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TRIAxIAL AND PLANE STRAIN CREEP RUPTURE OF AN

UNDISTURBED CLAY

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Undisturbed Clay**

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**ABSTRACT**

A comparative study of the undrained creep rupture characteristics of a saturated, normally consolidated, undisturbed marine clay has been carried out under triaxial and plane strain conditions. Creep rupture tests were performed on samples which were consolidated both isotropically and under  $K_0$  conditions to the same vertical effective stress. It is shown that for a given minimum creep rate or creep stress, large differences in rupture life are observed between conventional isotropically consolidated triaxial samples and  $K_0$  consolidated triaxial or plane strain samples. Similar discrepancies are introduced when conventional triaxial results are used to estimate remaining rupture life during tertiary creep stage when the real situation corresponds to either  $K_0$  consolidation or plane strain. Effective stress failure in creep rupture for a given type of test is governed by the same linear failure envelope which is obtained during constant rate of shear testing.

## Introduction

Soils, like other engineering materials, undergo time-dependent deformation under sustained shearing stresses. At relatively low stress levels, these time-dependent deformations, generally termed creep, may eventually appear to stop or continue at an imperceptible rate after very large elapsed times from the initiation of creep. At higher stress levels, however, the initially steady or decreasing creep rate may start to accelerate after a finite elapsed time and finally lead to creep rupture. In conventional soil mechanics design, the time-dependence of soil properties is often ignored. Such a practice can result in excessive deformations leading to failure or collapse with time. The need for an understanding of the creep rupture properties of clay soils is amply demonstrated by a number of foundation failures which have been attributed to long term movements (Peck et al. 1948, Haefeli and Schaerer 1953, Henkel 1957, Suklje 1961, Skempton 1964).

Laboratory investigations of soil creep at creep rupture stresses have been extremely limited. As a result of these limited studies together with some field observations, techniques have been proposed to deal with creep rupture (Saito and Uezawa 1961, Saito 1965, 1969a, 1969b, Singh and Mitchell 1969, Snead 1970, Kwan 1971). However, the data needed to formulate these techniques had been solely obtained from the conventional triaxial or unconfined compression tests. In these tests consolidation stresses are hydrostatic prior to creep loading. Most natural clay deposits, on the other hand, have been consolidated under the condition

of one-dimensional strain ( $K_0$  consolidated) and not under hydrostatic stresses. In order that laboratory test results could be appropriately translated for field applications, creep behavior in the laboratory should also be determined after  $K_0$  consolidation prior to creep loading. (Campanella and Vaid 1972a recently presented a study on creep rupture of a  $K_0$  consolidated natural clay). Furthermore, the axially symmetric stress conditions of the triaxial test are rarely representative of many practical problems of earth structures, which in most cases more closely approximate plane strain. Thus, it appears that the most representative laboratory tests for the study of creep rupture behavior of natural clays would consist of plane strain creep tests on initially  $K_0$  consolidated samples.

The investigations reported herein are aimed at a comparison of creep rupture behavior of a natural clay under  $K_0$  triaxial, conventional isotropic triaxial and plane strain conditions. It is also intended to point out the magnitude of error involved when conventional triaxial results are used where the real situation corresponds to either  $K_0$  consolidation or plane strain. The study is restricted to a normally consolidated clay and only undrained creep is considered. Normally consolidated clays on creep loading under fully or partially drained conditions undergo volume decreases and a consequent strength gain with time. Therefore the undrained condition is the controlling drainage condition under which a creep rupture failure may occur. Such clays would not creep rupture when fully or partially drained since they would have already creep ruptured in an undrained condition at

an earlier stage of the constant stress test. Furthermore, the condition of long term failure in deep thick beds of normally consolidated clays could be simulated by undrained creep rupture, since the low permeability and long drainage paths would permit practically no drainage.

### Material Used and Experimentation

A local undisturbed clay (called Haney clay) was used for the study. The clay was block sampled from an open pit. Haney clay is believed to have been deposited in a marine environment and later subjected to partial leaching due to surface infiltrations. It is a grey silty clay with liquid limit = 44%, plastic limit = 26%, maximum past pressure about  $3.5 \text{ kg/cm}^2$  and a sensitivity from 6-10. All the test samples were trimmed from blocks obtained from the same horizon. This ensured the least variation among individual samples.

A series of creep rupture tests was performed in each of the conventional triaxial,  $K_0$  triaxial and plane strain apparatuses. The special  $K_0$  triaxial and plane strain apparatuses employed in the study have been described elsewhere (Campanella and Vaid 1972b, 1973). In the conventional triaxial creep rupture series, samples were isotropically consolidated to an all round effective stress of approximately  $5.25 \text{ kg/cm}^2$ . Samples tested in the  $K_0$  triaxial and plane strain test series were  $K_0$  consolidated under a vertical effective stress which was equal to the hydrostatic effective stress ( $5.25 \text{ kg/cm}^2$ ) for isotropically consolidated

samples. The average value of  $K_0$  was found to be 0.55. Consolidation was allowed for a period of 36 hours which was followed by an undrained period of 12 hours under the consolidation stresses prior to creep loading. Most of the pore pressure generated due to the arrest of secondary consolidation was developed during this undrained period and thus the pore pressures measured during creep were not influenced by secondary compression effects.

The desired level of creep stress was 'instantaneously' applied by connecting a pneumatic rolling belloram loading piston to a preset air pressure through a 3-way valve. As the sample strains under the creep stress, the increase in area causes the stress to decrease slightly. Small additions to the vertical load were frequently made in order to maintain a constant creep stress. The test program was carried out in a constant temperature environment (maximum temperature variation  $\pm 0.25^\circ\text{C}$ ) in order to eliminate the influence of temperature as a variable. The test data were automatically recorded on a digital magnetic tape using a high speed Vidar Digital Data Acquisition System. High speed automatic recording was particularly useful to enable accurate measurements in the initial and final rupture stages of creep.

### Test Results

#### Strain-Time Behavior:

Typical creep rupture curves expressing axial strain as a function of elapsed time are shown in Fig. 1 for the three types of tests. The magnitude

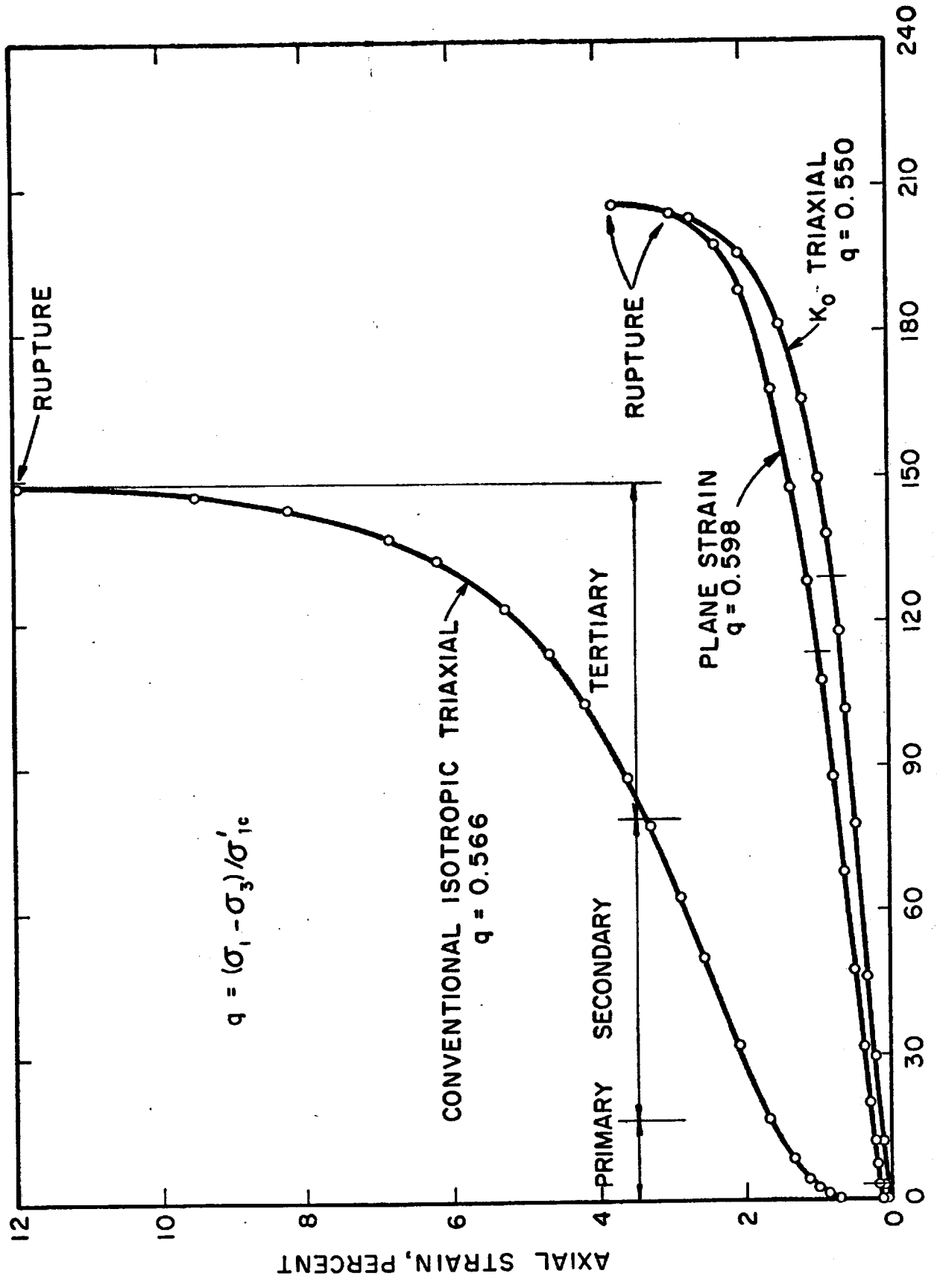


FIG. 1. TYPICAL CREEP CURVES FOR ISOTROPICALLY AND K<sub>0</sub> CONSOLIDATED TRIAXIAL AND K<sub>0</sub> CONSOLIDATED PLANE STRAIN SAMPLES - NORMALLY CONSOLIDATED UNDISTURBED HANEY CLAY.

of creep stress, expressed as the principal stress difference normalized with respect to the vertical effective stress during consolidation,  $q = (\sigma_1 - \sigma_3) / \sigma_{1c}'$ , has been indicated on the curves. The shape of the creep curve in each case was similar to that obtained for other engineering materials like metals and plastics. The three distinct regions, namely, the primary region of decreasing creep rate, the secondary region of essentially constant creep rate and finally the tertiary region of accelerating creep rate which eventually leads to rupture, can be easily recognised for each curve. However, the magnitude of creep stress to cause rupture in about the same time was widely different in isotropic triaxial,  $K_0$  triaxial and plane strain tests. It will be shown later that such differences in creep stress in a given type of test can result in times to rupture which differ by several orders of magnitude. Although the axial strain at which creep rupture occurred was not too different under  $K_0$  triaxial and plane strain conditions, the isotropically consolidated triaxial samples creep ruptured at axial strains which were as much as 4 to 5 times larger than those under plane strain conditions.

Fig. 2(a) shows the creep rate (axial strain rate) versus time behavior of samples in the  $K_0$  triaxial creep rupture series. The creep rate at a given time was computed by graphical differentiation of the strain-time data using Taylor's series approximation for the first derivatives. Fig. 2(a) shows that under a given constant creep stress  $q$ , the creep rate continuously decreased with elapsed time to a minimum value and thereafter increased until rupture. There does not appear to be a time interval over which the

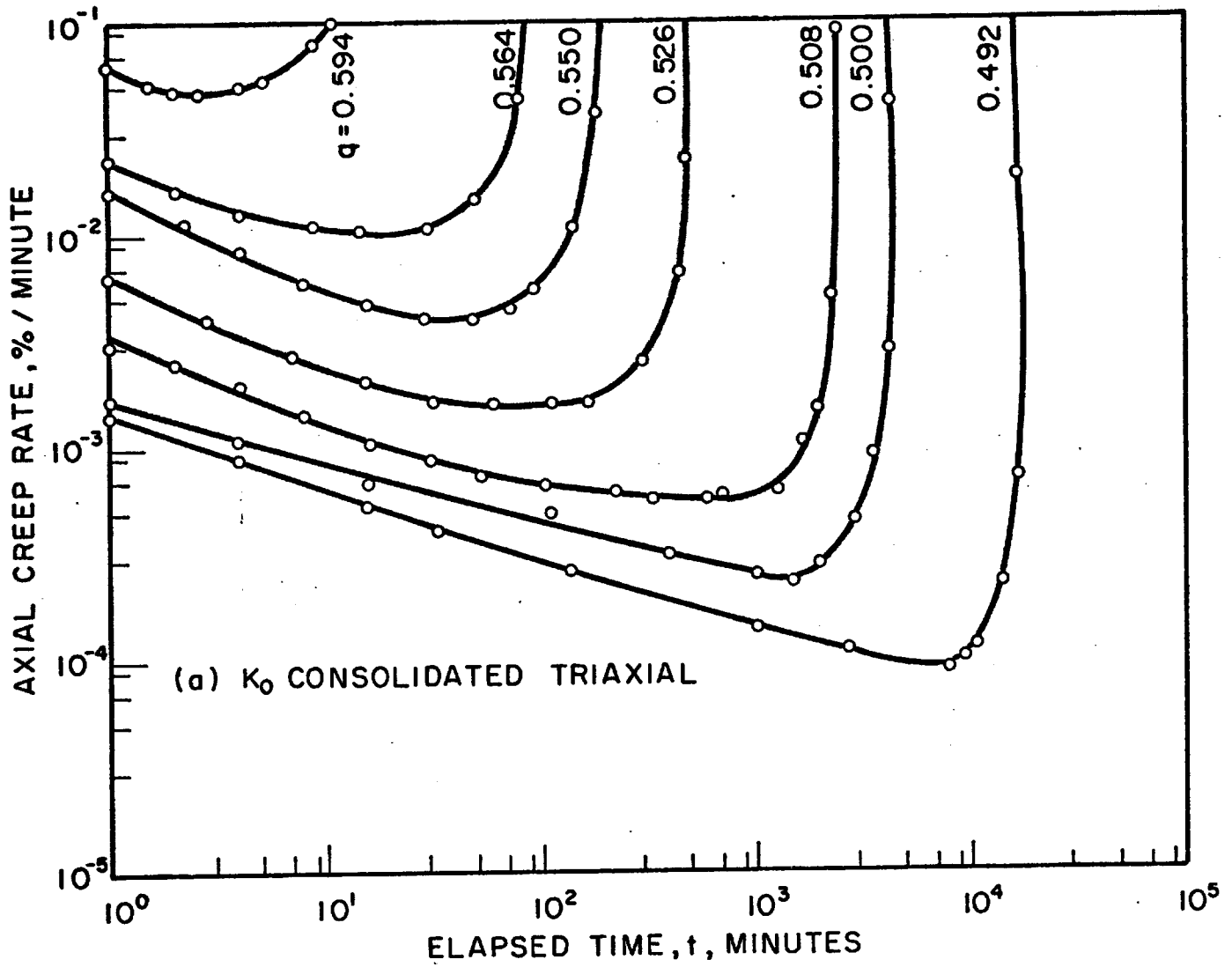


FIG.2. CREEP RATE BEHAVIOR OF NORMALLY CONSOLIDATED UNDISTURBED HANEY CLAY

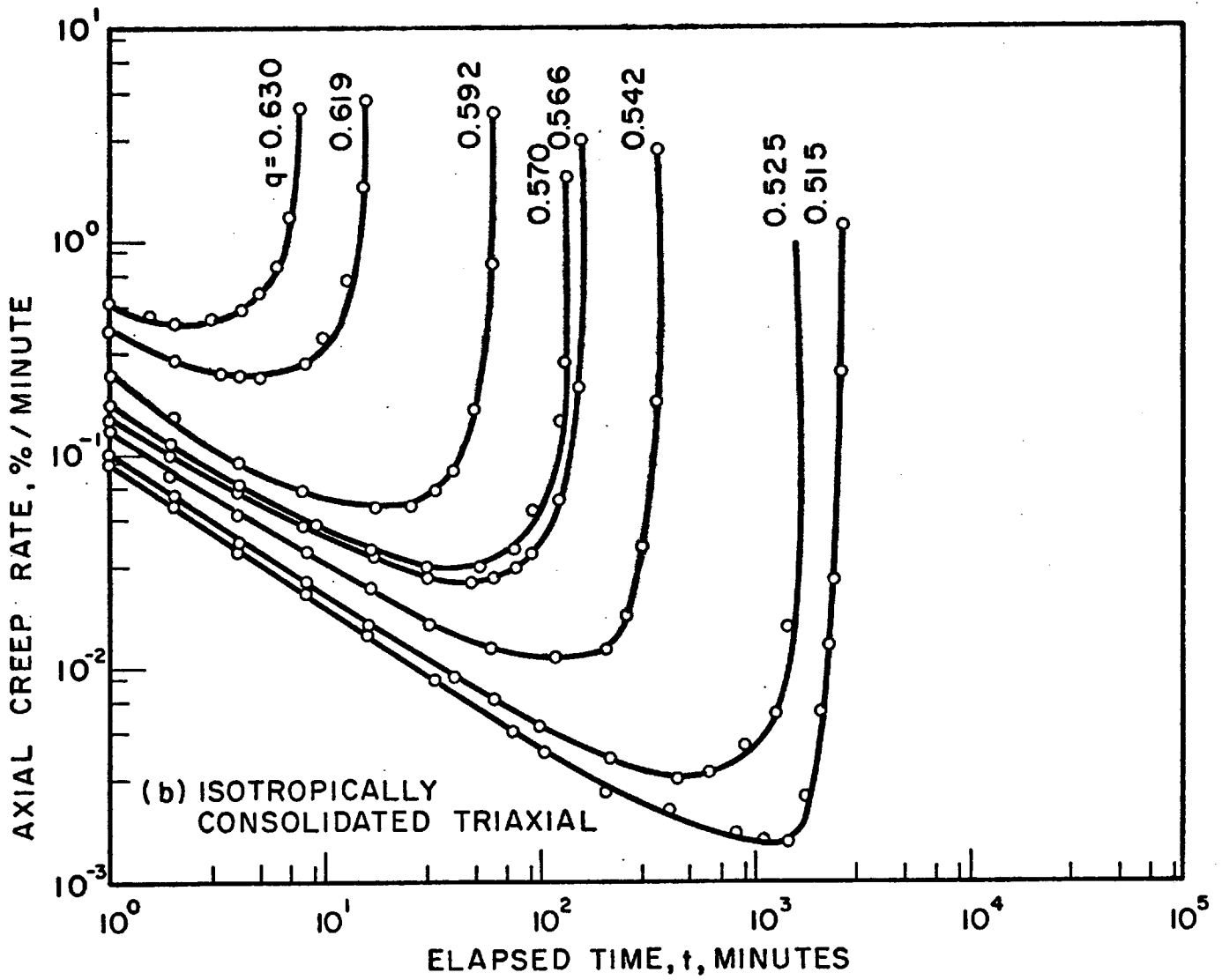


FIG.2. (CONT'D).

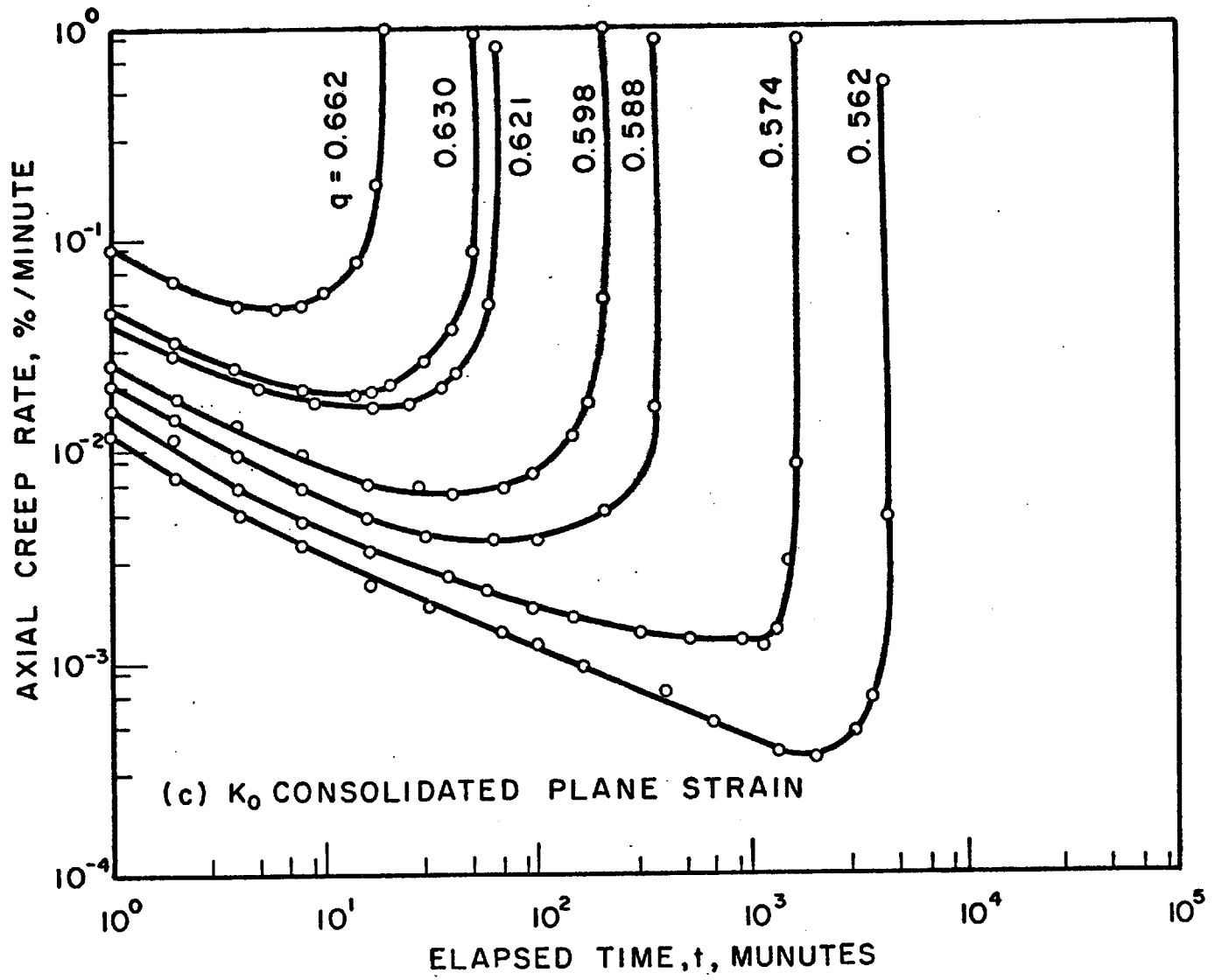


FIG.2. (CONT'D.)

creep rate could be considered constant. It was suggested in Fig. 1 that the creep curves could be divided into primary, secondary and tertiary creep. Fig. 2(a), however, shows that there was no secondary creep region, but was recognised as such on strain-time plot of Fig. 1 because of the scale of the strain axis. A similar observation was made by Snead (1970) in his triaxial creep rupture tests on isotropically consolidated Haney clay. Nevertheless, Fig. 2(a) shows that around the minimum creep rate, the variation in creep rate on either side of the time axis is small and thus the apparent constant secondary creep rate computed from the strain-time plot is essentially the same as the minimum creep rate noted in the creep rate-time plot. This was in fact found to be the case for creep at each stress level in each of the three series of creep rupture tests. Creep rate-time behavior in isotropic triaxial and plane strain series was similar to that in the  $K_0$  triaxial series and is shown in Fig. 2(b) and 2(c).

The results in Fig. 2 suggest that the onset of an accelerating creep rate in constant stress creep rupture tests indicates impending failure, since as long as the creep rate is increasing failure is inevitable. However, sufficient warning concerning rupture was usually present, since regardless of the type of test or the creep stress level, the elapsed time up to rupture was at least 2 1/2 to 3 1/2 times the elapsed time up to the point when the creep rate started accelerating. Fig. 3 shows the axial strain accumulated versus creep stress at the instant of the minimum creep rate. It is interesting to note that except at low stress levels in

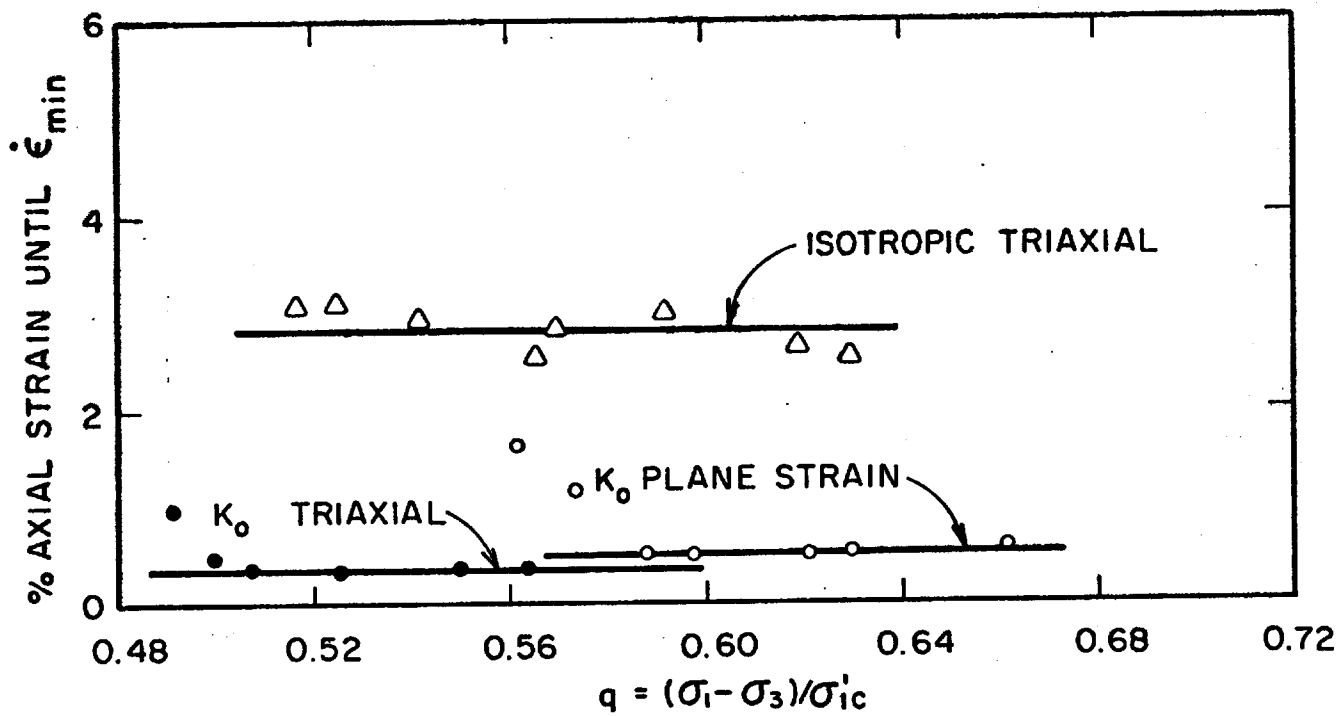


FIG.3. AXIAL STRAIN UNTIL MINIMUM STRAIN RATE AS A FUNCTION OF CREEP STRESS.

the  $K_0$  triaxial and plane strain series, the onset of the accelerating creep rate was characterised by a constant value of axial strain. This constant value of axial strain was essentially the same under  $K_0$  triaxial and plane strain conditions, but was about 6 times larger under conventional triaxial test conditions. A critical value of axial strain in a given type of creep test, thus appears to govern the onset of instability, which eventually leads to rupture failure.

#### Creep Rupture Life:

Rupture represents the terminal point on a creep curve. Hence it must be considered as a component part of the overall creep process, and it is reasonable to consider that the rupture point must be related to the preceding portions or characteristics of the creep curve. One such relation is apparent in Fig. 4, which is a log-log plot of total rupture life,  $t_f$ , against the corresponding minimum creep rate,  $\dot{\epsilon}_{\min}$ . Total rupture life is defined as the total elapsed time from the initiation of creep until final rupture. It is seen that for a given type of test, rupture life is linearly related to minimum creep rate on this log-log plot and the straight lines for the three series of tests are almost parallel to each other. The straight lines for the  $K_0$  triaxial and plane strain conditions are located very close to each other, but that for the isotropic triaxial is situated considerably higher. Thus, for the same minimum creep rate, the rupture life predicted under isotropic triaxial conditions is approximately 4 times larger than under  $K_0$  triaxial conditions. A similar prediction of rupture

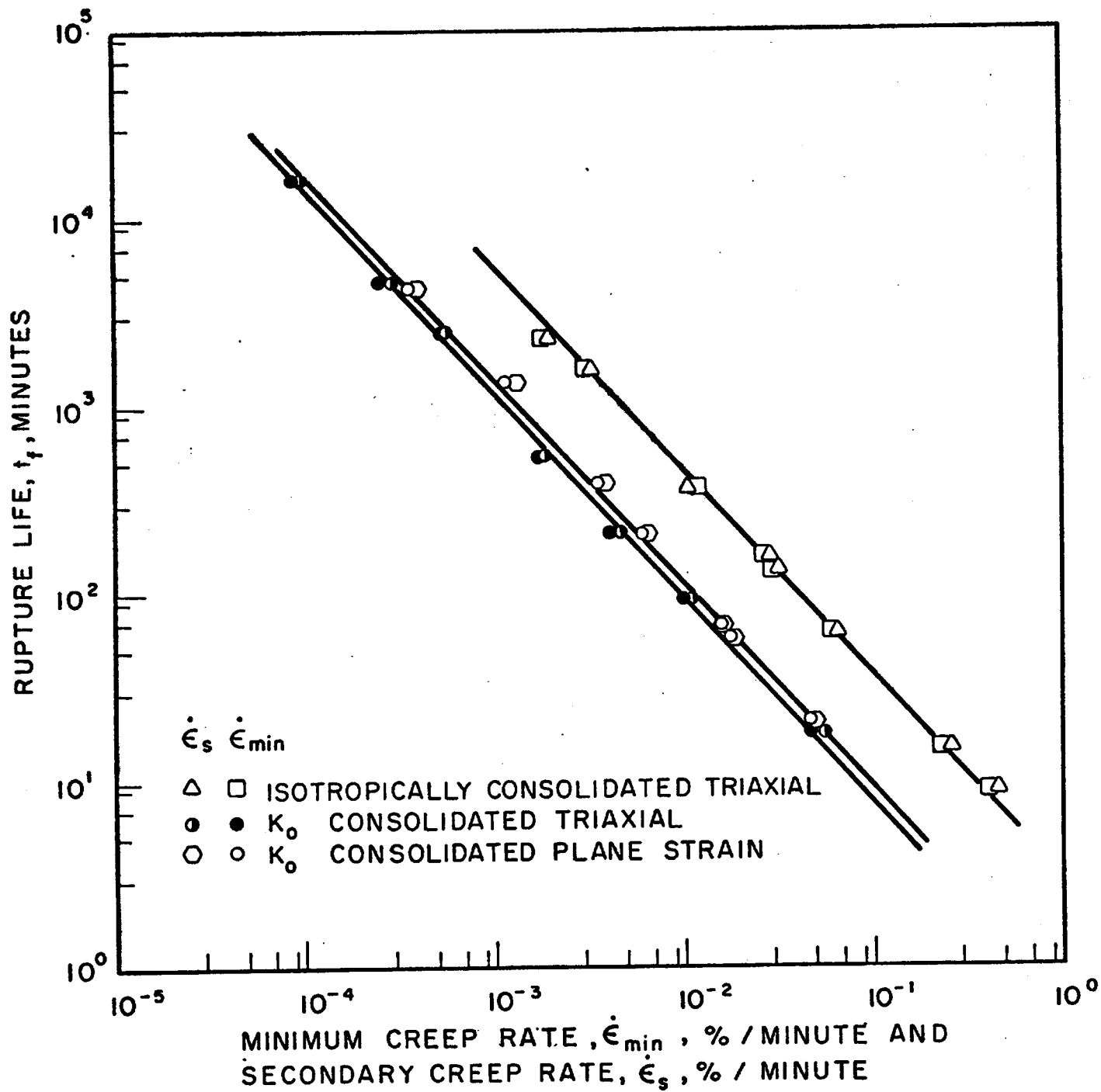


FIG. 4. RELATIONSHIPS BETWEEN RUPTURE LIFE AND MINIMUM CREEP RATE -  
 NORMALLY CONSOLIDATED UNDISTURBED HANEV CLAY.

life under  $K_0$  plane strain conditions does not differ from that under  $K_0$  triaxial by more than 15%. For Haney clay, therefore, the use of conventional triaxial results would lead to unconservative predictions of rupture life if the real situation corresponds to  $K_0$  consolidation or plane strain. Fig. 4 also shows, in addition to the minimum creep rates, the apparent constant secondary creep rates,  $\dot{\epsilon}_s$ , obtained from strain-time plot of each test. As pointed out earlier,  $\dot{\epsilon}_s$  in a given creep test was not too different from the corresponding  $\dot{\epsilon}_{min}$ . Hence the linear relationship between log rupture life and log minimum creep rate could be considered, with little error, the relationship between log rupture life and log apparent constant secondary creep rate. The straight lines in Fig. 4, for Haney clay can be adequately represented by

$$\begin{aligned} [1a] \quad \log_{10} t_f &= -0.214 - 1.09 \log_{10} \dot{\epsilon}_{min} && K_0 \text{ triaxial} \\ [1b] \quad \log_{10} t_f &= -0.142 - 1.07 \log_{10} \dot{\epsilon}_{min} && K_0 \text{ Plane Strain} \\ [1c] \quad \log_{10} t_f &= 0.457 - 1.11 \log_{10} \dot{\epsilon}_{min} && \text{Isotropic triaxial} \end{aligned}$$

where  $t_f$  is in minutes and  $\dot{\epsilon}_{min}$  is in percent per minute.

Linear relationship between log rupture life and log minimum creep rate have also been reported in the creep rupture of metals at elevated temperatures (Monkman and Grant 1956) and plastics (Pao and Marin 1952) as well as for soils with isotropic consolidation history (Saito and Uezawa 1961, Snead 1970). Unfortunately for soils, the tendency to include in a single relationship creep rupture results on various types of clays

with different consolidation histories and drainage conditions has resulted in very wide error bands, which makes such a relation unattractive for making any meaningful estimates of rupture life. For example, the width of the error band reported by Saito and Uezawa (1961) was  $\pm 0.59$  log cycles of rupture time, which implies that for a given minimum creep rate, rupture life could vary by a factor as high as 15. It appears that if the only variable considered is the creep stress level and the consolidation history, drainage conditions, temperature and type of test are held constant, the resulting rupture life - minimum creep rate relation may emerge with little scatter and thus provide a means to make meaningful estimates of rupture life. This was in fact the case for the clay tested, and is evident in Fig. 4.

#### Remaining Creep Rupture Life:

Since it will usually be case in creep problems of earth structures, that the time from the start of creep is not known, Eq. 1 is of little use for making estimates of the remaining creep life. Such estimates would be extremely useful in order to plan remedial measures. No estimate can be made of the remaining life of the sample, if the creep rate is decreasing, and in fact the sample may not fail at all. However, if at the instant considered the creep rate is accelerating, impending failure is indicated. A possible relationship between current accelerating creep rate and remaining rupture life,  $t_{rf}$  (remaining time until rupture), is investigated in Fig. 5, which shows plots of creep strain as a function of log of remaining

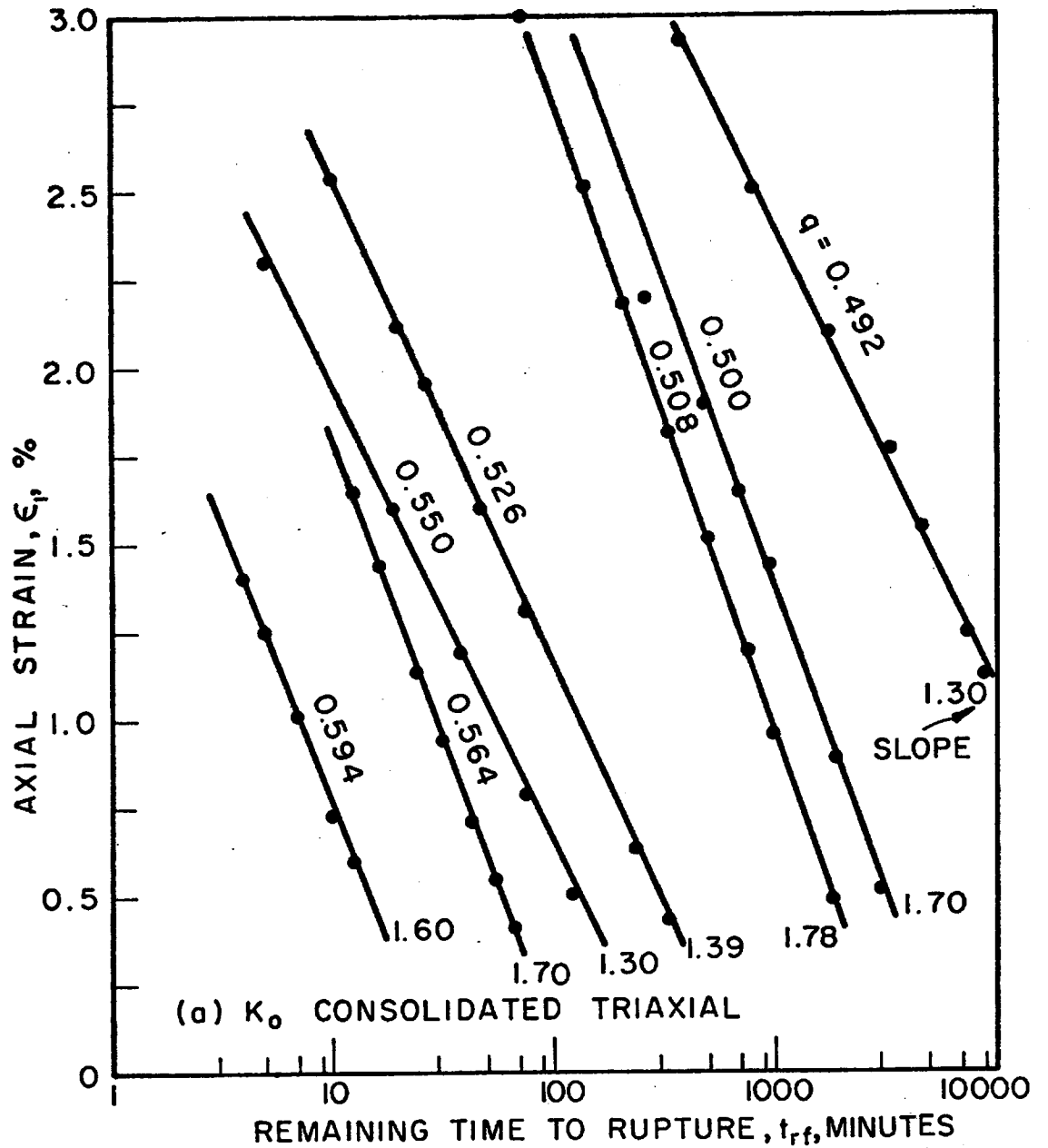


FIG.5. RELATIONSHIPS BETWEEN AXIAL STRAIN AND REMAINING TIME TO RUPTURE DURING TERTIARY CREEP - NORMALLY CONSOLIDATED UNDISTURBED HANEY CLAY.

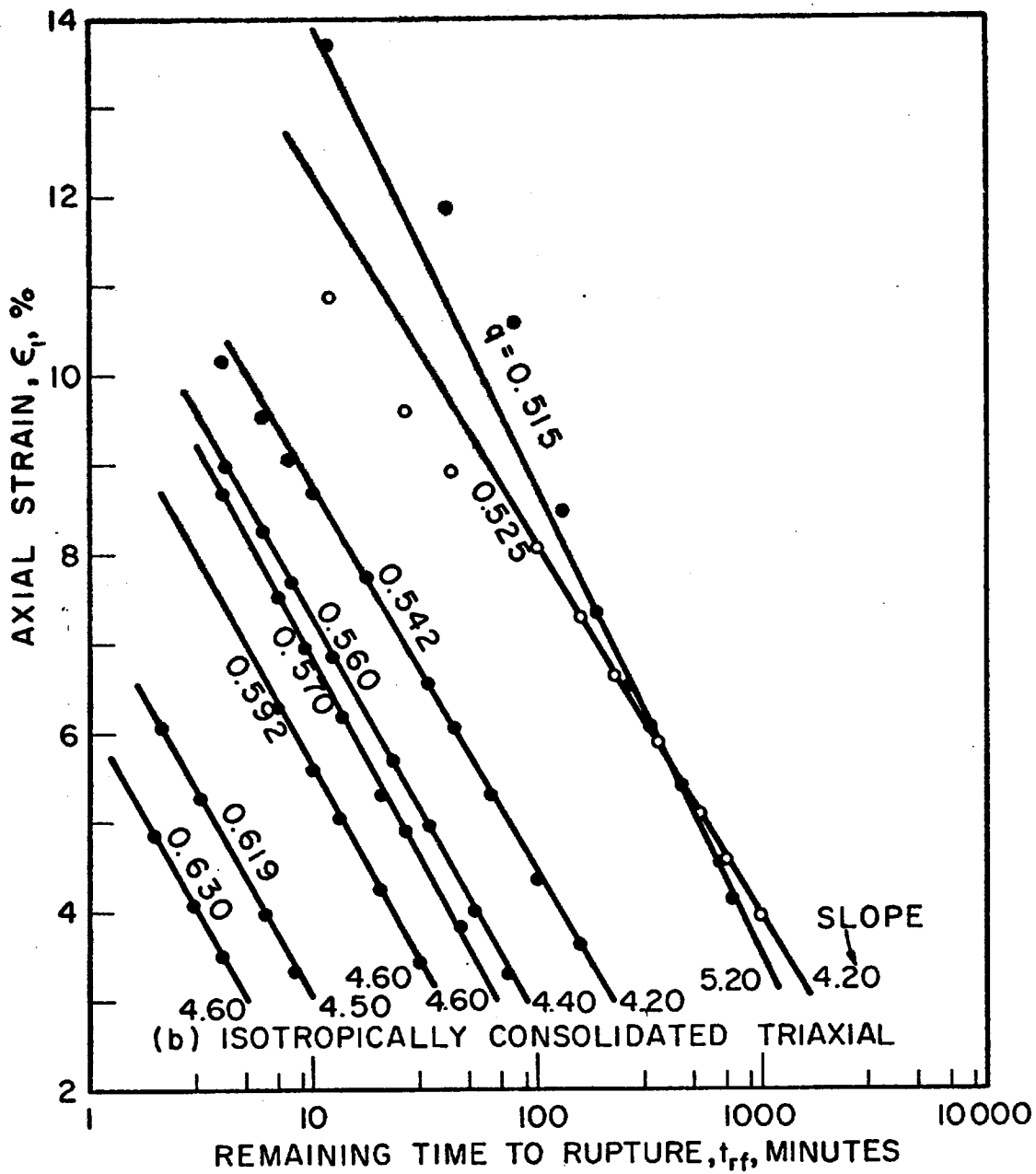


FIG.5. (CONT'D.)

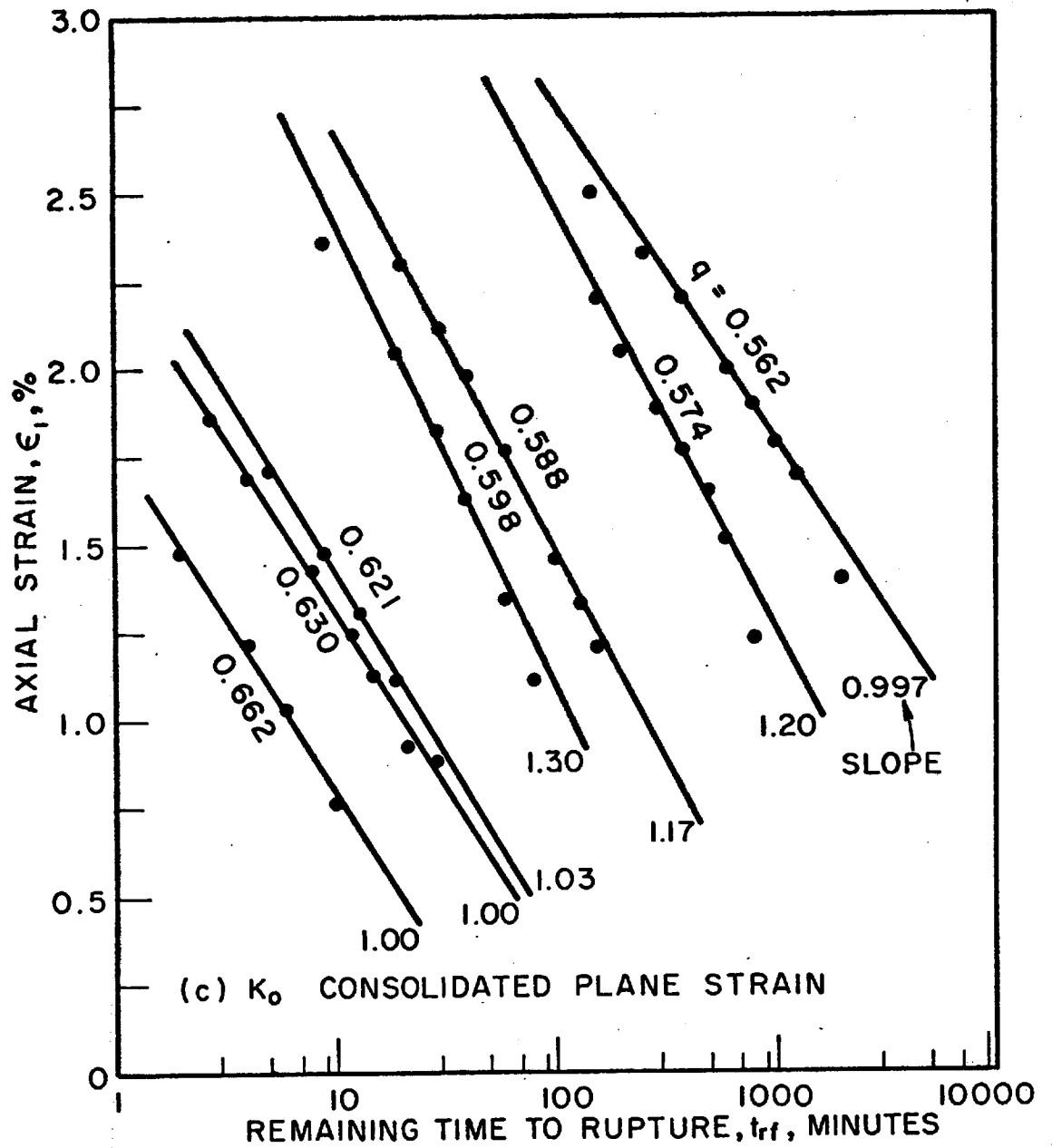


FIG.5. (CONT'D.)

time to rupture. It is seen that for a given type of test, linear relationships are obtained between creep strain and  $\log t_{rf}$  at each creep stress level. The slope of these straight lines for a given type of tests is essentially independent of the stress level; i.e.

$$\frac{d\epsilon_1}{d(\log_{10} t_{rf})} = -k$$

or

$$[2] \quad (\dot{\epsilon}_1)(t_{rf}) = \frac{k}{2.303}$$

Eq. 2 implies that the remaining rupture life is inversely proportional to the accelerating creep rate. The constant  $k$  in Eq. 2 has average values of 1.54, 4.54, 1.10 respectively for the  $K_0$  triaxial, isotropic triaxial and plane strain conditions, when  $t_{rf}$  is in minutes and  $\dot{\epsilon}_1$  is in percent per minute. Thus, for the same accelerating creep rate, predicted remaining time until rupture using isotropic triaxial results would be overestimated by a factor of about 4, if the real situation corresponds to  $K_0$  consolidation and plane strain. However, similar difference between remaining time to rupture for  $K_0$  triaxial and plane strain conditions is not too large and is within the range of scatter inherent in all creep test results. Linear relationships between accelerating creep rate and remaining time to rupture were also observed by Snead (1970) and Saito (1969b) in creep rupture of clays having isotropic consolidation history.

Time Dependence of Undrained Strength:

It was apparent in Fig. 2 that in any given type of creep rupture test, the level of creep stress progressively decreased as the time to creep rupture failure increased. Relationships between creep stress and the corresponding rupture life are shown in Fig. 6. These relationships characterize the process of strength reduction with time under each of the three test conditions. The data in Fig. 6 can easily be approximated by straight lines of best fit, one at the lower stress levels and another at higher stress levels. Thus, depending on the stress range of interest, stress-rupture life data can be expressed by

$$[3] \quad t_f = \exp(mq + c)$$

in which the parameters  $m$  and  $c$  depend on the type of test. Rupture life for any value of  $q$  can therefore be estimated provided appropriate values of  $m$  and  $c$  are known. Results similar to Eq. 3 have been reported in the creep rupture of metals (Finnie and Heller 1959, Rabotnov 1969) under uniaxial and biaxial states of stresses.

As the creep stress decreases, a lower limiting value of this stress is reached, which the sample would be able to sustain for an indefinite time without undergoing rupture. This is usually termed the upper yield strength (Murayama and Shibata 1961). The shape of stress-rupture curves

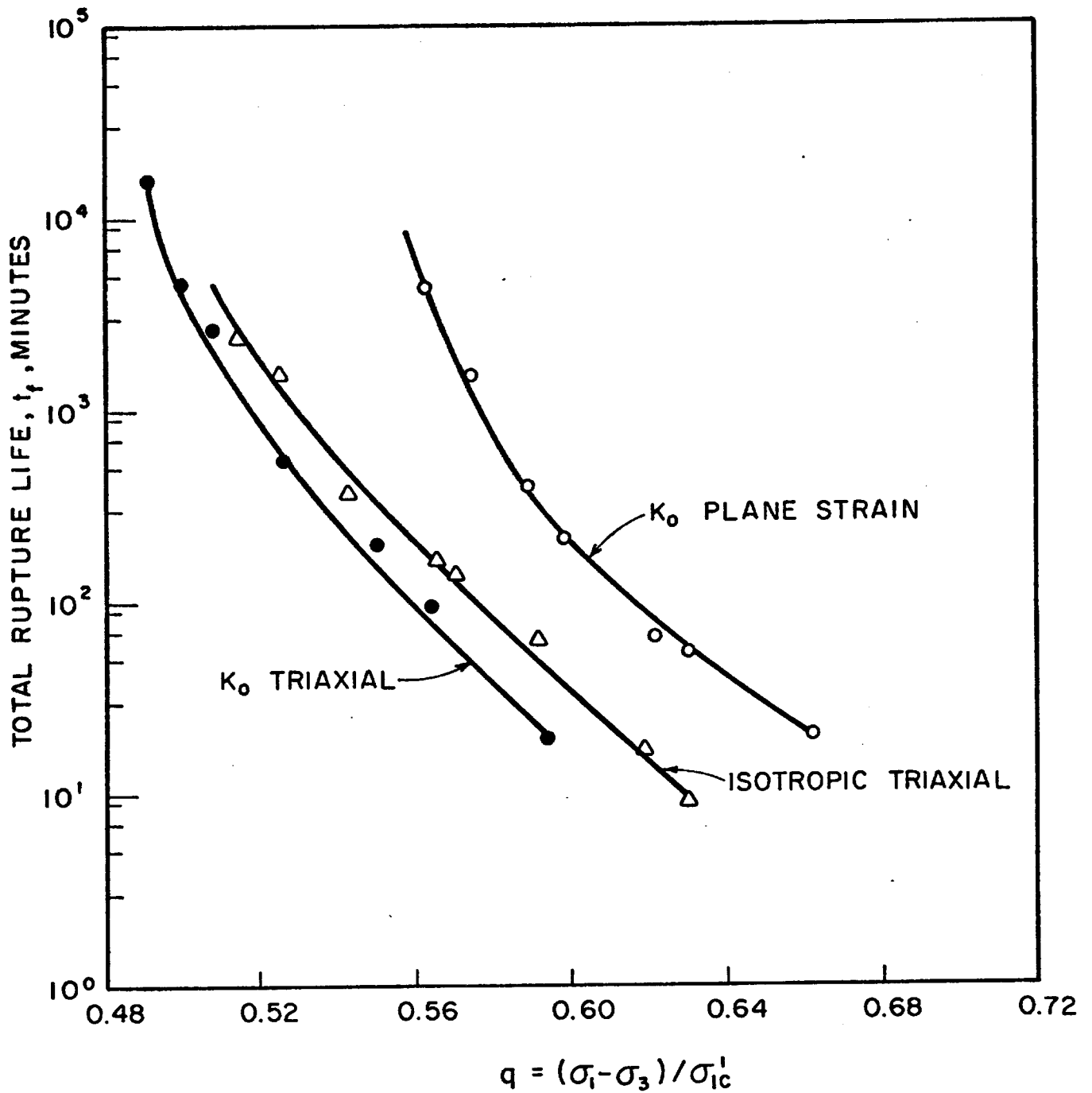


FIG. 6. VARIATION OF CREEP STRENGTH WITH TIME TO RUPTURE - NORMALLY CONSOLIDATED UNDISTURBED HANEY CLAY.

in Fig. 6 does point to an asymptotic approach to an upper yield strength, parallel to the time axis. Snead (1970) suggested a method to evaluate upper yield strength by using the relation

$$[4] \quad q = q_{uy} + K \dot{\epsilon}_{min}^{1/3}$$

where  $q_{uy}$  is twice the upper yield strength and  $K$  is a constant. Values of  $q_{uy}$  as determined in Fig. 7 using Eq. 4 were found to be respectively 0.470, 0.482 and 0.537 for  $K_0$  triaxial, isotropic triaxial and plane strain conditions. Thus, at a creep stress level of  $q = 0.537$ , a test sample would not rupture under plane strain conditions, whereas both the isotropic triaxial and  $K_0$  triaxial samples would rupture in 630 and 230 minutes, respectively. Similarly for  $q = 0.482$ , triaxial samples consolidated isotropically would not creep rupture, whereas similar samples consolidated under  $K_0$  conditions would undergo creep rupture after finite elapsed time. These results emphasize the need to obtain laboratory stress-rupture life information from tests which reproduce the consolidation history as well as the stress changes in a given field problem. Failure to do is likely to result in meaningless prediction of creep rupture life.

In the preceding comparison of stress-rupture life data, the stress parameter,  $\sigma_1 - \sigma_3$ , was normalized with respect to the vertical consolidation stress  $\sigma'_{1c}$ , and the sole purpose was to eliminate, in a given series of tests, small differences in rupture life arising due to slight variations in  $\sigma'_{1c}$  between individual samples. Since  $\sigma'_{1c}$  was essentially identical

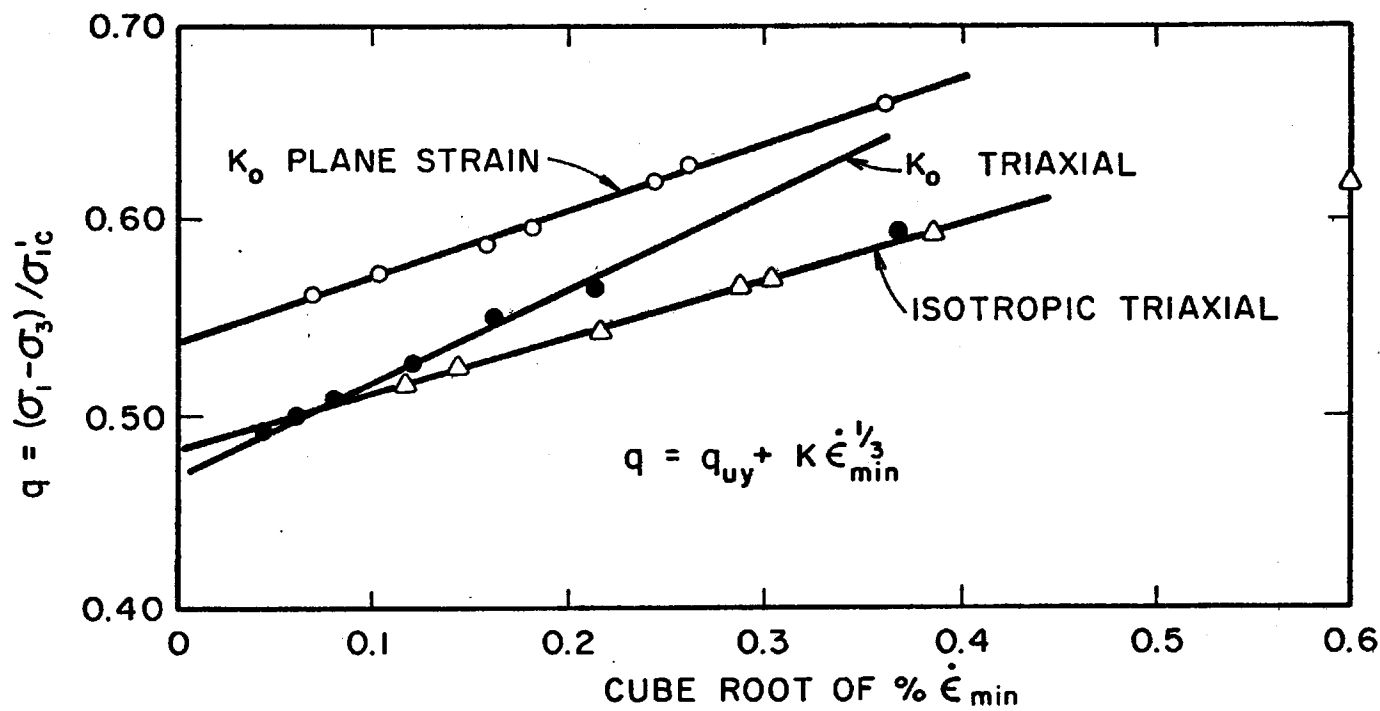


FIG.7. DETERMINATION OF UPPER YIELD STRESSES

for all tests, comparative results presented in Fig. 6 would remain unaltered even if  $\sigma_1 - \sigma_3$  was not normalized. Normalization of stress variables is useful only if samples considered have the same consolidation history and undrained results with different consolidation stresses are to be correlated. For example, the normalized undrained strength  $(\sigma_1 - \sigma_3)/2\sigma_{1c}'$  of a normally consolidated clay is independent of the magnitude of  $\sigma_{1c}'$ . However, its value in general depends on the consolidation history. The ratio of the strength of samples  $K_0$  and isotropically consolidated to the same vertical effective stress can lie between 0.75 and 1.0 (Lambe and Whitman 1969). For Haney clay, this ratio was found to be close to 1.00. Hence for this clay, normalization of creep strength with vertical consolidation stress is justified, as isotropic and  $K_0$  consolidated samples result in the same undrained strength for the same value of  $\sigma_{1c}'$ . Normalization of  $\sigma_1 - \sigma_3$  with mean consolidation stress  $\sigma_{mc}'$ , which is sometimes recommended for comparing results with different stress ratios during consolidation, is usually not justified, because it always predicts too high a strength under anisotropic compared to isotropic consolidation to the same  $\sigma_{1c}'$ .

For the same value of  $q$ , the difference between the rupture lives of  $K_0$  triaxial and plane strain samples may arise entirely due to the difference in their states of stress. Both these samples have an identical consolidation history, but the state of stress under triaxial conditions is uniaxial ( $\sigma_1 > \sigma_2 = \sigma_3$ ) as opposed to a multiaxial stress state ( $\sigma_1 > \sigma_2 > \sigma_3$ ) under plane strain conditions. In the study of creep rupture of certain metals under multiaxial states of stress, the octahedral shear stress,

$$[5] \quad \tau_{\text{oct}} = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

has been found to govern creep rupture life (Odquist 1972). During triaxial creep tests with  $q = \text{constant}$ ,  $\tau_{\text{oct}}$  also stays constant, since under this stress state  $\tau_{\text{oct}}$  is a constant multiple of  $q$ . However, in plane strain creep tests with  $q = \text{constant}$ , the intermediate principal stress,  $\sigma_2$ , continuously increases until rupture, and since  $\sigma_1, \sigma_3$  are both held constant,  $\tau_{\text{oct}}$  decreases. Therefore, plane strain tests do not correspond to constant  $\tau_{\text{oct}}$  creep test. In order to relate rupture life to  $\tau_{\text{oct}}$  an appropriate account must be taken of decreasing creep stress ( $\tau_{\text{oct}}$ ) under this test condition. No satisfactory method has so far been proposed, even in the creep rupture of metal, to take account of the influence of varying stresses on rupture life. Therefore, the question of relating rupture lives to octahedral stresses was not pursued further.

#### Creep Rupture in terms of Effective Stresses:

The creep rupture behavior of clays has generally not been analyzed in terms of effective stresses. It is often argued that around rupture when strain rates are high, the measured pore pressure at sample ends may not be representative of that existing in the failure zone. Thus, computations of effective stress parameters may be in error. Lo (1961, 1969) however, has shown that during undrained shear of normally consolidated clays the pore pressure developed was uniquely related to axial strain, and in particular independent of the rate at which this strain accumulates. His conclusions regarding the influence of strain rates on pore pressure were based on constant strain rate tests.

The influence of strain rate on triaxial shear induced pore pressure for isotropically consolidated Haney clay is shown in Fig. 8. Pore pressure generated during shear at constant rate of strain and during creep under constant stress is plotted as a function of axial strain. In the constant stress creep test, the axial strain accumulates at widely varying strain rates (see Fig. 2 for typical range of rate variation) in contrast to the constant rate of accumulation in constant rate of strain test. It can be seen in Fig. 8 that pore pressure-strain plot was essentially identical for the two tests, which confirms Lo's conclusions of dependence of undrained pore pressure on axial strain only and independence of past strain rate history.

Thus it appears that the accuracy of pore pressure measurements near rupture is probably acceptable. Furthermore, the rate of change of pore pressure with strain at strain levels approaching rupture failure was very small (Fig. 8), and in the absence of any observed discontinuity in pore pressure-strain curve in creep rupture test, particularly when rupture was approaching, acceleration of strain rates cannot possibly lead to any nonuniformity of pore pressure. Therefore effective stress parameters computed in the neighborhood of rupture failure can be considered reliable.

In conventional strain controlled shear tests, the failure condition of a saturated normally consolidated clay is characterized by a linear effective stress Mohr envelope. Since the shear resistance of a normally consolidated clay depends only on effective-stresses, the same linear

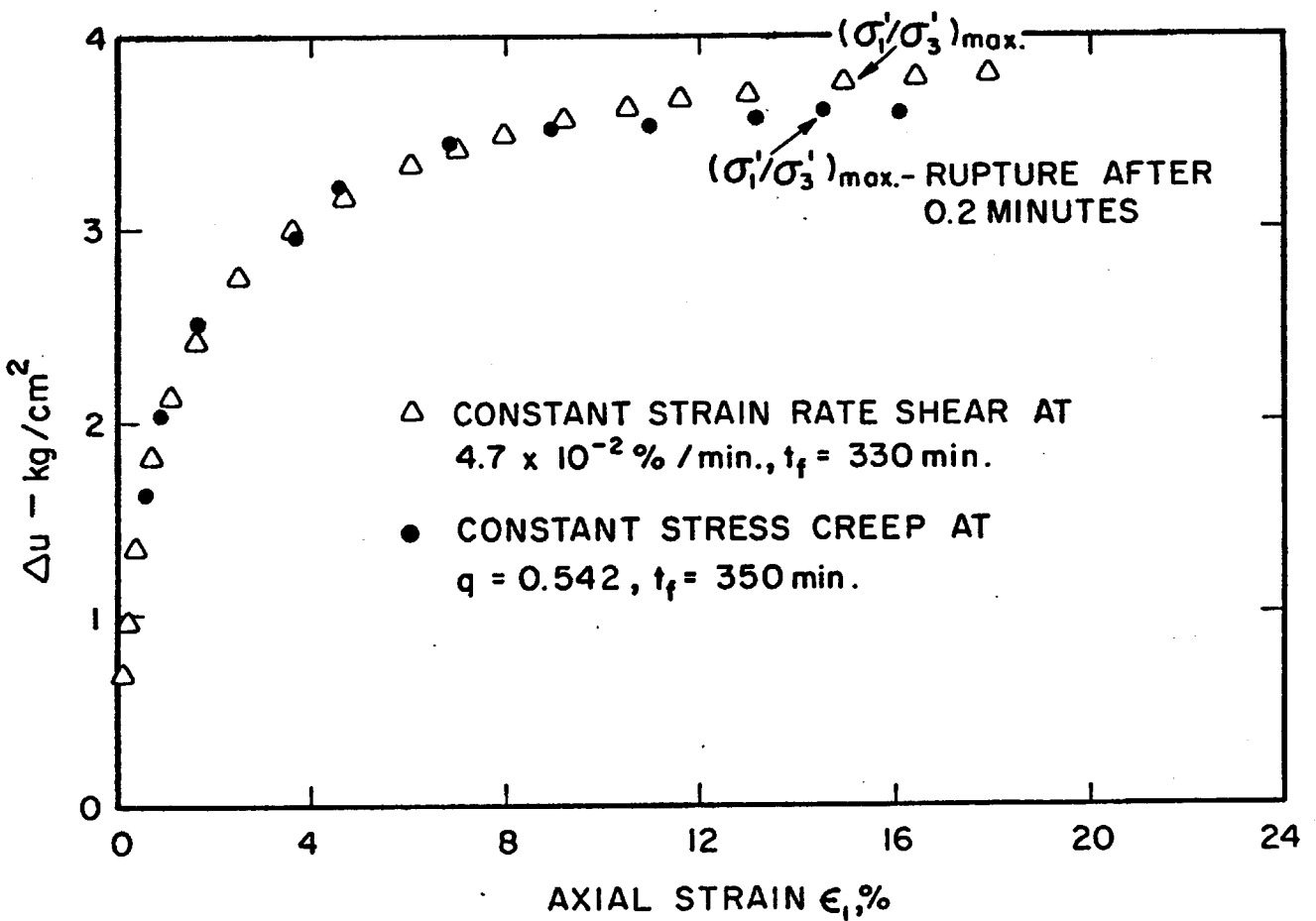


FIG.8. INFLUENCE OF STRAIN RATE HISTORY ON SHEAR INDUCED PORE PRESSURE - ISOTROPICALLY CONSOLIDATED UNDISTURBED HANEY CLAY.

envelope may also apply at creep rupture, as the nature of shear failure in strain controlled shear and creep rupture should be similar. The preceding argument is based on the assumption that the rheological component of shear resistance (Hvorslev 1960) is negligible. Fig. 9 shows the effective stress failure envelopes under each of the three test conditions corresponding to the instant of maximum mobilized friction ( $\max. \sigma_1'/\sigma_3'$ ). These envelopes were obtained from conventional strain controlled undrained shear tests. Also shown by data points in Fig. 9 are the effective stress conditions at the instant of maximum mobilized friction in creep rupture tests. This condition invariably occurred a few minutes before actual rupture (see Fig. 8). It can be seen from the coincidence of data points with the corresponding linear envelopes, that the effective stress failure in creep rupture and constant strain rate shear was indeed characterized by a unique failure envelope. Failure envelopes for plane strain and isotropic triaxial test conditions were virtually coincident, with  $K_0$  triaxial envelope located slightly lower. This may be due either to differences in initial consolidation histories or to the nature of stress changes during shear.

Fig. 10 shows the magnitude of axial strain at the instant of  $(\sigma_1'/\sigma_3') \max.$  during creep. As mentioned previously, occurrence of  $(\sigma_1'/\sigma_3') \max.$  and actual creep rupture was essentially coincident. For a given test type, irrespective of the creep stress level, rupture occurred at approximately the same magnitude of axial strain, which was equal to the failure strain in conventional constant strain rate undrained shear tests. This lends additional support to the fact that the effective stress failure phenomenon in creep rupture and

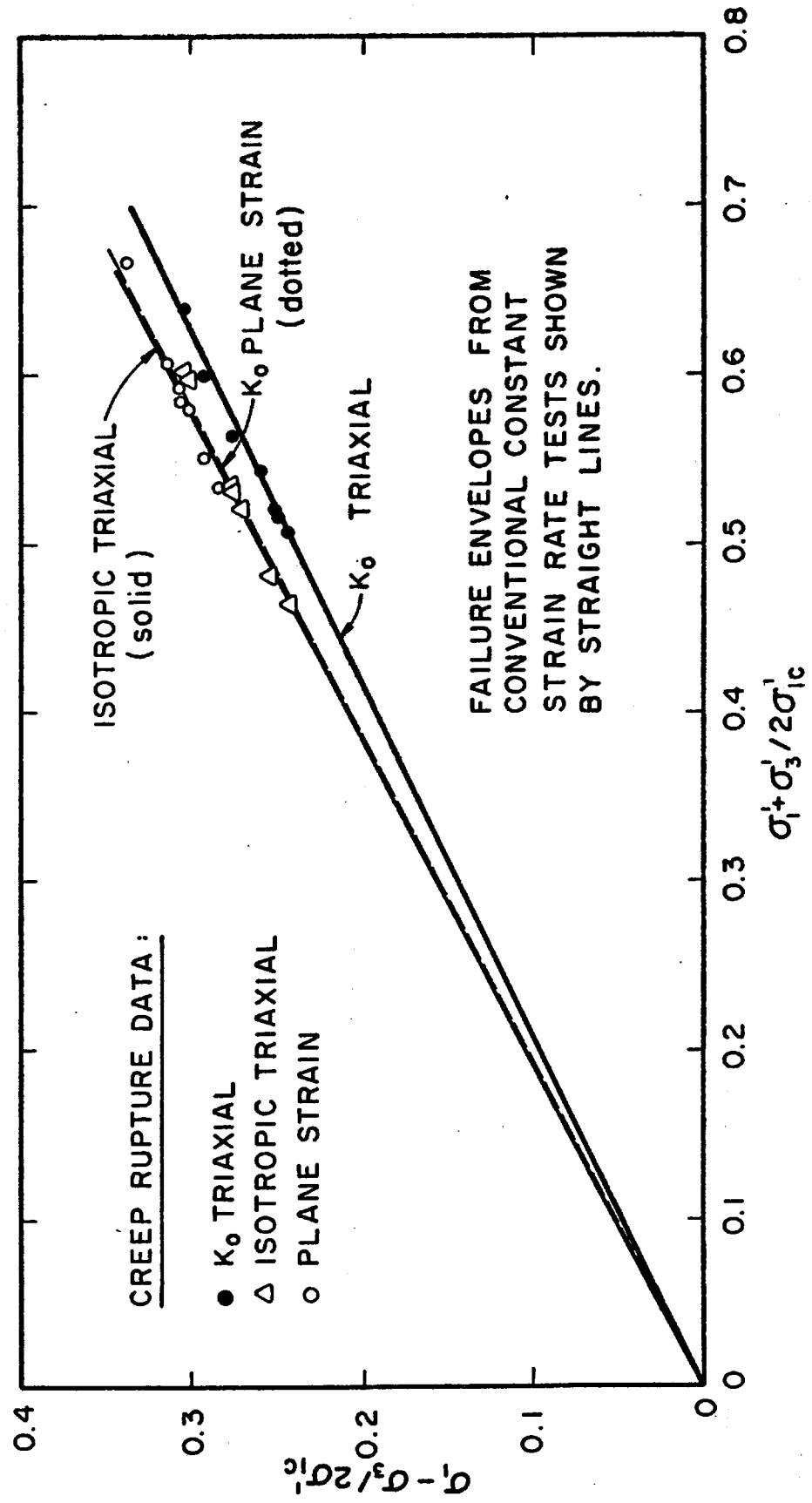


FIG.9. EFFECTIVE STRESS CONDITIONS AT CREEP RUPTURE

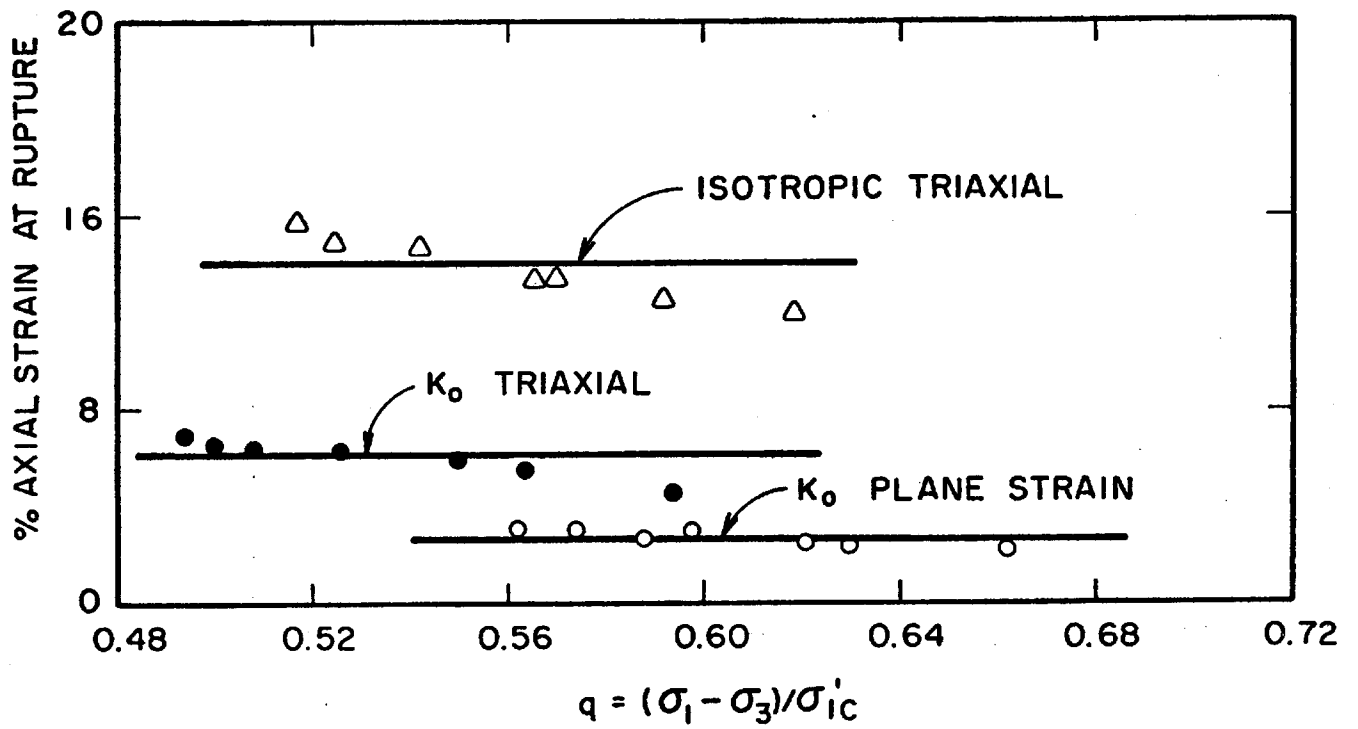


FIG.10. AXIAL STRAIN AT CREEP RUPTURE

conventional shear at constant rate of strain was similar. The magnitude of axial strain at creep rupture, however, was dependent on the test type. Plane strain rupture occurred at the smallest axial strain (approx. 3%) followed by a larger failure strain under  $K_0$  triaxial (approx. 6%) and finally the largest failure strain for isotropic triaxial (approx. 14%).

## Conclusions

Based on a comparison of  $K_0$  triaxial, conventional isotropic triaxial and  $K_0$  plane strain undrained creep rupture test results on a saturated, normally consolidated, marine clay, the following conclusions can be drawn:

1. For a given test type, linear relationships exist between log minimum creep rate and log rupture life and also between log current tertiary creep rate and log remaining time to rupture. However, for the same creep rate, the conventional isotropic triaxial test would result in an unconservative estimate of rupture life or remaining time to rupture by a factor of about 4 if the real situation corresponds to  $K_0$  consolidation or plane strain.
2. For a given creep stress,  $K_0$  triaxial conditions result in the smallest creep rupture life and  $K_0$  plane strain the largest. Due to these differences in stress-rupture life relationships, a meaningful estimate of rupture life can only be obtained by duplicating in the laboratory the in situ consolidation and creep stress changes.
3. In terms of effective stresses, both creep rupture and failure in conventional constant strain rate shear tests are defined by a unique linear failure envelope. These failure envelopes were slightly different for each of the three types of tests.

## List of References

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## Appendix I - Notation

$K_0$  = coefficient of earth pressure at rest;

$\sigma_1, \sigma_2, \sigma_3$  = major, intermediate and minor principal stresses respectively;

$\sigma_1, \sigma_3$  = major and minor principal effective stresses respectively;

$\sigma_{1C}, \sigma_{2C}, \sigma_{3C}$  = major, intermediate and minor consolidation stresses respectively;

$\sigma_{mc}$  = mean consolidation stress =  $\frac{1}{3}(\sigma_{1C} + \sigma_{2C} + \sigma_{3C})$ ;

$\tau_{oct}$  = octahedral shear stress;

$q = (\sigma_1 - \sigma_3) / \sigma_{1C}$  ;

$\epsilon_1$  = axial strain;

$\dot{\epsilon}_{min.}$  = minimum creep rate;

$\dot{\epsilon}_S$  = secondary creep rate;

$t_f$  = total rupture life;

$t_{rf}$  = remaining time to rupture;

$q_{uy}$  = upper yield strength.