct to suggest nonzero strain with zero stress. The magnitude of $S_{u1.0\%}$ can never be equal to zero. As the discusser notes, (3) can be solved for $M_R = 0$ to get a magnitude of $S_{u1.0\%}$ equal to 807 kPa (117 psi). The correlation is based on experimental data and properly cannot be extrapolated beyond the range of its data (Fig. 7). This figure also shows the quality of the correlation decreases for magnitudes of $S_{u1.0\%}$ larger than about 172 kPa (25 psi).

The parameter $S_{u1.0\%}$ has nothing to do with the definition of M_R. An examination of the (3) parameters (p. 134) indicates that M_R has been defined at a maximum axial stress of 41.4 kPa (6 psi) and a confining pressure of 20.7 kPa (3 psi). Hence, an arbitrarily large stress level of 806.7 kPa (117 psi), as suggested by the discusser, has no theoretical significance for (3). Subgrade stress levels of such large magnitudes are not expected.

Finally, as both M_R and unconfined compression tests were performed on the same samples, sampling disturbances and changes induced in-service would be reflected in both tests; they would, thus, not affect the correlation for (3).

APPENDIX. REFERENCE

Lee, W. (1993). "Evaluation of in-service subgrade resilient modulus with consideration of seasonal effects," PhD thesis, School of Civ. Engrg., Purdue Univ., West Lafayette, Ind.

[a]February 1997, Vol. 123, No. 2, by Woojin Lee, N. C. Bohra, A. G. Altschaeffl, and T. D. White (Paper 12188).

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