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SYNOPSIS The investigation considered effects of on-going or previous drained creep on the low-amplitude dynamic shear modulus of normally consolidated artificial and natural clay soils. Resonant column tests using the Hardin and Hall devices determined the low-amplitude shear modulus. Results indicated that the strain-rate of on-going creep determined the kind of effect on shear modulus. High strain-rates produced reduced values whereas low strain-rates slightly increased values of modulus, compared to the no-creep values. Previous creep produced higher values of modulus, when the clay was tested under after-creep isotropic confinement. The rate of secondary increase of shear modulus was not affected by the drained creep action. The behaviors of the remolded kaolinite clay and the undisturbed natural clay were remarkably similar.

INTRODUCTION

The low-amplitude shear modulus, G_o, is a key parameter for the establishment of the dynamic shearing stress - shearing strain curve of soils, and for establishing the reference strain, γ_r, which helps in providing dimensionless stress-strain curves for soils (Hardin and Drnevich, 1972b; Richart, 1975; Hardin, 1978). It is recognized today that the use of advanced analytical techniques has resulted in an ability in analysis far outstripping the test ability to furnish the required input parameters, one of which is G_o. Values of G_o are obtained today by in-situ tests, laboratory tests, or empirical equations. Regarding cohesive soils, the agreement between the above methods is poor when time effects are neglected (Anderson and Stokoe, 1978; Woods, 1978). Probably the most important time effect to be taken into account when measuring G_o in the laboratory is the duration of confinement, t. Numerous studies have shown that G_o continues to increase under sustained isotropic confinement even after the completion of the primary consolidation. This increase takes the form of a straight line in the G_o vs. log t plot (Afifi and Woods, 1971; Marcuson and Wahls, 1972; Anderson and Woods, 1976; Stokoe et. al., 1980; Kim and Novak, 1980). When the confinement is anisotropic, the shear stresses developed in the soil mass initiate creep deformations. Although the literature is full of information regarding the creep behavior of cohesive soils and the creep effects on the strength of cohesive soils, only meager information is available for the creep effects on the stiffness of cohesive soils.

Schmertmann(1976), analyzing experimental results found by Bea(1960), noted that the initial tangent moduli (obtained from triaxial tests) for specimens that had undergone undrained creep were greatly increased compared to moduli obtained from specimens without previous creep. Mitchell(1976), summarizing the effects of creep on the soil stiffness, states that it ordinarily produces an increase in stiffness to the action of subsequent loading. Hardin and Black (1968) have shown that the shear modulus of normally consolidated clays subjected to anisotropic sonsolidation is essentially independent of the deviatoric component, τ_o, of the ambient effective stress. However, they did not include time effects in their study, since each test was terminated after approximately one day of confinement.

This study represents an attempt to examine the effect of either on-going or previous drained creep deformations on the low-amplitude shear modulus, G_o, of an artificial and a natural clay soil tested in resonant column devices in their normally consolidated state. The results may also be utilized for the detection of clay structure changes that occur during drained creep.

TEST MATERIALS

An artificial and a natural clay were used in this investigation. The artificial clay was prepared by mixing a commercially available powdered clay (Ball Clay) with sufficient amounts of distilled water to give a water content of 43% and a degree of saturation of 97 to 100%. The mixture was then extruded through a Vac-Aire extrusion machine, to produce specimens with a slightly spiraled, but uniform and reproducible clay structure. This clay is denoted herein as BALL CLAY(VAC-AIRE). The natural undisturbed soil is a uniform saturated silty clay from the Detroit area, being part of a glacial lake deposit and known locally as Belle River Clay. This clay is denoted herein as BELLE RIVER CLAY. Table I gives some index properties and the mineralogy of the two clays.

TABLE 1. Index Properties and Mineralogy of Tested Soils.

SOIL	PL	PI	G_s	SOIL MINERALOGY
BALL CLAY	32	39	2.64	KAOLINITE, QUARTZ
BELLE RIVER CLAY	21	18	2.78	KAOLINITE, ILLITE W/TRACES OF CHLORITE

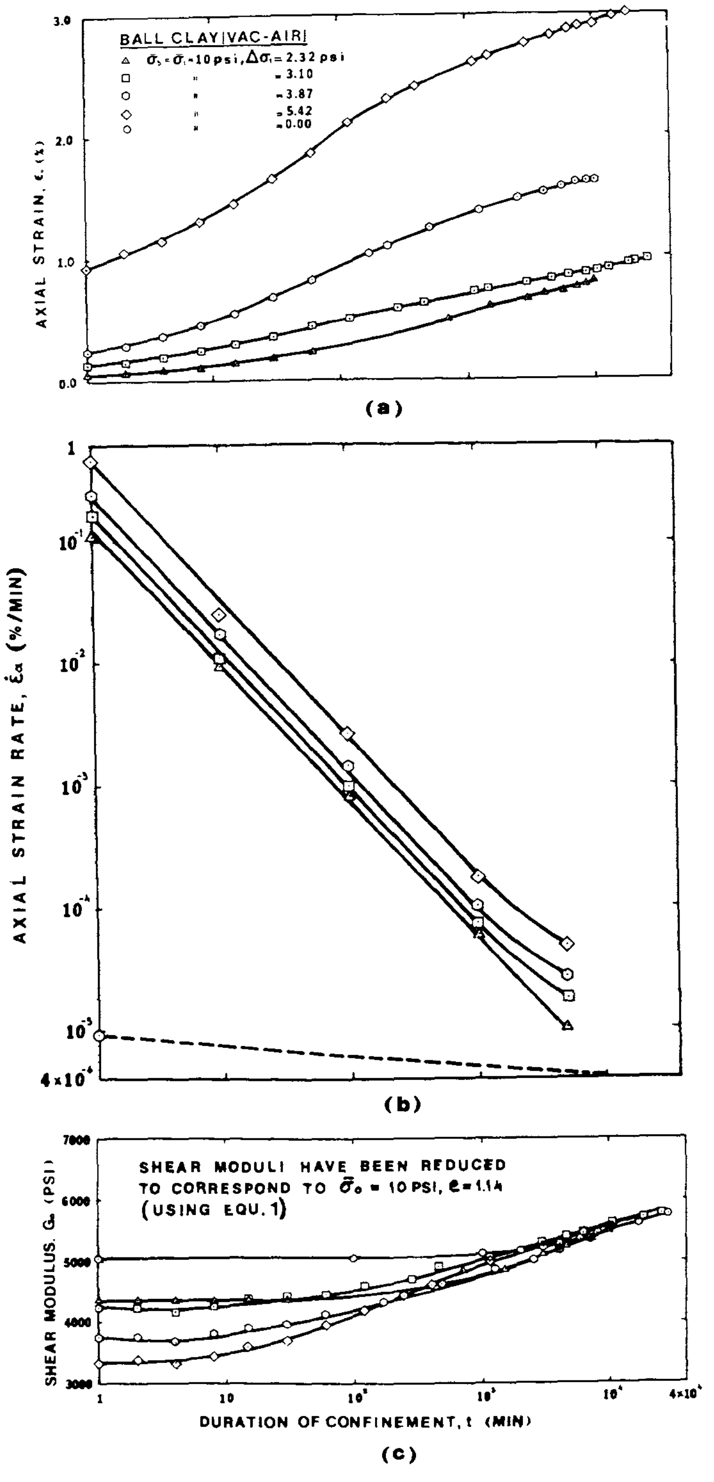

Fig. 1. Variation of (a) Axial Strain, (b) Axial Strain Rate, and (c) Low-amplitude Shear Modulus with Duration of Anisotropic Confinement, for Ball Clay.

TEST EQUIPMENT

Three resonant column devices were used in this investigation, one of the Hardin-type and two of the Hall-type. The Hardin-type device has been described by Hardin(1970). It permits the measurement of G_o of a cylindrical specimen under either isotropic or anisotropic states of ambient stresses; thus it can be utilized for the evaluation of on-going creep effects on G_o. The Hall-type device has been described by Richart, Hall, and Woods(1970). It permits the measurement of G_o of a cylindrical specimen under only isotropic state of ambient stress. This type of device was slightly modified to permit the application of anisotropic states of ambient stresses on the specimen prior to vibratory testing. This permitted the evaluation of the effects of previous creep on the value of G_o measured under subsequent isotropic states of stresses.

EXPERIMENTAL PROGRAM

The experimental program was divided into two parts:

A. On-going Creep Investigation. Five duplicate specimens of Ball Clay were first tested in the Hardin device. Each specimen was first isotropically consolidated under a cell pressure of 10 psi for a period of 2800 min. Then an axial stress increment, $\Delta\sigma_1$, was instantaneously superposed under drained conditions on four of the five specimens. Values of $\Delta\sigma_1$ ranged from 2.32 to 5.42 psi and they were selected to give a reasonable variation of creep strains without causing failure of the specimen. On the fifth specimen, the isotropic pressure of 10 psi was applied throughout the test. The results of the fifth test were used as the reference to which the rest of the tests were compared and they are called herein "no-creep" results. The instant of $\Delta\sigma_1$ application was taken as zero time and the variation of axial strain, $\varepsilon\alpha$, axial strain rate, $\dot{\varepsilon}\alpha$, and G_o (for shear strain equal to 5 X 10^{-6}) was established as a function of time. Since for different applied values of $\Delta\sigma 1$ the average effective stress $\bar{\sigma}o$, acting on the specimen and the void ratios were different, the values of G_o during creep had to be reduced to the same value of $\bar{\sigma}_o$ and void ratio. Equ. 1 was used for this reduction (based on Hardin's 1978 empirical equation):

$$G_o(\bar{\sigma}_{or},e_r)=G_o(\bar{\sigma}_{oa},e_a)\left[\frac{0.3+0.7e_a^2}{0.3+0.7e_r^2}\right]\cdot\left[\frac{\bar{\sigma}_{or}}{\bar{\sigma}_{oa}}\right]^{1/2} \quad (1)$$

where: $G_o(\bar{\sigma}_{or},e_r)$ = Shear modulus under the reference conditions $(\bar{\sigma}_{or},e_r)$

$G_o(\bar{\sigma}_{oa},e_a)$ = Shear modulus under the actual conditions $(\bar{\sigma}_{oa},e_a)$

By using this reduction scheme the influence of $\bar{\sigma}_o$ and e on G_o was essentially eliminated and the influence of other parameters could be revealed.

The above procedure was repeated for the undisturbed samples of Belle River Clay. In this series of tests, four sepcimens were used and the preconsolidation pressure was 25 psi to assure that the specimens were tested in the normally consolidated state. The values of $\Delta\sigma_1$ were selected to produce the same range of axial strains found for the Ball Clay. Finally Eq. 1 was also applied for eliminating $\bar{\sigma}_o$ and void ratio effects.

B. Previous Creep Investigation. This series of experiments was performed only on Ball Clay specimens. Seven duplicate specimens mounted on the pedestal of the Hall resonant column device were

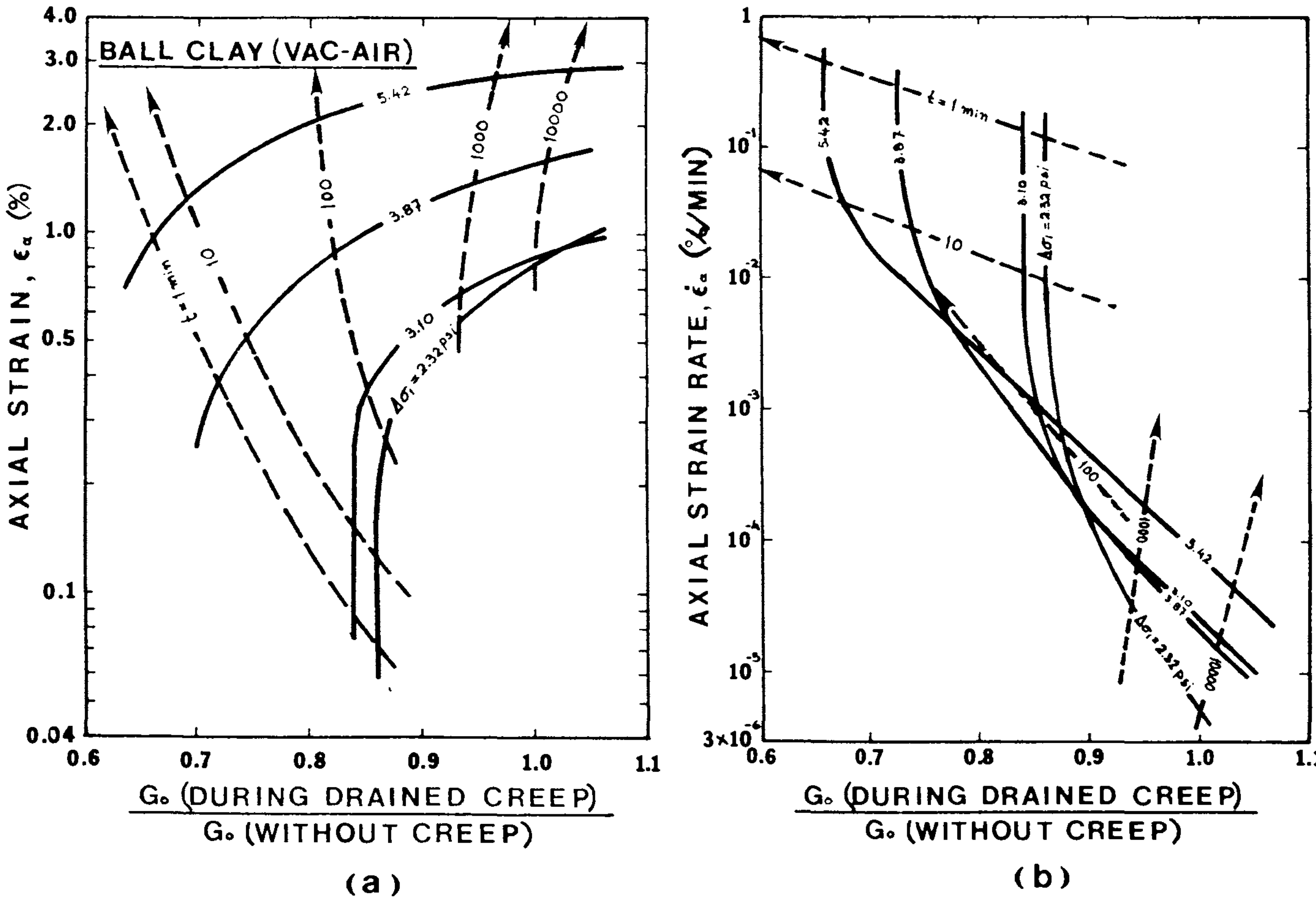

Fig. 2. Influence of (a) Axial Strain, Deviator Stress, Time of Confinement, and (b) Axial Strain-rate, Deviator Stress, Time of Confinement on Low-amplitude Shear Modulus for Ball Clay.

first isotropically consolidated under a cell pressure of 10 psi for a period of 2800 min. Then an axial stress increment $\Delta\sigma_1$ was superposed instantaneously on six of the seven specimens under drained conditions. Values of $\Delta\sigma_1$ varied from 1.16 to 5.42 psi and the specimens were allowed to creep for one week (10,000 min) under this $\Delta\sigma_1$. At the end of the week the axial stress and the cell pressure were removed from the specimen for a period of approximately 30 min while the Hall driving mechanism was attached to the specimen. Then an isotropic confining pressure was applied to the specimen, equal to the average effective stress which acted on the particular specimen during its drained creep phase. The instant of application of this after-creep isotropic confinement was taken as zero time and the value of shear modulus, G_o, (for shear strains = 5 X 10^{-6}) was monitored as a function of time. For the seventh specimen the cell pressure was removed for 30 min. after the completion of the 2800 min. period of isotropic confinement and then reapplied. The time of reapplication of the confinement was taken as zero time and the shear modulus was measured as a function of time. Values of modulus obtained from this seventh specimen were the reference values, herein denoted as "no-creep" values. Values of shear modulus were reduced to the same $\overline{\sigma}_o$ and void ratio using Eq. 1.

TEST RESULTS AND DISCUSSION

On-going Creep Investigation. Fig. 1. shows the results from the Ball Clay tests. The axial strain, axial strain-rate, and reduced shear modulus are shown as a function of duration of confinement. As confinement time increases the axial strain increases, the axial strain-rate decreases, and the shear modulus, which immediately after the application of the axial stress increment was significantly reduced, again increases. After approximately 3000 min of confinement, the shear modulus of the creeping specimens has regained the "no-creep" value. The rate of secondary increase is also essentially the same. Thus, Fig 1 suggests that during the early stages of creep the shear modulus is reduced, but as the creep progresses the shear modulus regains its "no-creep" value and slightly exceeds it. To help demonstrate the individual influences of axial strain and axial strain-rate on the value of G_o, Fig. 2 was prepared by cross-plotting the three subfigures of Fig. 1. Fig. 2a depicts the relationship between axial creep strain and shear modulus for different values of $\Delta\sigma_1$ and at different instants of time (isochrones) It shows that the reduction of shear modulus

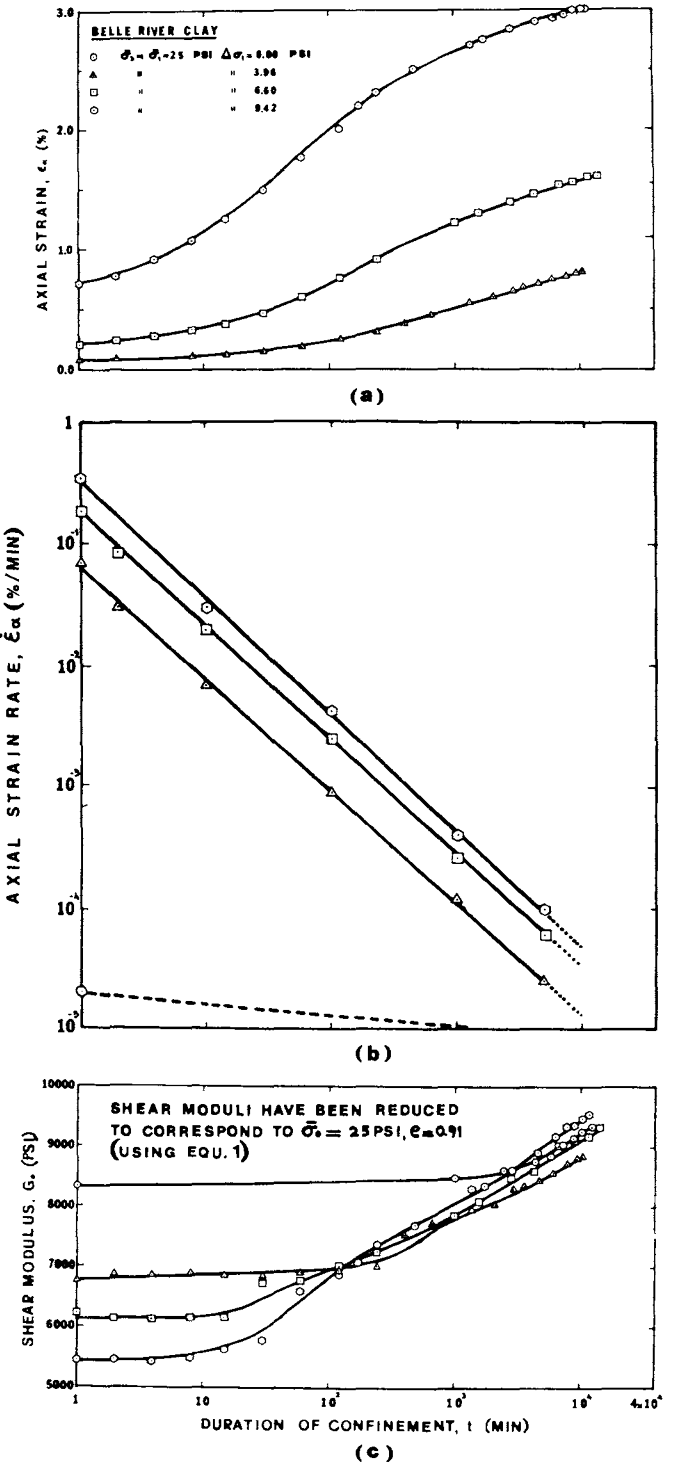

Fig. 3. Variation of (a) Axial Strain, (b) Axial Strain-rate, and (c) Low-amlitude Shear Modulus with Duration of Anisotropic Confinement for Belle River Clay.

during the early stages of creep ranged from 15% to 35% (the greater the $\Delta\sigma_1$ the greater the reduction), whereas during the later stages the value of G_o is slightly increased with respect to the "no-creep" value (the greater the $\Delta\sigma_1$ the greater the increase). Fig. 2b illustrates the relationship between axial strain-rate and shear modulus for different values of $\Delta\sigma_1$ and different isochrones. It shows that for each value of $\Delta\sigma_1$, a critical value of axial strain-rate exists above which the shear modulus does not change with increasing values of strain-rate. For values of strain-rate below the critical value, the shear modulus increases with decreasing axial strain-rate. It is interesting to note that the above mentioned critical value of strain-rate depends on the $\Delta\sigma_1$ value and decreases with decreasing $\Delta\sigma_1$.

Fig. 3 and Fig. 4 show pertinent results from the Belle River Clay tests. They are very similar to the results obtained for the Ball Clay regarding the general trends as well as the numerical values. Thus a vacuum-extruded remolded clay and an undisturbed natural clay exhibited similar behavior during drained creep in spite of differences in the structure of the two materials. This agrees with Schmertmann's(1976) statement that all the shear behavior phenomena he has investigated using a similar remolded Kaolinite clay, will occur in-situ in undisturbed clays, although one should expect great variations in degree.

The above discussion demonstrates the fact that creep strain can only act as a stiffening factor, for the structure of a clay, when the rate of deformation is lower than a limiting value. Schmertmann(1976) concludes also that under the very slow strain-rates characterizing such processes as preconsolidation, aging, and creep the initial modulus of the material is increasing.

Previous Creep Investigation. Fig. 5a shows the variation of the shear modulus vs. the axial strain developed during the drained creep phase for different durations of after-creep isotropic confinements. This figure shows first that the shear modulus increases as the axial strain due to drained creep increases. It also shows that G_o after creep is higher than that without creep. Finally it shows that as the duration of the after-creep isotropic confinement increases, the influence of previous creep becomes less pronounced. Thus, after a duration of isotropic confinement equal to 10,000 min, the after-creep modulus shows an increase relative to the "no-creep" value ranging from 4% to 22%. This range of increase can be compared with the range of the 10,000 min isochrone of Fig. 2a which is from 0% to 3%. One might expect that these two ranges were the same, since they refer to the same soil, under the same average effective stress, void ratio, and creep history. However, there is a difference in the loading history of the two series of experiments. In the series of tests shown in Fig. 5a, the confinement was removed for 30 min after the end of creep phase, whereas this did not happen in the series of tests shown in Fig. 2a. Thus it may be deduced that the temporary removal of the pressure caused an enhancement of the creep effects on the stiffness of the clay.

Fig. 5b shows the previous creep effects on the normalized, N_G, and non-normalized, I_G, rate of secondary increase of shear modulus under after-creep isotropic confinement. The use of N_G is preferred, rather than using I_G, since it is less dependent on the level of confinement and shows less scatter. Fig. 5b shows that previous creep reduces the value of N_G, by 26% to 48% compared with the "no-creep" value. However, Fig. 1c suggests that the rate of secondary increase is not affected by the on-going creep. This difference

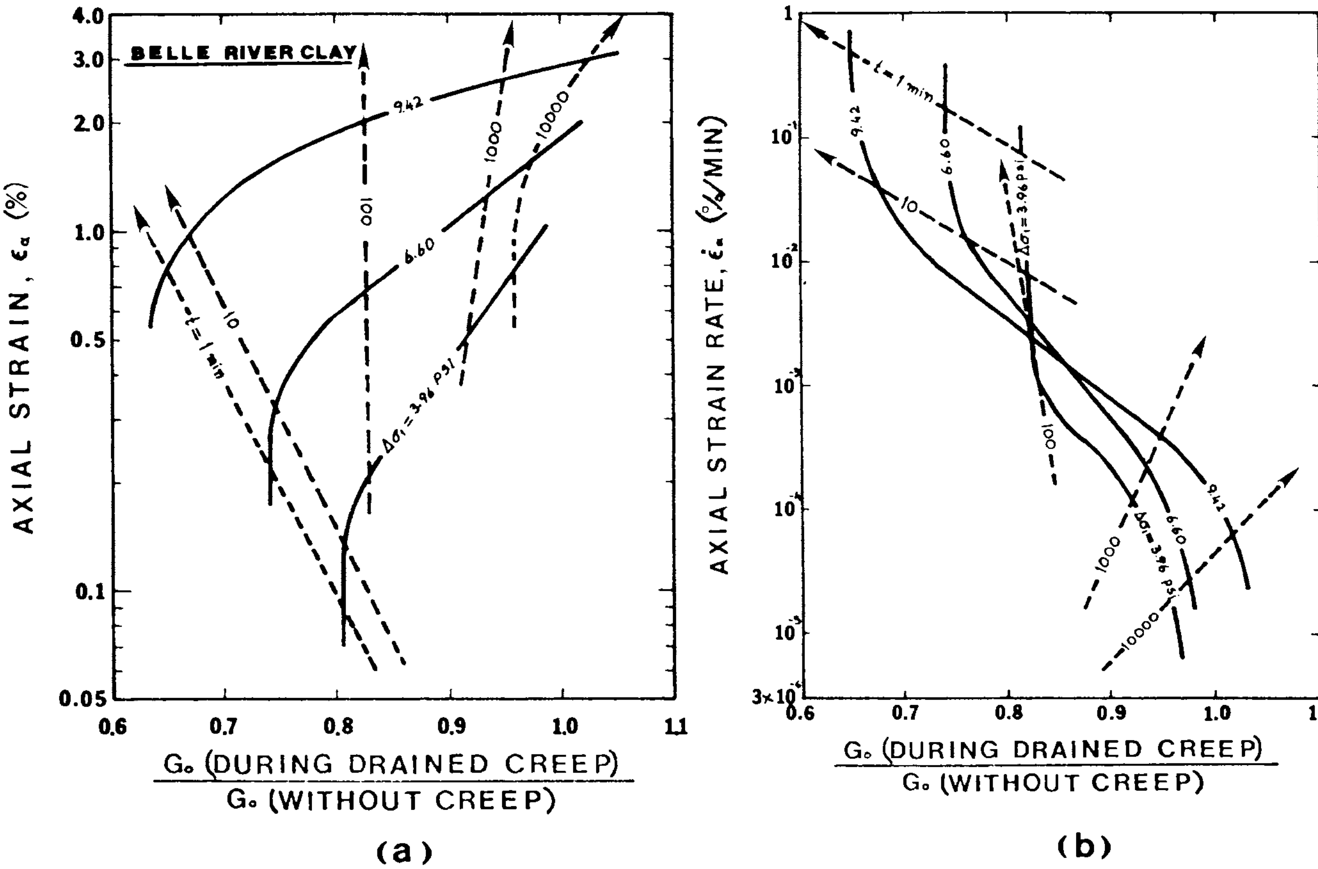

Fig. 4. Influence of (a) Axial Strain, Deviator Stress, Time of Confinement and (b) Axial Strain-rate, Deviator Stress, Time of Confinement on Low-amplitude Shear Modulus for Belle River Clay.

in behavior is explained as follows: on-going research at the University of Michigan has shown that the rate of secondary increase estimated from a resonant column test depends on the duration of aging of the clay, before the start of the test. It has been found that the longer the aging, the lower the value of subsequent rate of secondary increase. A difference in aging of 10,000 min, e.g. can produce a 55% reduction in the rate of secondary increase. When we take this finding into account, we find that in Fig. 5, the confinement removal for the six creep tests has occurred after 12,800 min of confinement whereas for the reference test it occurred after 2800 min of confinement. Thus the reduction in the rate of secondary increase shown in Fig. 5b is not due to previous creep, but to a 10,000 min difference in duration of aging. In Fig. 5b, if the N_G line is translated by 50% to the right, it then indicates that the rate of secondary increase was not affected by the previous creep, at least for creep strains greater than 0.5%.

CONCLUSIONS

1. The rate of deformation during drained creep determines whether the shear modulus increases or decreases. For fast rates of deformation, the shear modulus takes values lower than the no-creep value, whereas for slow rates the shear modulus is unaffected or slightly increased with respect to no-creep value.

2. The accumulation of axial strain can only stiffen a normally consolidated clay when the rate of deformation is below a critical value.

3. The rate of secondary increase is not affected significantly by the action of drained creep.

ACKNOWLEDGEMENT

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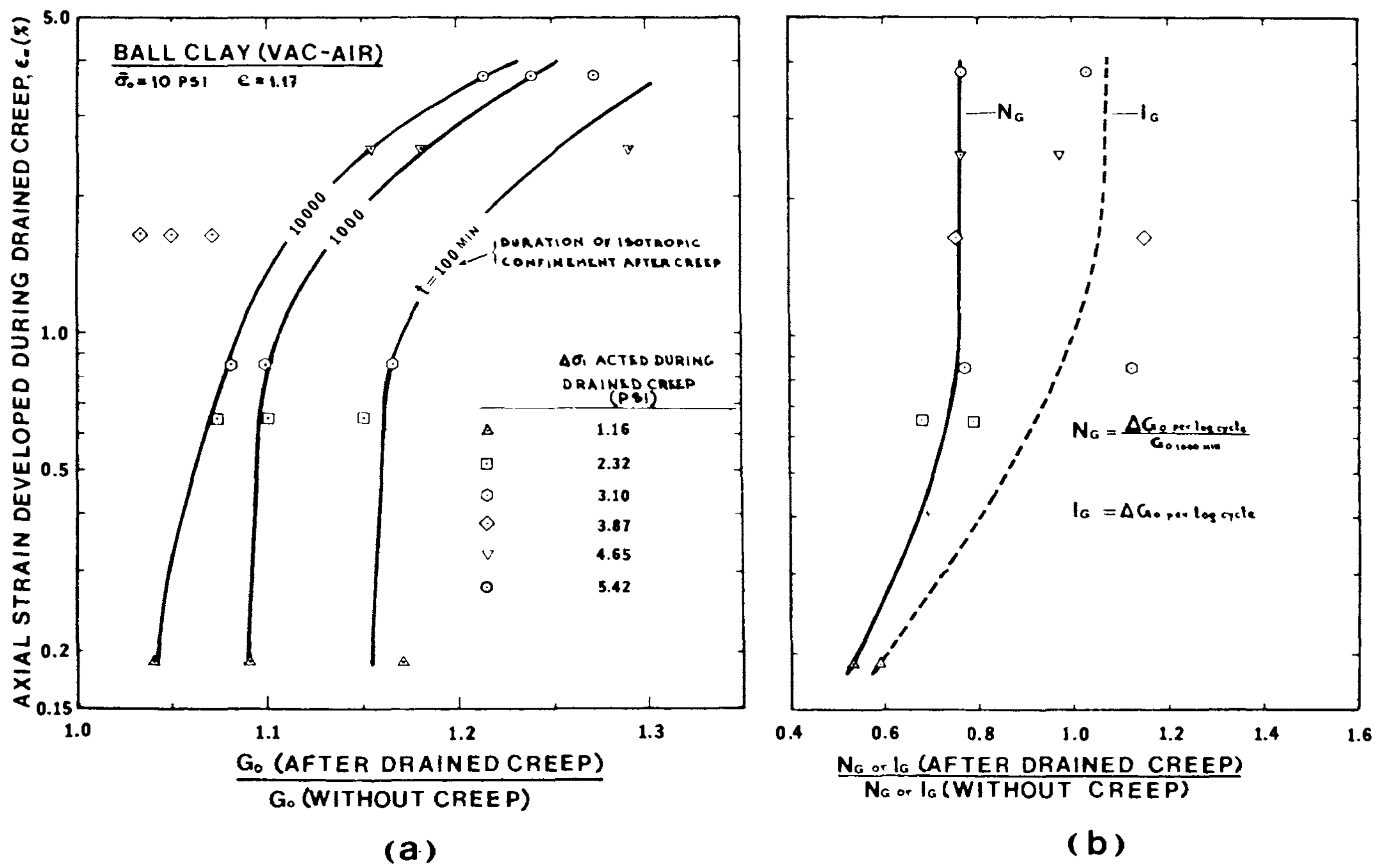

Fig. 5. Effect of Previous Drained Creep Straining on (a) Low-amplitude Shear Modulus and (b) Rate of Secondary Increase for Ball Clay.

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