#13

TIME-DEPENDENT BEHAVIOR OF AN UNDISTURBED CLAY

by Y.P. Vaid and R.G. Campanella

SUMMARY: The effects of strain rate, strain rate history, aging and thixotropy on the stress-strain and strength behavior of a natural clay has been studied. Results from tests with a variety of time loading histories are correlated using current rate of deformation as the unifying time variable.

KEY WORDS: Aging, Clays, Creep, Geotechnical Engineering, Shear strength, Strains, Strain rates, Stresses, Thixotropy, Time, Triaxial tests, Upper yield.

ABSTRACT

Time dependence of undrained stress-strain and strength behavior of a natural, sensitive marine clay has been investigated with particular reference to the effects of strain rate, strain rate history, aging and thixotropy. Triaxial samples, identically consolidated, were sheared under a variety of time loading histories in order to simulate various deformation rate histories. The stress-strain and strength results from these tests were correlated using the hypothesis that stress is a function of current strain and strain rate only. It is shown that a stiffer stress-strain response and an increase in undrained strength results from an increase in rate of strain, length of aging and thixotropic hardening. However, the failure in terms of effective stresses is found to be independent of time effects of any kind whatsoever.

TIME-DEPENDENT BEHAVIOR OF AN UNDISTURBED CLAY

by Yoginder P. Vaid* and Richard G. Campanella[†], M.ASCE

INTRODUCTION

Both strength and deformation behavior of clays is time-dependent. Several investigators (1,2,3,6,8,9,15,16,18) have shown that the undrained strength measured in the laboratory during the conventional shear tests depends on the speed of testing; the increase in strength with speed of testing being more pronounced in clays with higher plasticity index. Similar time effects are observed during creep loading, where deformation increases under constant applied stresses and the rupture life decreases as the level of creep stress increases (7,8,11,14,17). In general, the stress-strain and strength response of a clay is a function of the time history of loading or deformation. No attempt has so far been made to correlate stress-strain-strength behavior from test results with different time deformation histories.

Bjerrum (4) pointed out the importance of time effects in the interpretation of field vane strength data. He showed that, the vane strength must be corrected for rate effects for accurate prediction of end of construction failures. Reduction in undrained strength due to creep effects was apparently the cause for the failure of an underwater slope (10). It is clear that the rate effects on undrained strength are of considerable practical importance.

Aging and thixotropic hardening are other forms of time effects which influence the undrained shear behavior (5,12). Aging refers to the length of time for which a clay sample is left to consolidate before shear. Thixotropic hardening is the build up of shear resistance under a prolonged rest period

---

* Associate Professor of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada.

formerly, Research Associate, University of British Columbia, Vancouver, B.C.

† Professor of Civil Engineering, University of British Columbia, Vancouver, B.C. Canada.

at constant composition (13). Natural clay deposits are aged and thixotropically hardened for several years. It is therefore important to determine the influence of these variables for a rational assessment of the field undrained strength and stress-strain response.

The study reported herein is concerned with the influence of rate of deformation and other time effects on the undrained stress-strain and strength characteristics of an undisturbed, saturated, sensitive marine clay. Normally consolidated samples of this clay were sheared under triaxial test conditions using a variety of deformation or loading rate histories. The type of tests carried out consisted of conventional constant rate of strain shear, constant stress creep, variable stress creep and constant rate of loading shear among others. The stress-strain and strength results from these tests were correlated by introducing rate of deformation as a unifying variable. Furthermore, the effect of aging and thixotropic strength gain was studied, though on a limited scale.

EXPERIMENTATION

A local undisturbed clay (called Haney Clay) was used for this study. Haney clay is believed to have been deposited in a marine environment and later subjected to partial leaching due to surface infiltration. It is a grey silty clay with liquid limit = 44%, plastic limit = 26%, maximum past pressure about 3.5 kg/cm^2 (340 kPa) and a sensitivity from 6 to 10. The clay was block sampled from an open pit and all the test samples were trimmed from blocks obtained from the same horizon. This ensured the least variation among individual samples.

All test samples were normally consolidated under an all round pressure of approximately 5.25 kg/cm^2 (515 kPa). Consolidation was allowed for a period of 36 hours except in the series of samples tested for effects of aging, where consolidation time up to 48 days was used. Samples were left undrained for 12 hours under the consolidation stresses prior to shear loading. Most of the pore pressure generated due to the arrest of secondary consolidation was developed during this undrained period and thus the pore pressure measured during the shearing stage was not influenced by secondary compression effects. Later in the study some tests were carried out on samples consolidated under an all round pressure of 6.25 kg/cm^2 (615 kPa) in order to investigate the existence of normalised shear behavior.

For study of rate effects, a variety of time histories of loading (Fig. 1) were imposed on identical sample in order to include various types of deformation rate effects. Constant stress creep rupture loading (1) results in an intially decreasing deformation rate which is later followed by an accelerating rate of loading to rupture. Subfailure level creep loading gives a continuously decreasing deformation rate. Deformation rate history imposed in constant load creep (2) is similar to that in constant stress creep. A continuously increasing rate history with time was imposed in constant rate of loading shear (3). Conventional constant rate of strain shear (4) imposes a constant deformation rate history. Some types of loading,e.g. step creep (5) and step change in constant rate of strain (6) were also carried out in order to simulate a discontinuity in deformation rate history.

In order to study the effect of aging, a series of samples was consolidated for periods ranging from 1.5 days to 48 days. They were subsequently sheared under conventional constant rate of strain.

A set of samples was subjected to subfailure creep loadings. When the deformation had essentially ceased, they were left undisturbed for an extended length of time, after which a constant rate of deformation was imposed to induce failure. These tests were designed to demonstrate the thixotropic hardening effects.

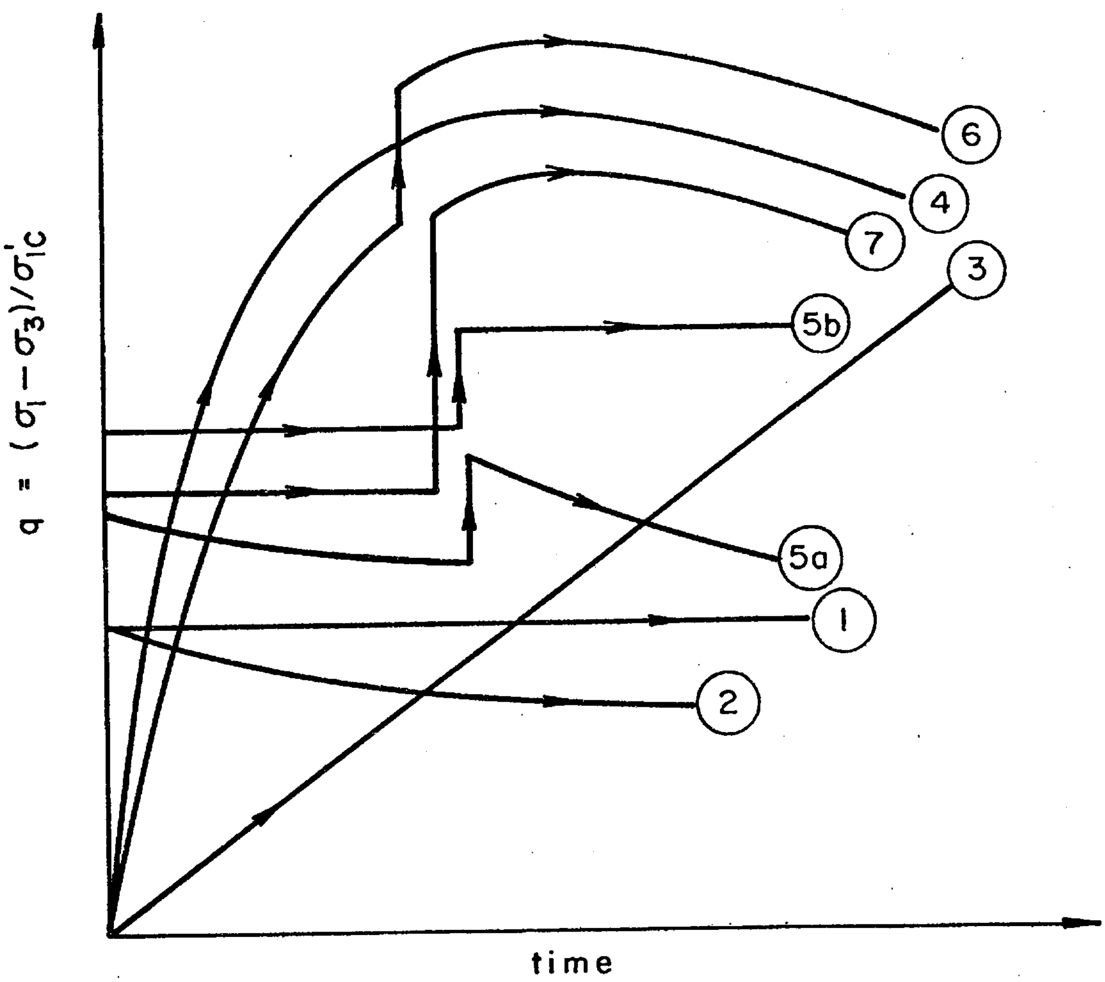

FIG. 1 **TIME HISTORIES OF LOADING**

1. constant stress creep
2. creep under decreasing stress – constant load creep
3. constant rate of loading
4. constant rate of strain
5. step creep
   a) constant load
   b) constant stress
6. constant rate of strain shear with step increase in rate
7. constant stress creep followed by constant rate of strain

All measurements were done electronically and the test data were automatically recorded on a digital magnetic tape using a high speed Vidar Digital Data Aquisition System. High speed automatic recording (10 channels per second) is particularly useful to enable accurate measurements especially when the sample deformation rates are high. The test program was carried out in a constant temperature environment (maximum temperature variation ± 0.25°C) in order to eliminate the influence of temperature on deformation rates and pore pressure measurements.

TEST RESULTS

Constant rate of strain:

The influence of variation in the constant rate of strain on the resulting stress strain response is shown in Fig. 2. Curves for only a few typical strain rates are shown. The deviator stress $q = (\sigma_1 - \sigma_3)/\sigma'_{1c}$ has been normalized with respect to the consolidation pressure. Fig. 2 shows that the stress-strain relation for Haney Clay is dependent on the rate of strain. The peak deviator stress at the fastest rate was as much as 30% larger than the corresponding value at the slowest rate. It is interesting that the axial strain at peak deviator stress was essentially independent of the rate of strain and was in the neighbourhood of 2.5 to 3%. Similar results have been reported for undisturbed Mexico City Clay (1).

Fig. 3 shows the variation of undrained strength, q_m , with rate of strain. (Constant stress creep results will be discussed later). There was essentially a linear increase in undrained strength with the log of strain rate in the region of higher rates. However, in the domain of low strain rates, a lower limit of undrained strength (commonly called upper yield) was approached and a further reduction in rate did not result in additional loss in strength.

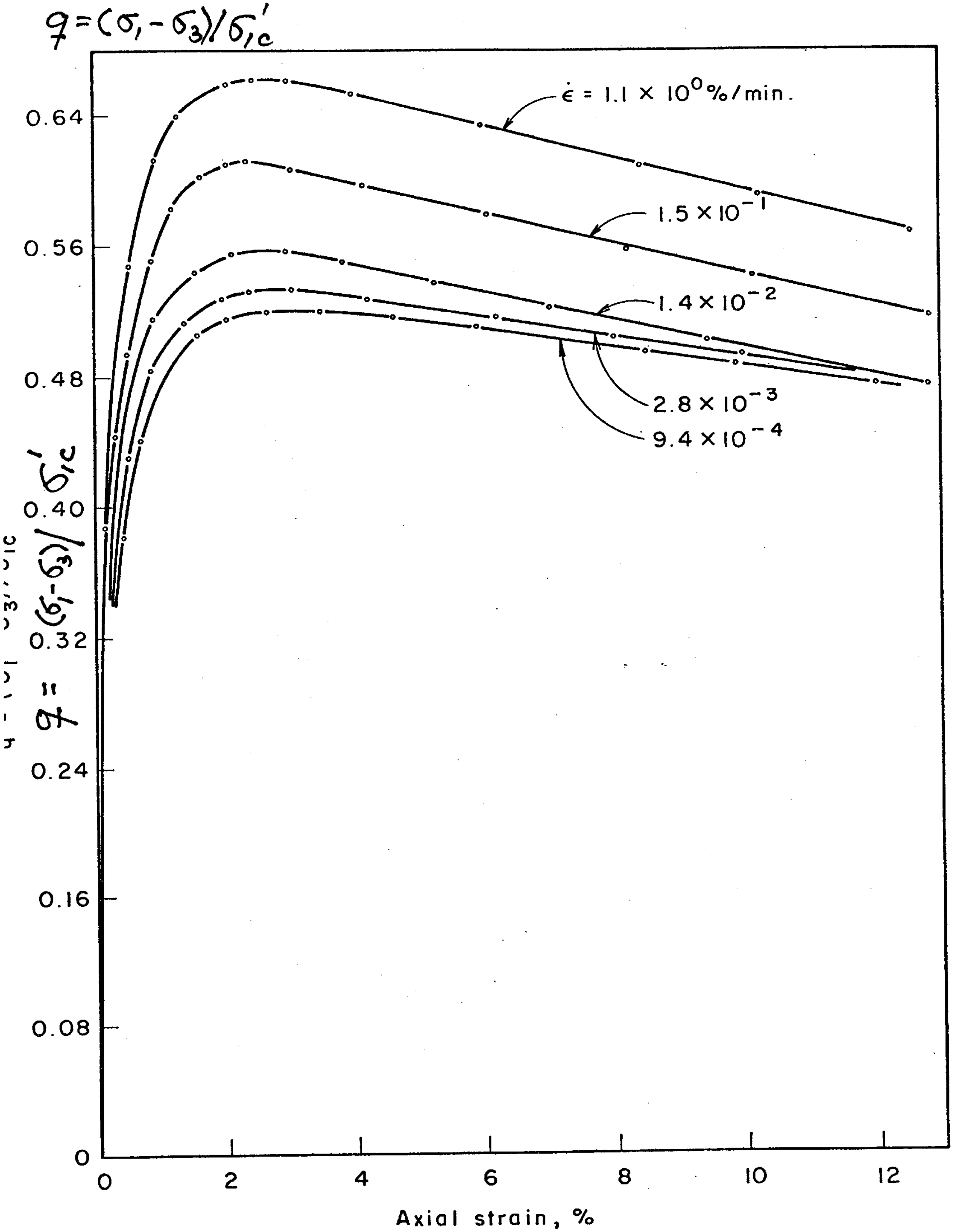

FIG. 2 INFLUENCE OF RATE OF STRAIN ON UNDRAINED STRESS-STRAIN BEHAVIOUR IN CONSTANT RATE OF STRAIN SHEAR.

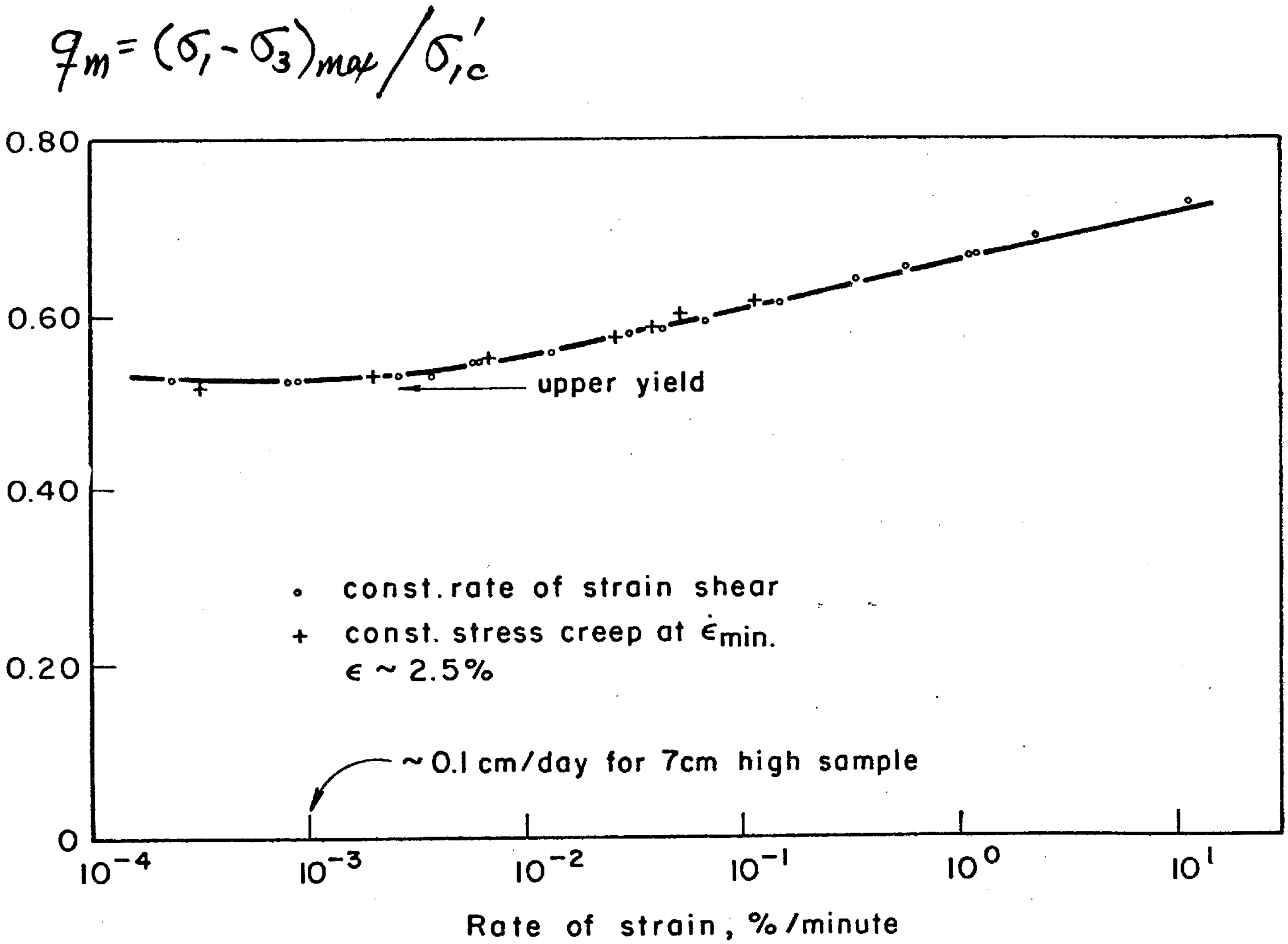

FIG. 3 STRAIN RATE DEPENDENCE OF UNDRAINED STRENGTH IN CONSTANT RATE OF STRAIN SHEAR AND CONSTANT STRESS CREEP.

Rate dependence of undrained strength of saturated clays has been reported by many investigators (1,2,3,6,8,9,15,16,18). In most cases the strength increased by 5 to 10 percent for an 10 fold increase in rate of testing and the phenomenon was observed in both normally and overconsolidated clays, undisturbed or remolded. The Haney clay tested showed a high increase in strength (approximately 10 percent per log cycle of strain rate) in the region of higher strain rates. Similar results were reported by Berre and Bjerrum (2) for an undisturbed Norwegian clay.

Constant stress creep:

The constant stress creep behavior of Haney clay under isotropic triaxial test conditions has been reported earlier (7). However, since a different 'batch' of clay was used in the present study, a new series of tests was carried out in order to be consistent with the data from other types of tests. The results of this new series (Fig. 4) were essentially identical to those reported in the earlier publication (7).

The development of axial strain with time at various levels of creep stress, q, is shown in Fig. 4. For stress levels q = 0.518 and larger, the samples progressively strained with time until eventual rupture. Under stress levels q = 0.500 and lower, a continuously decreasing deformation rate was noted until an elapsed time up to 2 to 3 weeks when the tests were terminated. The time history of deformation rates (axial strain rate) in this series of creep tests is illustrated in Fig. 5, which was derived by differentiating strain time plots of Fig. 4. For samples which eventually failed, the deformation rate initially decreased until a minimum value was reached before its subsequent acceleration leading to rupture. Samples which did not rupture showed a continuous decreasing deformation rate with time.

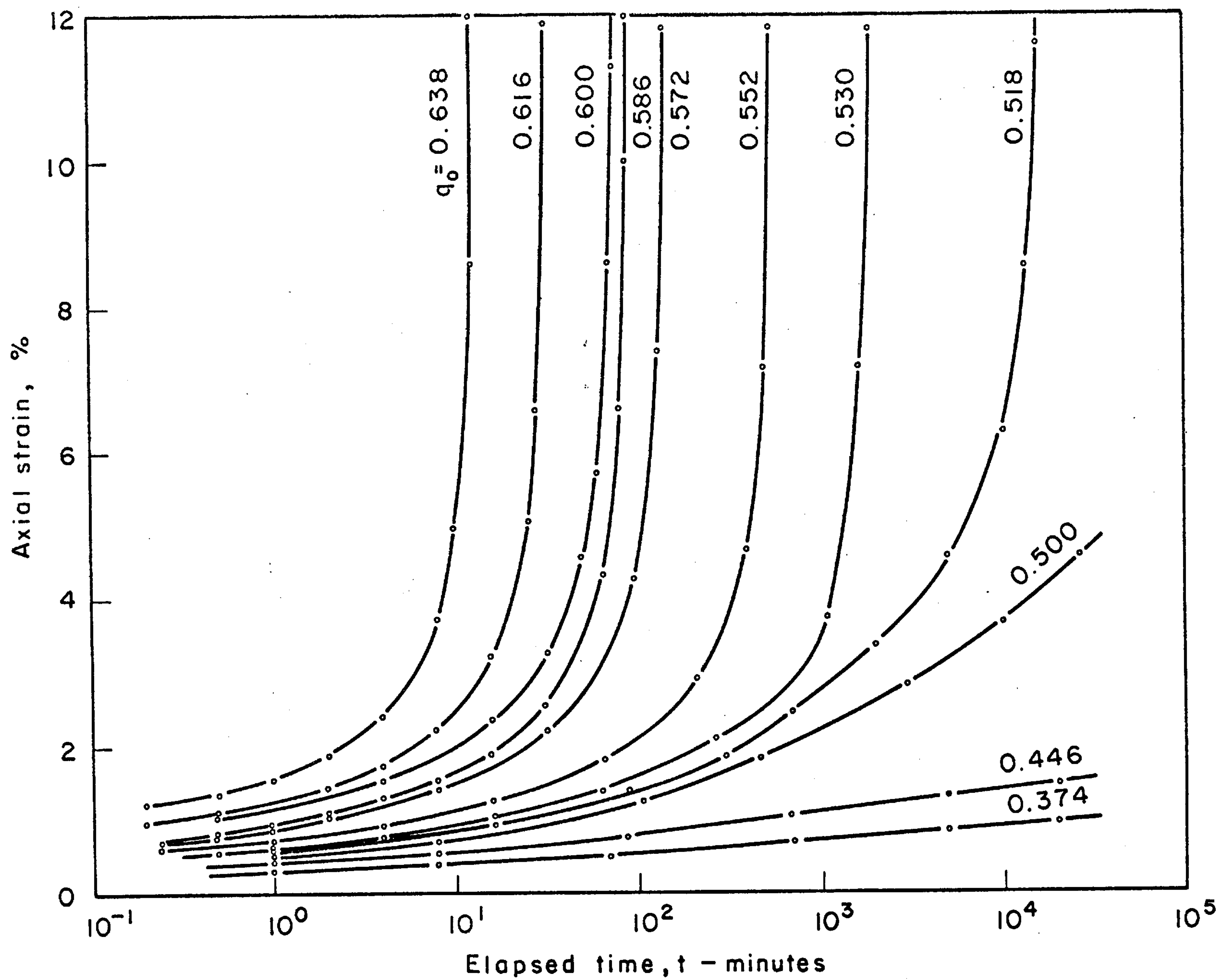

FIG. 4 RESULTS OF CONSTANT STRESS CREEP TESTS ON UNDISTURBED HANEY CLAY.

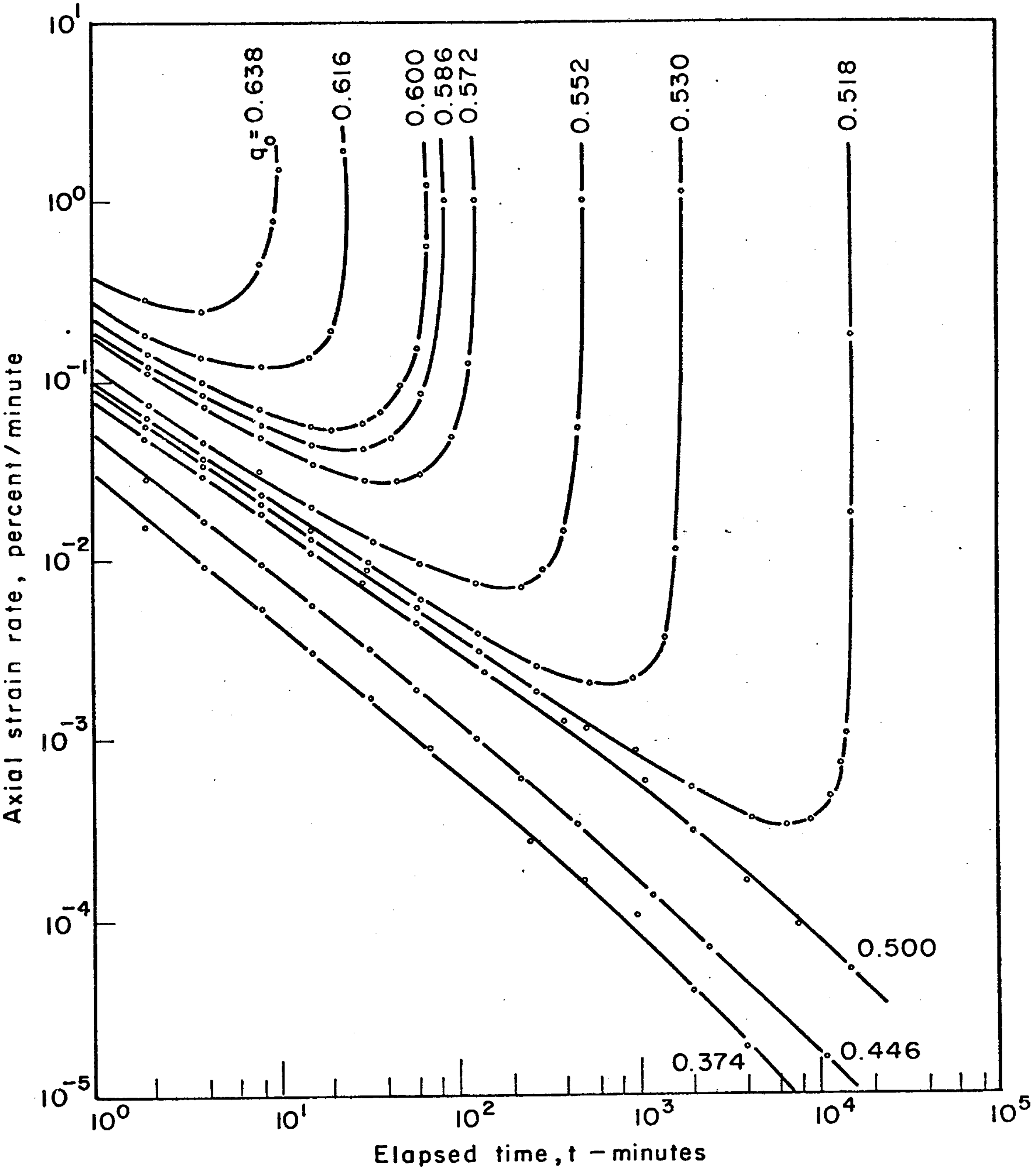

FIG. 5 VARIATION OF CREEP RATE WITH TIME IN CONSTANT STRESS CREEP.

Fig. 6 shows the variation of rupture life (time from the initiation of creep until final collapse) with creep stress. The data also includes the results of tests with higher consolidation stresses. It may be seen that the use of normalized creep stress q, instead of the deviator stress, $\sigma_1-\sigma_3$, results in a unique relationship between creep stress and rupture life which is independent of the consolidation pressure.

Fig. 6, in effect, represents the process of reduction of undrained strength with time. A given level of stress cannot be sustained by the soil for more than a fixed time without undergoing collapse. However, the shape of the stress-rupture life relationship tends to be asymtotic to the time axis, indicating the existence of an upper yield strength below which creep rupture will not occur. If it is assumed that the sample with q = 0.500 (which did not rupture in about 3 weeks) will never rupture, then the upper yield strength value would lie between this q = 0.500 value and the next higher value of q = 0.518, under which creep rupture occurred in the longest observed time in the laboratory. It is also interesting that when the minimum strain rates, $\dot{\varepsilon}_{min}$, and corresponding stress levels, q, given in Fig. 5 are plotted on Fig. 3, they correspond closely with the results of constant rate of strain tests and the same value of upper yield strength is predicted. This comparison will be discussed further in a later section.

Constant Load Creep:

Constant load creep represents creep under stresses decreasing with time. Test samples in this series of tests were instantaneously loaded with pre-determined loads which were held constant with time. As the deformation progressed, the sample area increased, thereby resulting in a continuous decrease in creep stress.

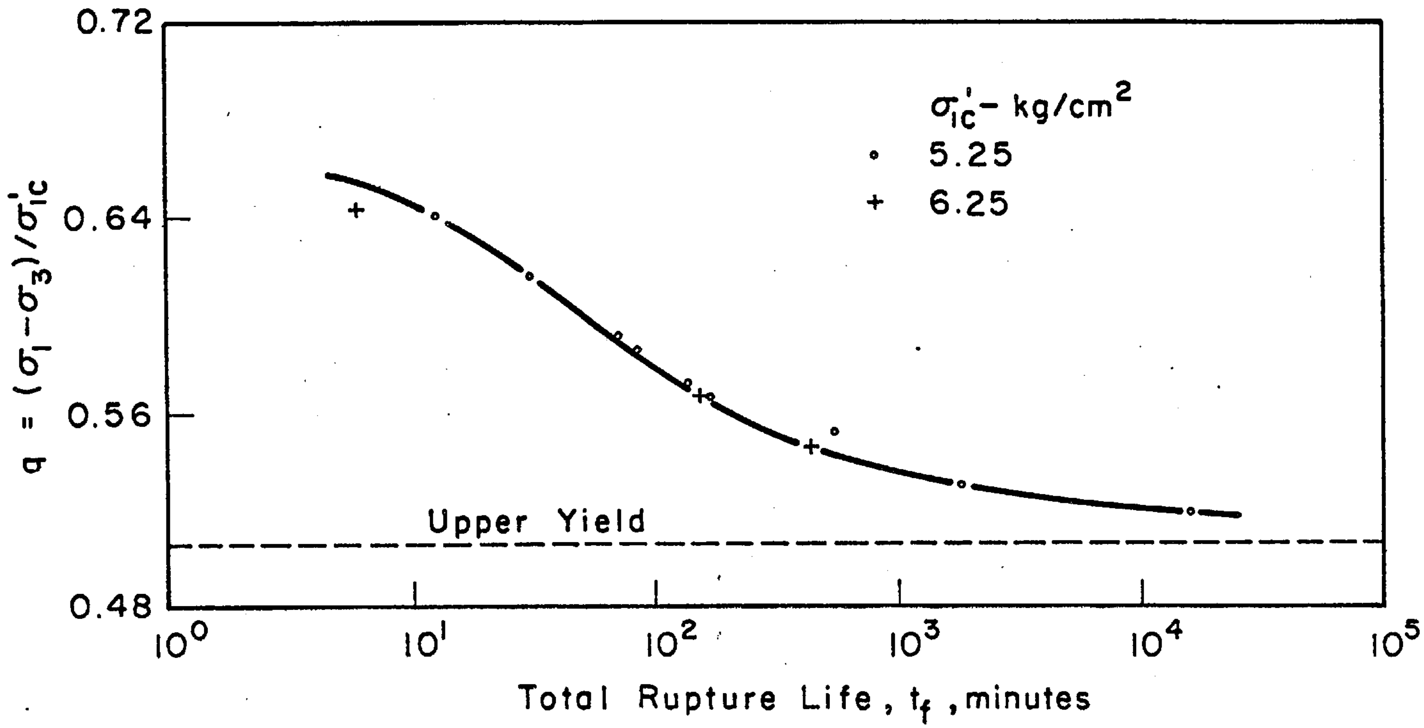

FIG. 6 TIME DEPENDENCE OF UNDRAINED STRENGTH IN CONSTANT STRESS CREEP.

The deformation time behavior under constant load creep (Fig. 7) was essentially similar to that under constant stress creep (Fig. 4), except that for the same magnitude of initial creep stress, q_o, deformation proceeded more slowly in constant load creep than in constant stress creep. The smaller deformations at any given time was a direct consequence of creep stresses decreasing with time. For initial stress levels q_o = 0.540 and larger, the samples progressively strained with time until rupture. There was, however, no catastrophic collapse of the specimens as observed under constant stress creep. Any tendency for the deformation rate to accelerate was partially counteracted by an opposite effect due to a decrease in creep stress as the cross-sectional area of the sample increased. Under initial stress levels q_o = 0.532 and lower, a continuously decreasing deformation rate was observed until elapsed times upto 2 weeks when the tests were terminated.

The time history of axial strain rate is illustrated in Fig. 8. Samples which eventually failed, demonstrated a characteristic decreasing strain rate until a minimum was reached before its subsequent acceleration leading to rupture. A continuously decreasing strain rate with time was observed with samples creeping under subfailure stresses. Thus, the time history of deformation rates in constant load creep was also similar to that under constant stress creep.

The rupture life as a function of initial creep stress level is shown in Fig. 9, which also includes results from tests with higher consolidation stresses. It may be seen that the relationship between q_o and rupture life is independent of the magnitude of initial consolidation stress. Rupture life progressively increases with decreasing q_o. No upper yield strength is implied by the poorly defined asymptotic q_o value, because the stress value used is the initial and not the actual stress at rupture.

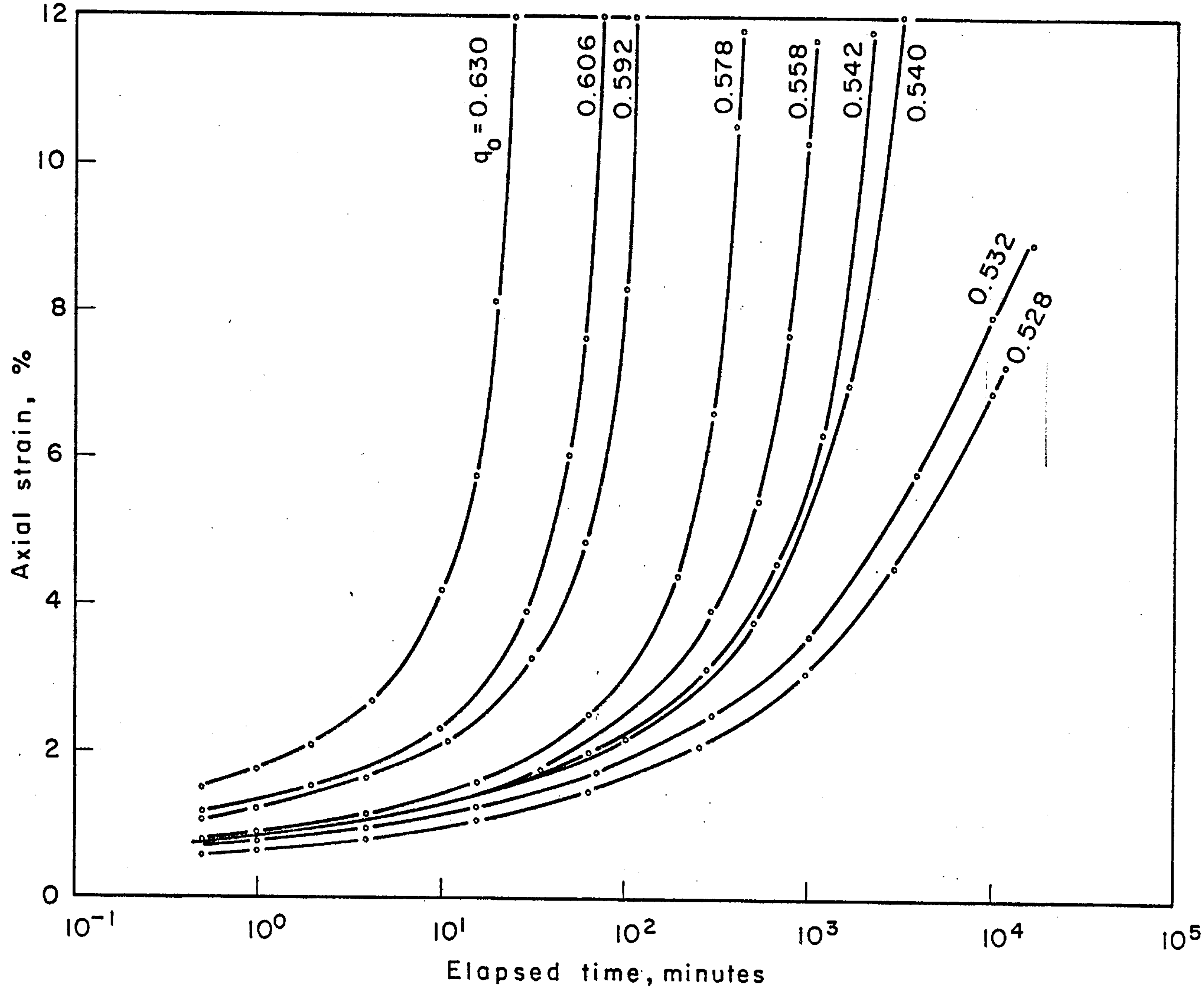

FIG. 7 RESULTS OF CONSTANT LOAD CREEP ON UNDISTURBED HANEY CLAY.

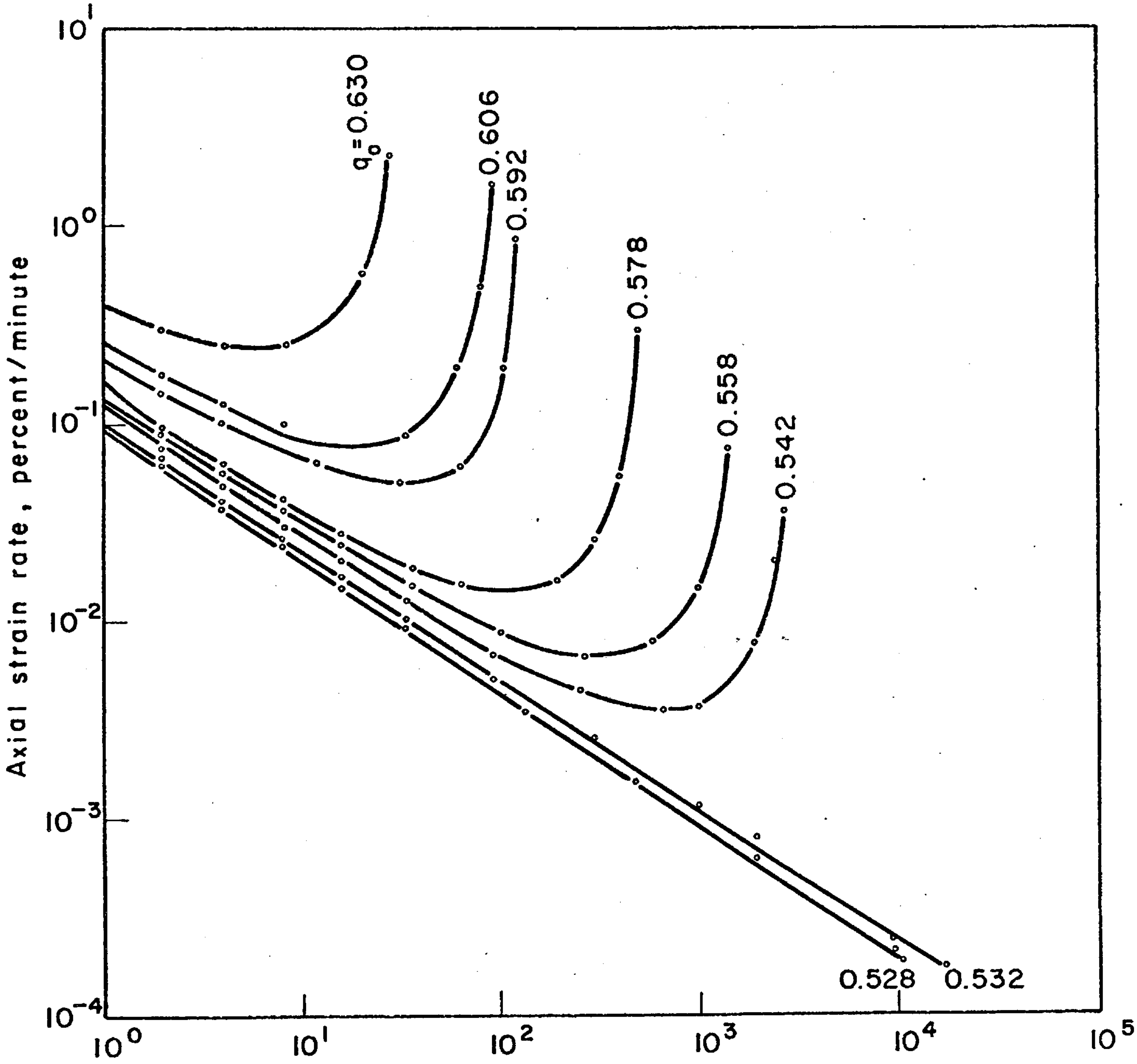

FIG. 8 VARIATION OF CREEP RATE WITH TIME IN CONSTANT LOAD CREEP.

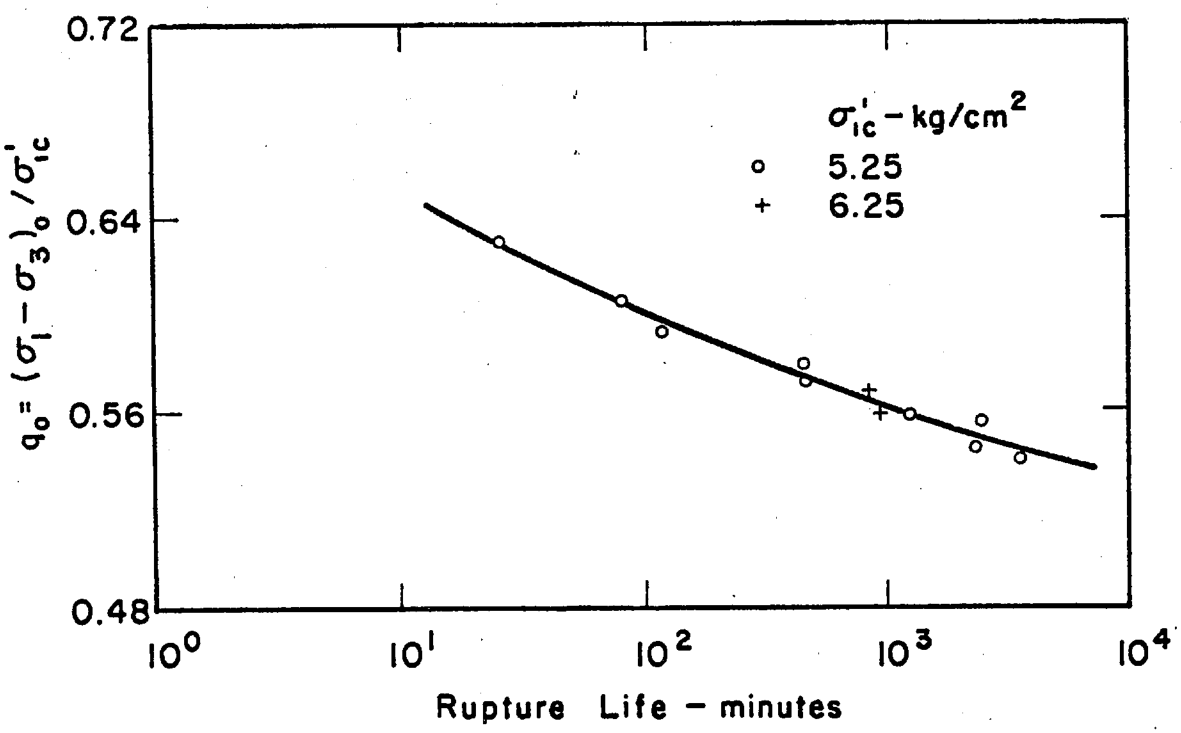

FIG. 9 TIME DEPENDENCE ON UNDRAINED STRENGTH IN CONSTANT LOAD CREEP.

Constant Rate of Loading:

Samples were loaded in this series of tests by linearly increasing the axial force with time. This continuous loading is different from the usual incremental loading shear tests in which samples are loaded with fixed increments of loads at constant time intervals. Constant rate of loading imparts to the samples a continuous strain rate history whereas incremental loading causes discontinous strain rate history.

The effect of rate of loading on the stress-strain response is shown in Fig. 10. The faster the rate of loading the higher was the stress-strain curve and consequently the larger the undrained strength. A comparison of Fig. 10 with Fig. 2 shows a characteristic smaller post peak drop in shear stresses under constant rate of loading than under constant rate of strain loading. After the occurrence of peak, the strain rate is continuously increasing in the constant rate of loading test (Fig. 10) but is constant in the other (Fig. 2). Thus the smaller loss in post peak resistance under constant rate of loading appears to be a consequence of continuously increasing strain rates at all levels of post peak strains.

The effect of rate of loading on the undrained strength, q_m, (peaks of stress-strain curves in Fig. 10) is illustrated in Fig. 11. There was a linear increase in undrained strength when rate of loading varied over 4 orders of magnitude. This increase in undrained strength was approximately 7% for 10 fold increase in rate of loading. Fig. 11 also shows that the relationship was independent of the magnitude of consolidation stress. The loading rates shown in Fig. 11 do not appear to be slow enough to indicate an upper yield strength value.

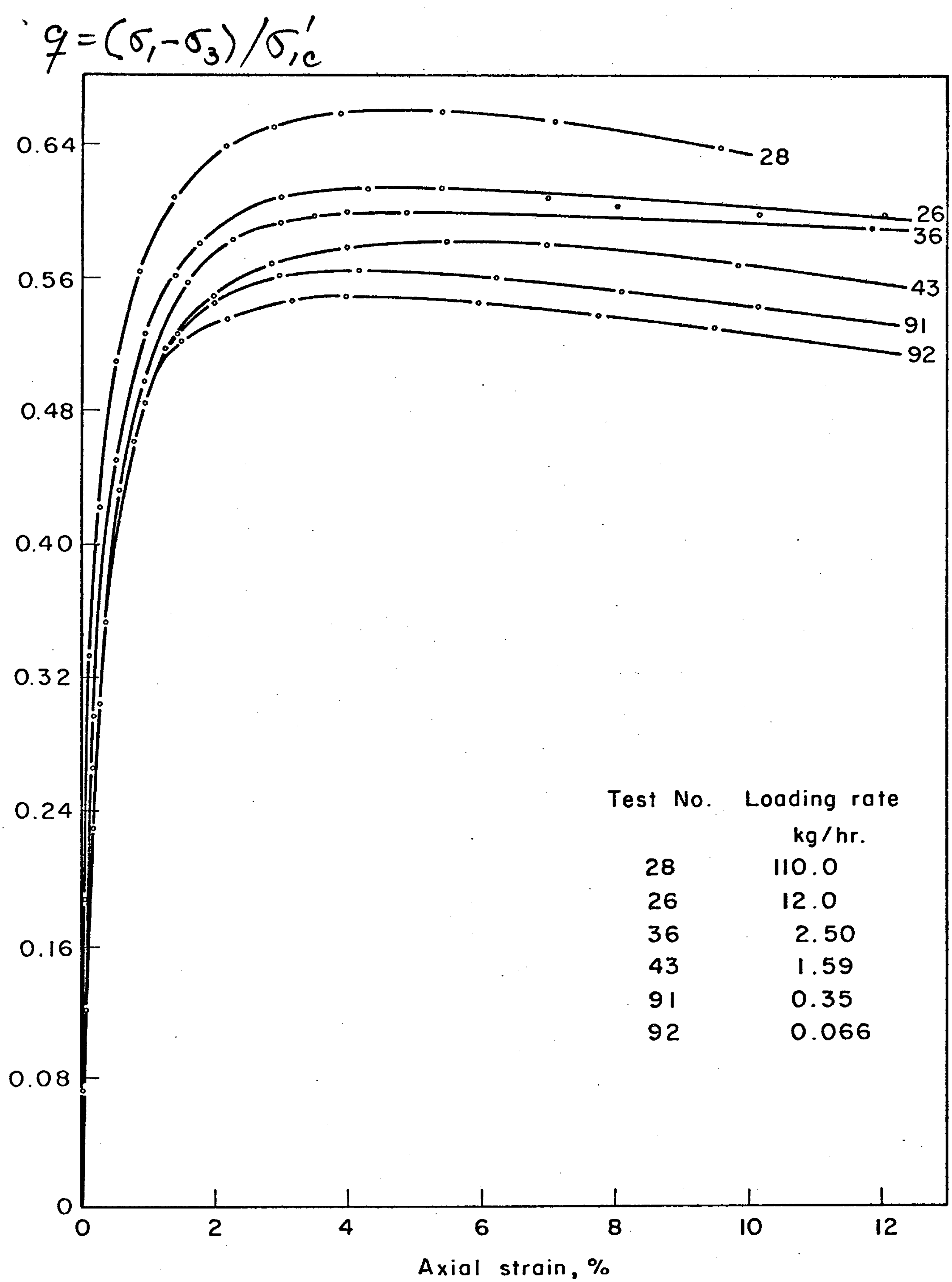

FIG. 10 INFLUENCE OF RATE OF LOADING ON UNDRAINED STRESS-STRAIN BEHAVIOUR IN CONSTANT RATE OF LOADING SHEAR.

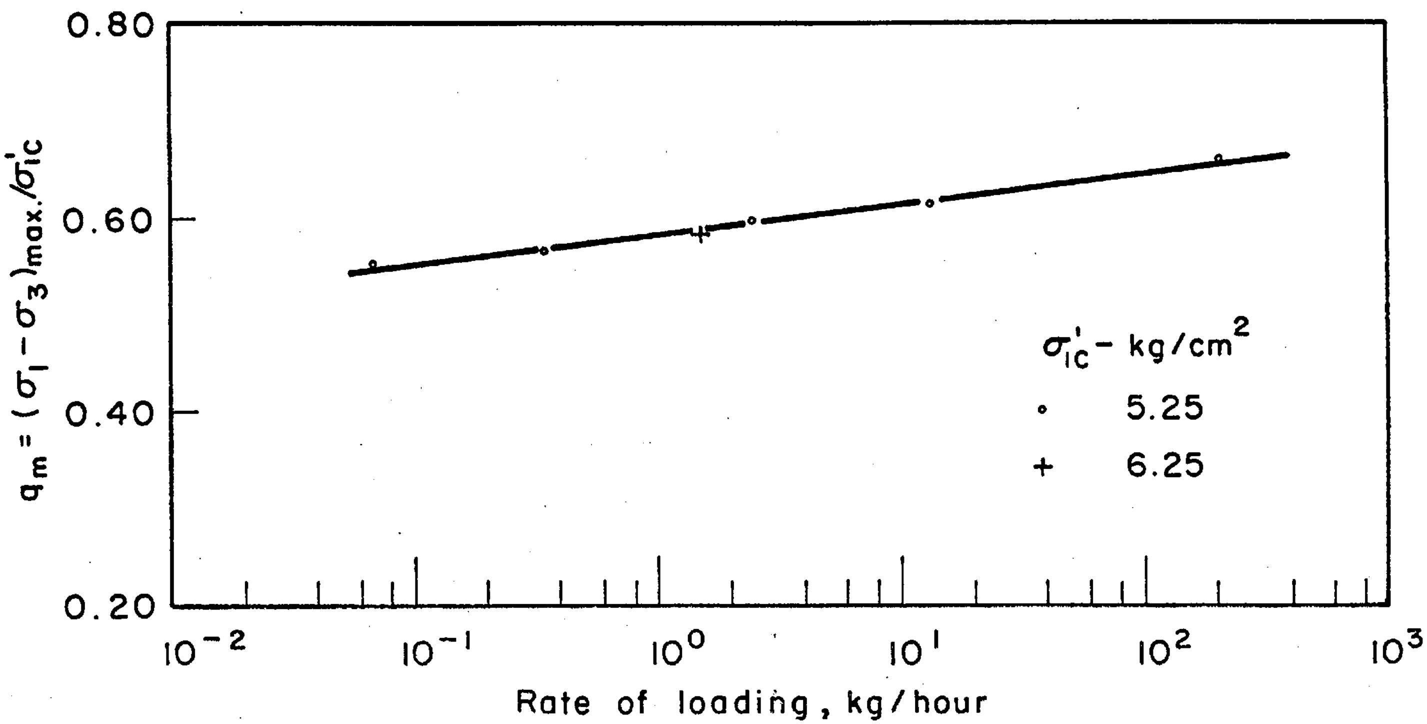

FIG. 11 TIME EFFECTS ON UNDRAINED STRENGTH IN CONSTANT RATE OF LOADING SHEAR.

CORRELATION OF TEST RESULTS WITH VARIOUS TIME-LOADING HISTORIES

The foregoing test results clearly demonstrate that the stress-strain-strength behavior of the clay tested cannot be described without including the effect of time. For example, no unique value of stress can be specified for a given level of strain without reference to the time loading history of the specimen. It is felt that if suitable account can be taken of the manner in which the time affects the stress-strain-strength response of a clay, then the test results obtained under all time-loading histories would complement each other. With the time effect duly accounted for, it would then be possible to predict clay behavior under one type of loading, e.g., constant rate of strain from the results under another type of loading, e.g., constant stress creep tests and vice-versa. One such approach to correlate results from various time loading histories is now considered.

It is well known that an increase in deformation rate results in increased undrained resistance at any strain level. A clear manifestation of this phenomenon can be seen in conventional constant rate of strain tests (Fig. 2). It may be reasonable to consider that the clay samples possess identical structure at a given value of strain (axial), regardless of the manner in which this strain was accumulated with time. It is now hypothesised that at a given value of strain, ε, (or structure) the shear stress, q, is a function only of the instantaneous rate of strain, $\dot{\varepsilon}$, and is independent of the past strain rate history. Thus, in tests where the rate of strain varies with time, the instantaneous rate of strain is considered as the time variable affecting the magnitude of stress at a given level of strain. In other words, during the deformation process, if the state of clay is described by the instantaneous state variables q, ε, $\dot{\varepsilon}$, then these variables are uniquely related in the following manner

$$q = q(\varepsilon, \dot{\varepsilon}) \tag{1}$$

Eq.(1) is similar to the equation of state for ideal gases where at any time the state variables - volume, V, pressure, P, and temperature, T, of a given amount of gas are uniquely related ($\frac{PV}{T} = R$) regardless of the manner in which the individual variables arrived at the current state. Some of the consequences of the proposed hypothesis are now considered and test data presented to verify the resulting predictions.

Step change in rate in constant rate of strain loading:

The solid curves in Fig. 12 show stress-strain data from two identical samples (I and II) sheared at constant rates of strain of 3.5×10^{-3} and 4.7×10^{-2} percent per minute. A third identical sample (III) was similarly tested at the rate equal to that of sample I, but at a strain level of about 0.8%, the rate of strain was suddenly increased to a value equal to that of sample II. If the proposed hypothesis, i.e., stress, q is a function of current strain, ε and strain rate, $\dot{\varepsilon}$ is applicable to the clay tested, the stress-strain curve of sample III after the increased rate of strain would coincide with that of sample II. For strain levels less than 0.8% the response of sample I and III would coincide, both tested at the same rate of strain. The measured stress-strain curve of sample III is shown in Fig. 12 by data points. It may be seen that the measured response agrees very closely with that predicted thus lending support to the proposed hypothesis.

Step change in stress in constant stress creep:

Two constant stress creep tests were carried out on identical samples (I and II) at stress levels $q_1 = 0.554$ and $q_2 = 0.586$. The resulting strain time plots are illustrated by solid curves in Fig. 13. A third identical sample (III) was initially subjected to a creep stress equal to that used

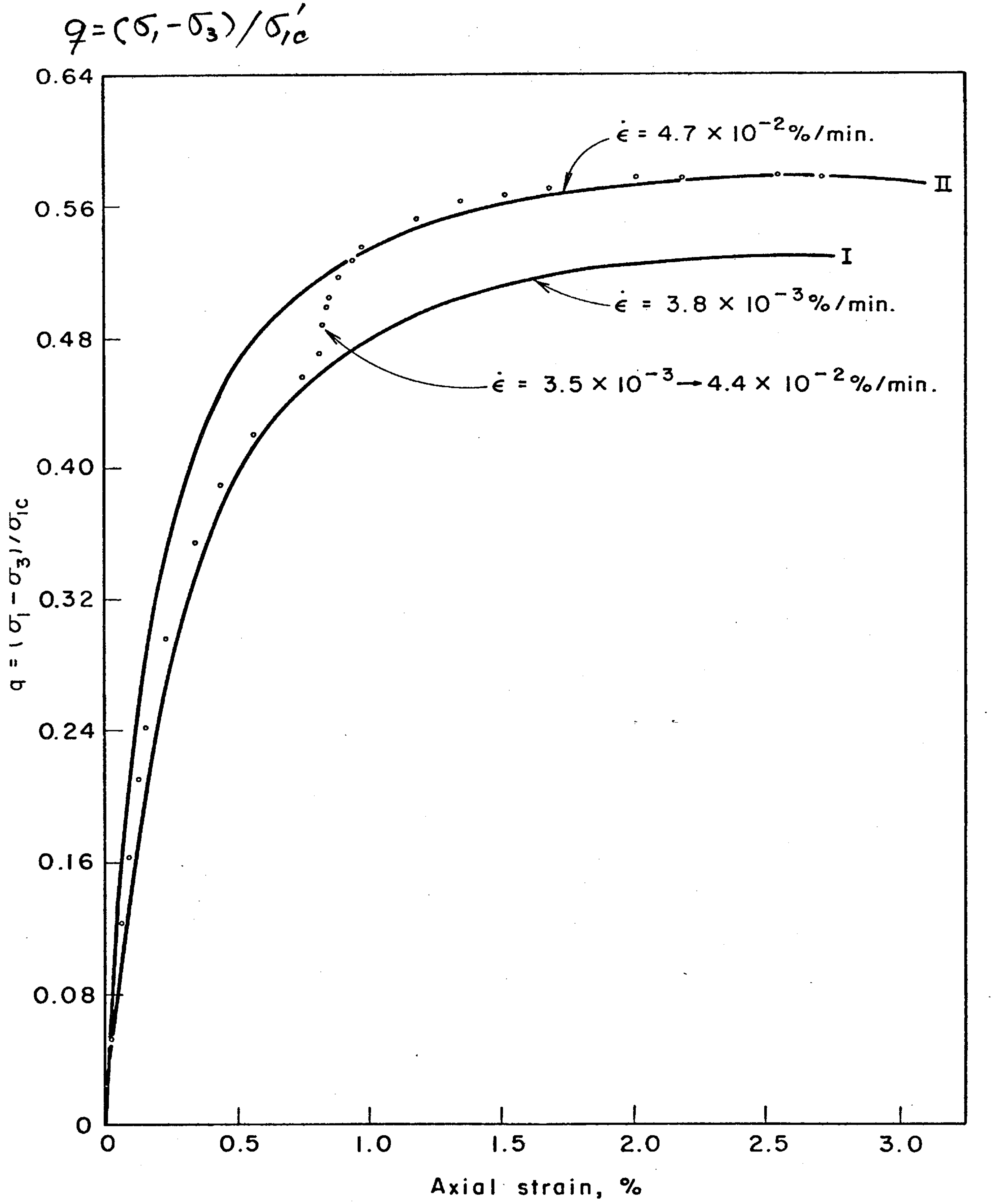

FIG. 12 INFLUENCE OF STEP CHANGE IN CONSTANT RATE OF STRAIN ON UNDRAINED STRESS-STRAIN RESPONSE.

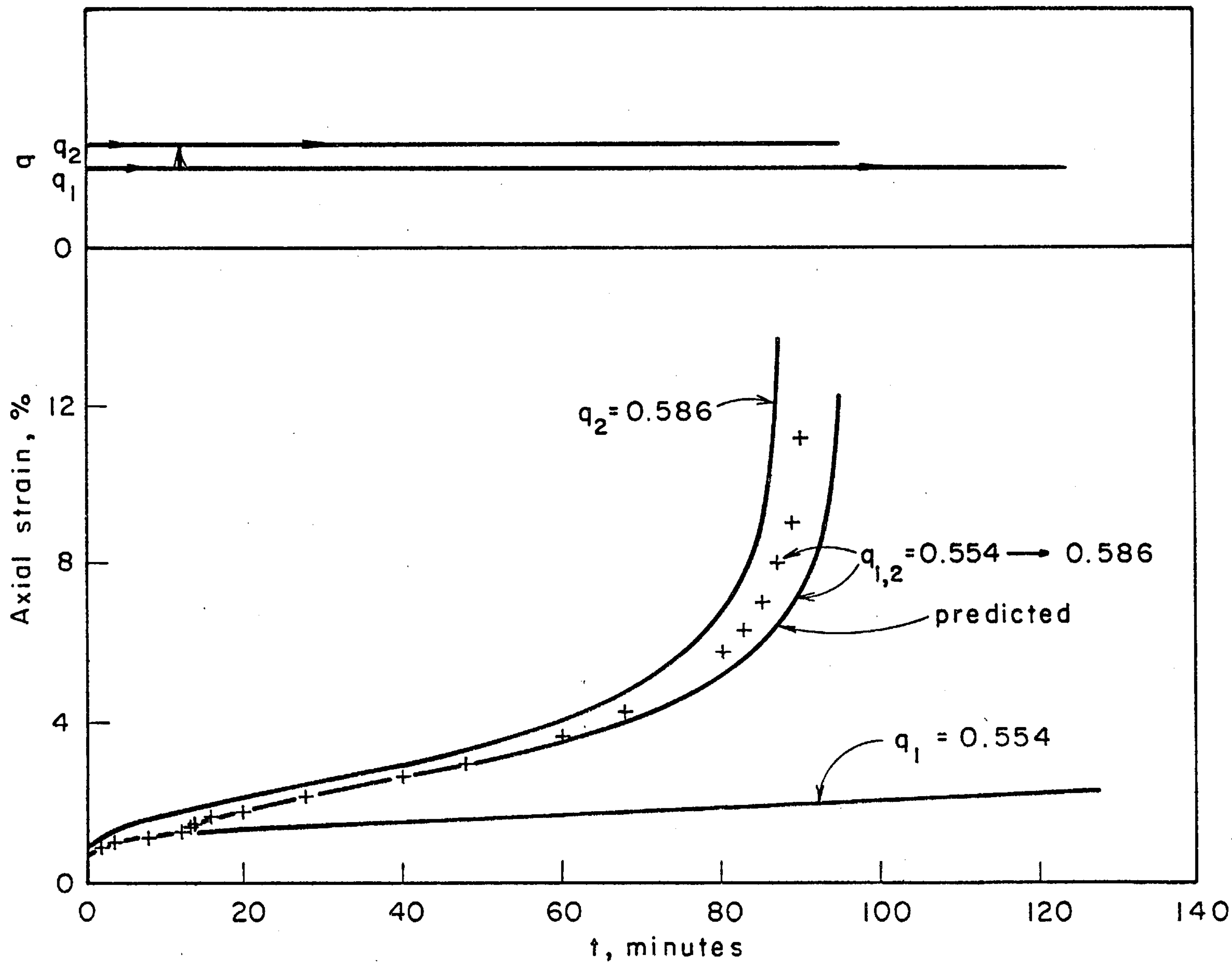

FIG. 13 COMPARISON OF PREDICTED AND OBSERVED CONSTANT STRESS-STEP CREEP RESULTS

for sample I, i.e., $q_{1,2} = 0.554$. After an elapsed time of 13 minutes the creep stress was suddenly raised to the value equal to that used for sample II, i.e., $q_{1,2} = 0.586$. Since the creep stress was identical for samples I and III for the first 13 minutes of creep, their resulting strain - time response would be identical. At the instant the creep stress was raised to q_2 the strain in sample III was 1.3%. As q is hypothesised a function of current ε and $\dot{\varepsilon}$, the change in creep stress for sample III from q_1 to q_2 at $\varepsilon = 1.3\%$ must result in an increase in $\dot{\varepsilon}$ to a value equal to that corresponding to point a on the creep curve of sample II with $q = q_2$. The predicted strain-time response of sample III under q_2 will thus be obtained by a horizontal translation to the right of the portion of creep curve of sample II ($q = q_2$) beyond point a, by an amount 'ab' in Fig. 13. This predicted strain-time relationship for sample III is shown by a solid curve whereas the measured relationship is indicated by data points. Excellent agreement can be seen to exist between predictions and observed relationship, lending further support to the proposed hypothesis.

<u>Prediction of constant rate of strain data from test results with other time-loading histories:</u>

The proposed concept that stress is a function only of current strain and strain rate is used in Fig. 14 to illustrate the interrelation between constant rate of strain and constant stress creep tests. Fig. 14(a) shows typical stress-strain curves (q vs ε) obtained under constant rates of strain, $\dot{\varepsilon}_1 > \dot{\varepsilon}_2 > \dot{\varepsilon}_3$. A constant stress creep test with $q = q_1$ is represented by a horizontal line in Fig. 14(a). Since stress is a function of current strain and strain rate only, the intersection of this horizontal line with stress-strain curves yields a set of points (ε, $\dot{\varepsilon}$) for the constant stress creep test. These points are shown plotted in Fig. 14(b) to yield the predicted

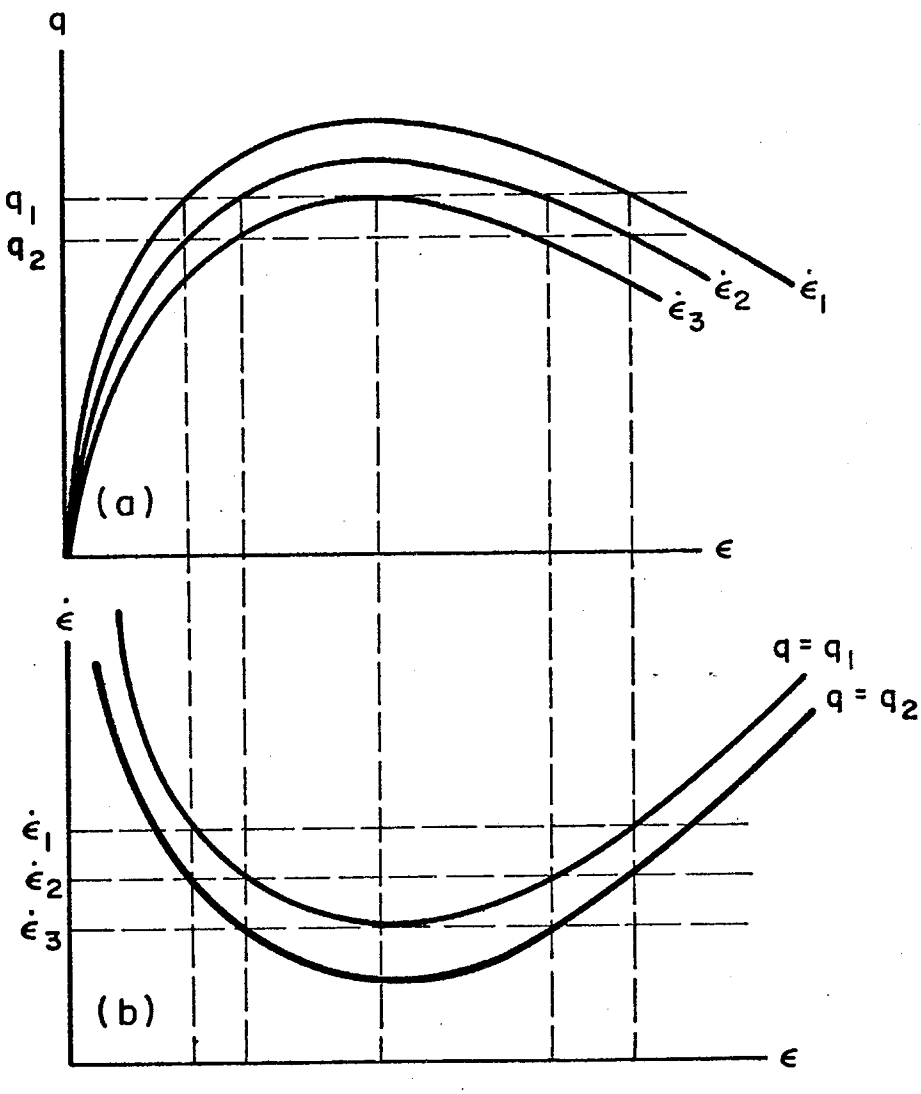

FIG. 14 PREDICTION OF CONSTANT RATE OF STRAIN TEST RESULTS FROM THE RESULTS OF CONSTANT STRESS CREEP TESTS AND VICE VERSA.

relationship between ε and $\dot{\varepsilon}$ in a constant stress creep test with $q = q_1$.

Alternatively, constant rate of strain behavior can be predicted from a series of constant stress creep tests or tests with other time-loading histories. A constant rate of strain test in Fig. 14(b) is represented by a horizontal line corresponding to the value of strain rate in question. Intersections of this line with creep curves yield a set of data points (q,ε) defining the predicted stress-strain relation under the chosen constant rate of strain. Plots similar to Fig. 14(b) can similarly be constructed for shear tests under other time-loading histories illustrated in Fig. (1). These plots can again be entered with the value of strain rate equal to that of the constant rate of strain test, and the magnitudes of strain read at the intersections. The stress values corresponding to these strain values are then read off the appropriate stress-strain curves of the tests.

In Fig. 15, the solid line shows the stress-strain curve measured under a constant rate of strain of 1.5×10^{-1} percent/minute. The predicted behavior at this constant rate from tests with other time-loading histories is shown by data points. The time-loading histories considered include, constant stress creep, constant load creep, step creep and constant rate of loading shear, and reflect loading under a variety of strain rate histories. It can be seen from Fig. 15 that excellent agreement exists between measured and predicted relationships. Thus, for the clay tested the concept of stress being a function of current strain and strain rate only can be used to correlate stress-strain-time behavior. Fig. 16 and Fig. 17 show further comparisons between predicted and observed stress-strain behavior at other constant rates of strain. Again, excellent agreement can be seen to exist between observed and predicted behavior.

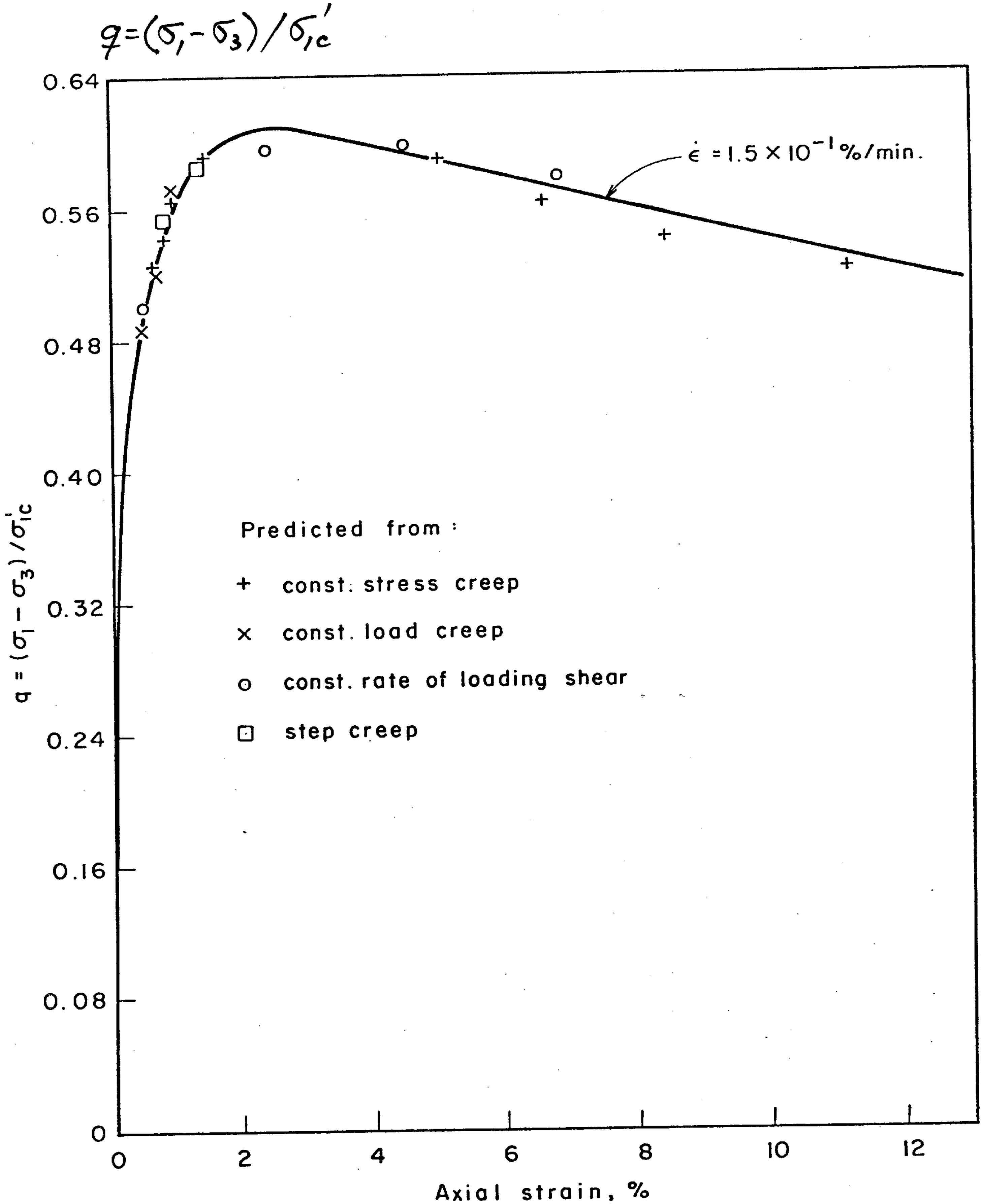

FIG. 15 COMPARISON OF STRESS-STRAIN DATA FROM CONSTANT STRAIN RATE HISTORY WITH THAT PREDICTED FROM VARIABLE STRAIN RATE HISTORIES.

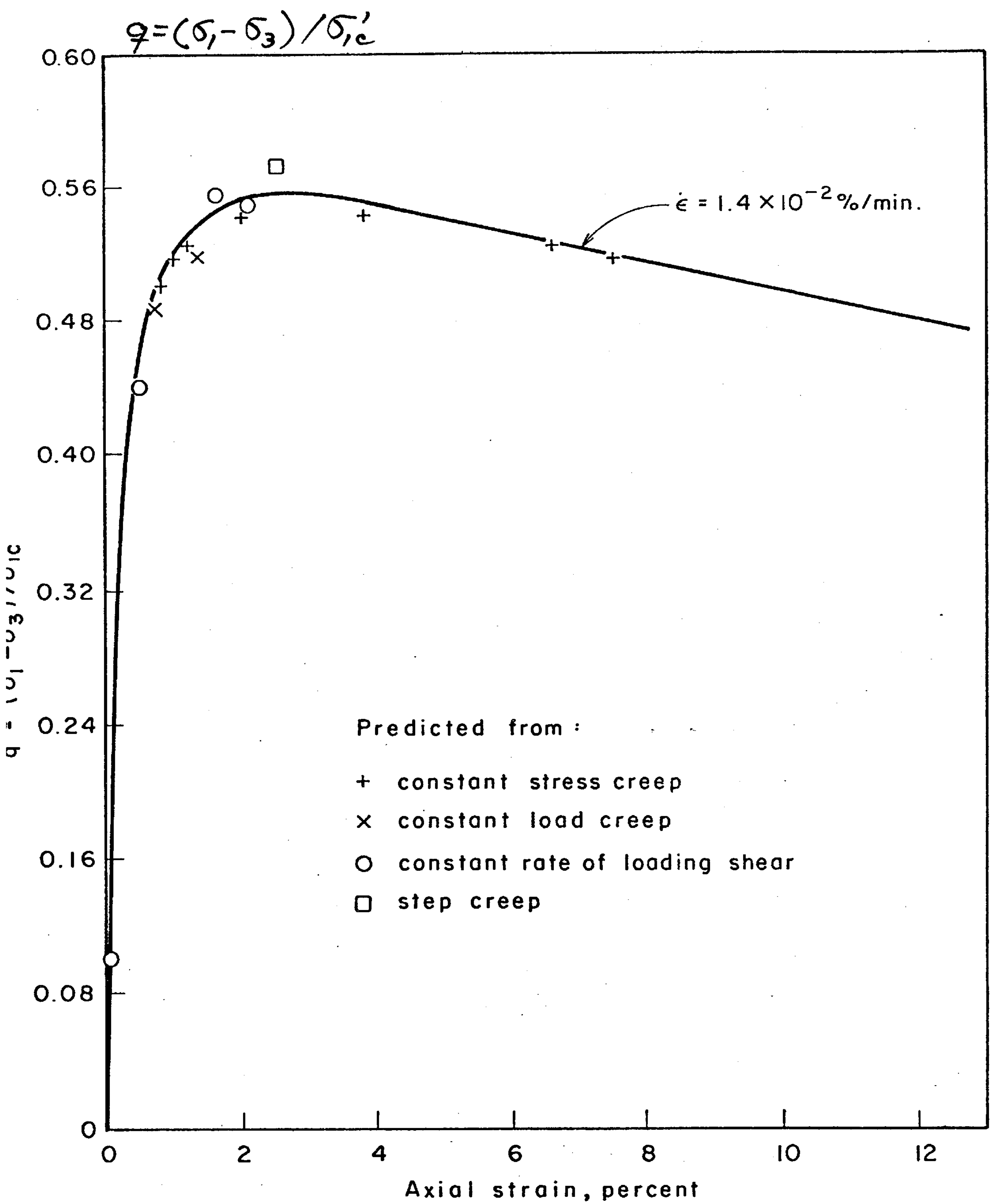

FIG. 16 COMPARISON OF STRESS-STRAIN DATA FROM CONSTANT RATE OF STRAIN HISTORY WITH THAT PREDICTED FROM VARIABLE STRAIN RATE HISTORIES.

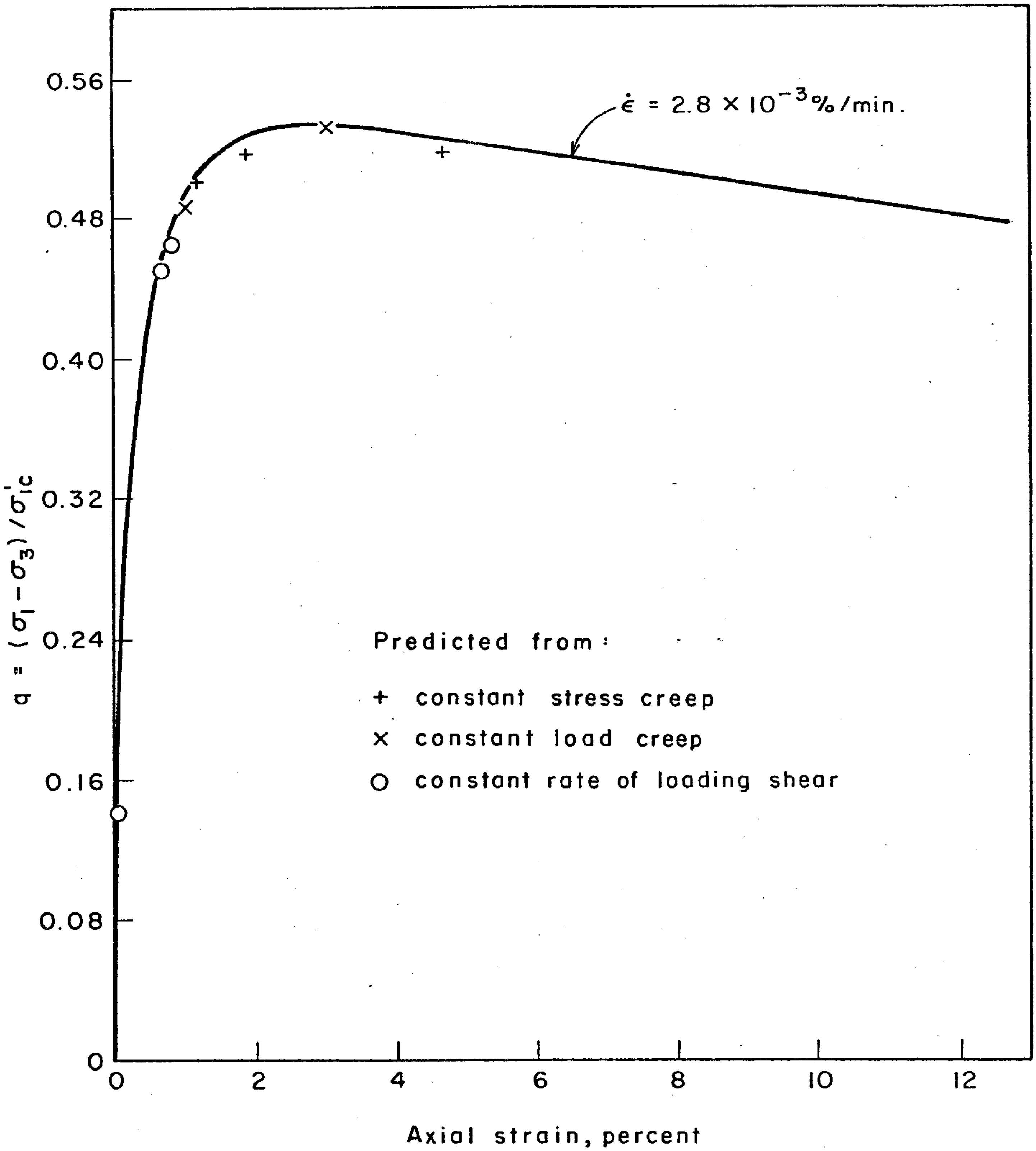

FIG. 17 COMPARISON OF STRESS-STRAIN DATA FROM CONSTANT RATE OF STRAIN HISTORY WITH THAT PREDICTED FROM VARIABLE STRAIN RATE HISTORIES.

Another important consequence of the proposed hypothesis is now considered. If a constant rate of strain test was carried out at the strain rate equal to the minimum creep rate of a constant stress creep test with $q = q_1$ (see Fig. 14), then the peak stress in constant rate of strain test would equal q_1 and occur at the same strain as the minimum creep rate in the creep test. Fig. (3) shows experimental data to support such a prediction. In this Figure, data from constant stress creep tests at the instant of minimum creep rate has been shown along with the data corresponding to peak stress in constant rate of strain shear. In creep tests the condition of minimum creep rate occurred in the neighbourhood of 2.5 percent axial strain and was essentially independent of the creep stress level. Similarly the strain corresponding to peak stress in constant rate of strain shear was about 2.5 to 3 percent and was essentially independent of the rate of strain. Thus Fig. (3) represents results from the two types of tests corresponding to the same value of strain. It may be seen from this figure that the predictions of the proposed hypothesis are in excellent agreement with the observed Haney clay behavior.

INFLUENCE OF AGING

Samples of Haney clay were aged for periods ranging from 3 to 48 days. They were subsequently sheared under identical constant rate of strain equal to 1.4×10^{-2} percent per minute. The observed difference in stress-strain behavior was thus solely a result of aging. The secondary volumetric strain due to the prolonged consolidation period of even the longest duration was very small (0.3 percent compared to total volumetric strain of 11.6 percent). Primary consolidation was essentially complete in the first 5 hours.

The undrained strength, q_m, of Haney clay was found to increase with the length of aging. This is illustrated in Fig. 18, where it may be seen

$q_m = (\sigma_1 - \sigma_3)_{max} / \sigma_{1c}'$

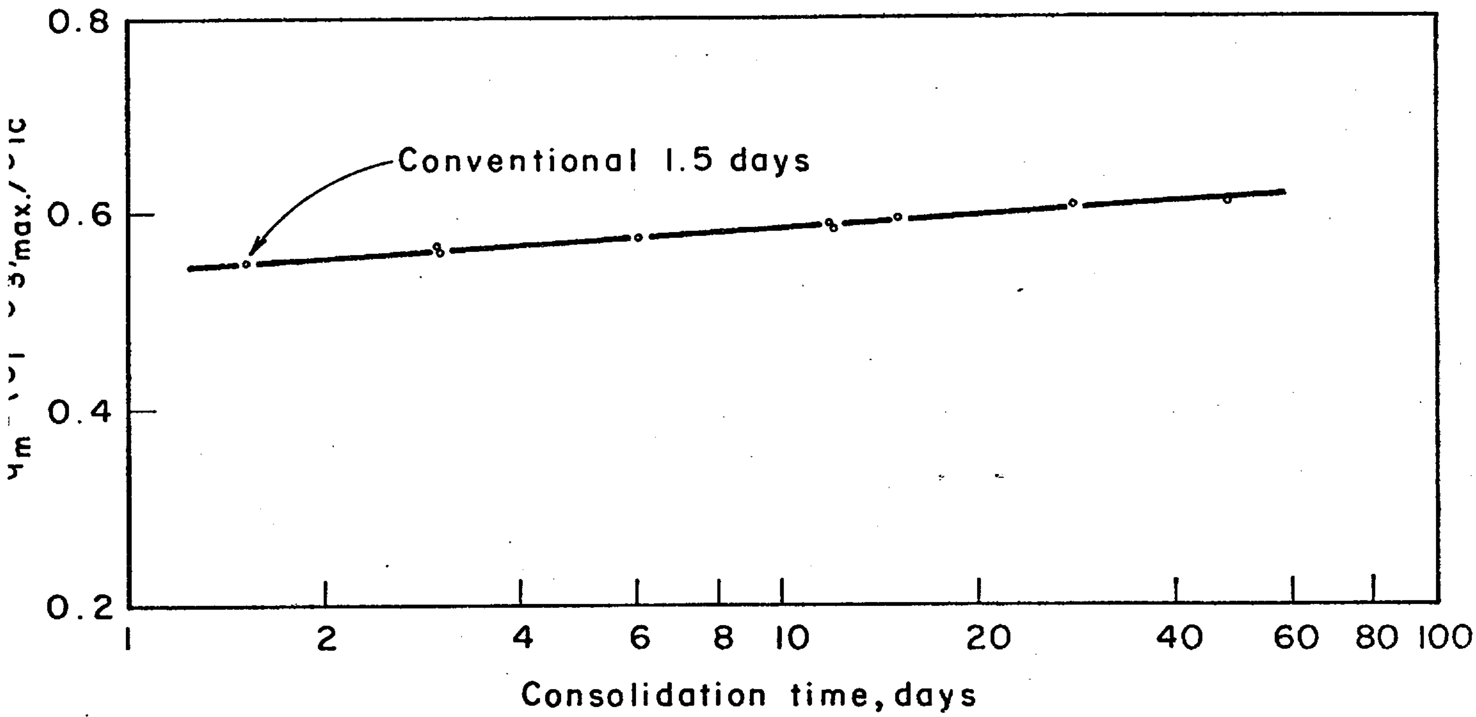

FIG. 18 EFFECT OF AGING ON UNDRAINED STRENGTH - CONSTANT RATE OF STRAIN SHEAR AT 1.4 x 10^{-2}% / MIN.

that the undrained strength increases approximately linearly with logarithm of length of aging. The increase in undrained strength corresponds to about 7 percent for a 10 fold increase in time of aging. Similar results have been reported by Ladd (12) and Bjerrum and Lo (5). The strain at which the undrained strength was mobilized in the clay tested was essentially independent of the length of aging. However, Bjerrum and Lo (5) report reduction in failure strain with increase in time of aging. The observed increase in undrained strength with aging has been attributed to the growth of cohesive bonds at interparticle contacts (5). The strength of these bonds is considered to increase with time of aging.

THIXOTROPIC EFFECTS

As pointed out earlier, the term thixotropy is used to described increase in strength with time at constant composition (13). Such a gain in strength can occur even if the clay is under the influence of external shear stresses. The prerequisite for gain in strength is a period of prolonged rest with or without imposed external shear stresses.

Fig. 19 shows measured undrained stress-strain curves of three identical samples. Sample I was tested at a constant rate of strain of 1.4×10^{-2} percent per minute. Sample II was subjected to a constant stress creep loading with $q = 0.374$ for a period of 20,000 minutes giving the strain time relationship previously shown in Fig. 4. It may be noted that after the first 10,000 minutes of creep, only 0.04 percent additional strain occurred in the sample in the remaining 10,000 minutes. The sample can therefore be considered practically at rest and thixotropic effects, if any, would develop in this rest period. The sample was then subjected to a constant rate of strain shear at the same strain rate as sample I. It may be seen in Fig. 19 that the peak strength mobilized by sample II was considerably higher than

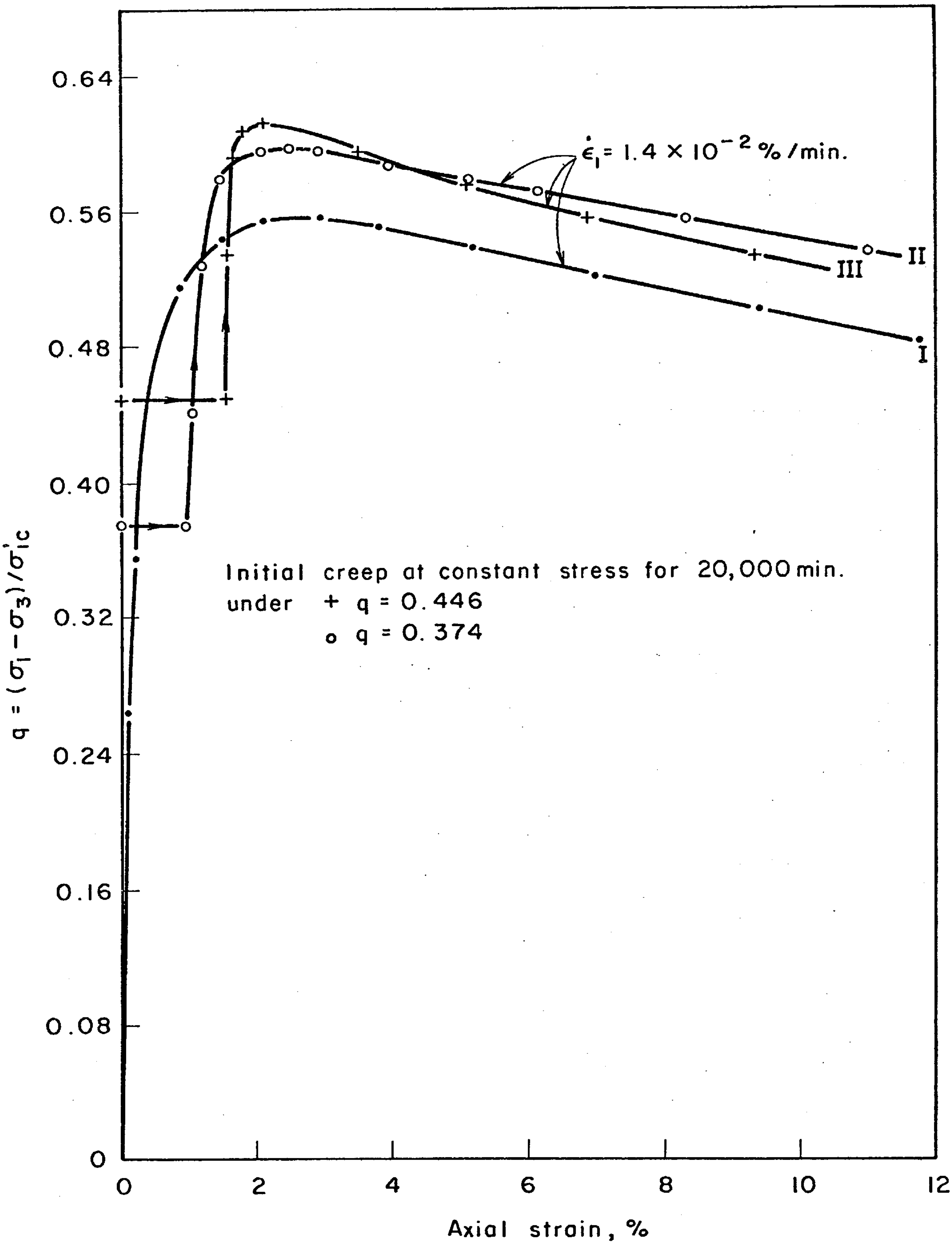

FIG. 19 GAIN IN UNDRAINED STRENGTH DUE TO THIXOTROPIC EFFECTS.

sample I. Since the rate of strain during shear was identical, the additional strength of sample II is a result of thixotropic strength gain. A third sample was similarly subjected to a different constant stress creep loading for 20,000 minutes with $q = 0.446$ (also shown in Fig. 4) and subsequently sheared at constant rate of strain equal to that for samples I and II. Similar thixotropic gain in undrained strength may again be noted. It is interesting to note that the axial strain at which the peak strength was mobilized was not affected by thixotropic effects. Furthermore, the increased strength due to thixotropic hardening persisted even beyond the peak in the stress-strain curves.

EFFECTIVE STRESS FAILURE

Fig. 20 shows a modified Mohr's plot representing stress conditions at the instant of maximum mobilized friction, i.e. $(\sigma_1'/\sigma_3')_{max}$. The data in this figure includes all type of undrained tests performed in this study. In order to maintain clarity data points from each and every test are not shown, but representative tests of each kind have been included. It may be seen in Fig. 20 that the effective stress failure of normally consolidated Haney clay is uniquely defined by a linear Mohr's envelope passing through the origin. Failure in terms of effective stresses is thus independent of the time effects of any kind whatsoever. Similar conclusions were arrived at in an earlier study of Haney clay, (7), though under a limited number of time-loading histories. Furthermore, the condition of $(\sigma_1'/\sigma_3')_{max}$ occurred at large strains (13 to 14% axial strain) irrespective of the type of test or time loading history, while the undrained strength occurs at about 3% axial strain and is dependent on time effects.

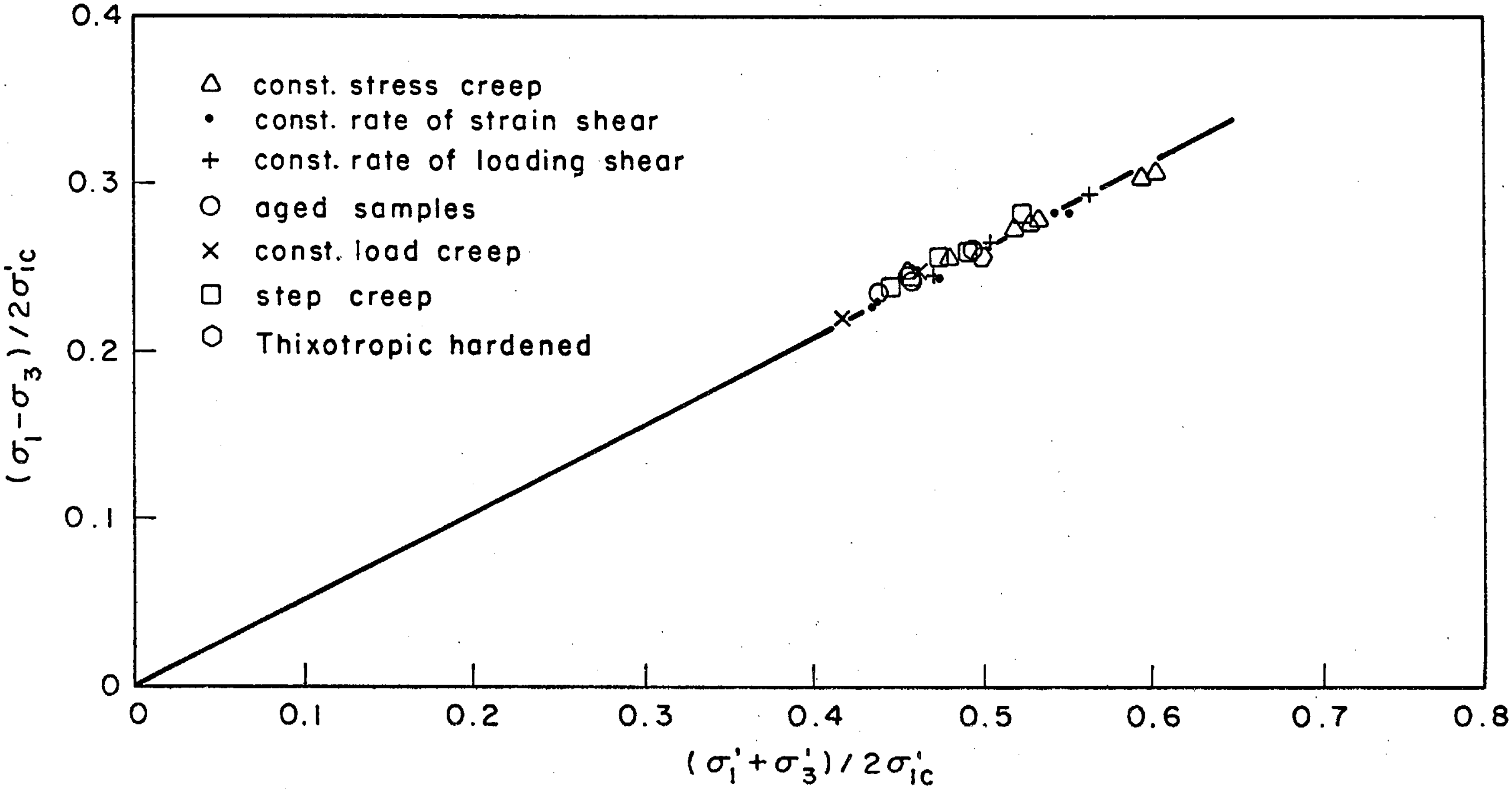

FIG. 20 STRESS CONDITIONS AT $(\sigma'_1/\sigma'_3)_{MAX.}$

CONCLUSIONS

Increase in strain rate, length of aging and thixotropic hardening, all result in stiffer undrained stress-strain response and higher undrained strength of the natural clay tested. For a given consolidation history, a unique stress-strain rate relation was found to exist which permits prediction of clay behavior under one type of loading from the results under another type of loading. For example constant stress creep results can be used to predict stress, strain and strength response under constant rate of strain loading. Effective stress failure was found to be unaffected by any kind of time effects.

ACKNOWLEDGMENTS

Financial assistance under Grant A3401 of the National Research Council of Canada is gratefully acknowledged.

Appendix I - REFERENCES

1. Alberro, J.A. and Santoyo, E.Y., "Long term behavior of Mexico City clay," Proceedings, 8th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1.1, 1973, pp. 1-9.

2. Berre, T. and Bjerrum, L., "Shear strength of normally consolidated clays," Proceedings, 8th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1.1, 1973, pp. 39-49.

3. Bishop, A.W. and Henkel, D.J., "The triaxial test," Edward Arnold Ltd., London, 2nd Ed. 1962.

4. Bjerrum, L., "Embankments on soft ground," Proceedings ASCE Specialty Conference on Earth and Earth Supported Structures, Vol. 2, 1972, pp. 1-54.

5. Bjerrum, L. and Lo, K.Y., "Effect of aging on the shear strength properties of a normally consolidated clay," Geotechnique, Vol. 13, 1963, pp. 147-157.

6. Bjerrum, L., Simons, N., and Torblaa, I., "The effect of time on the shear strength of a soft marine clay," Proceedings, Brussels Conference on Earth Pressure Problems, Vol. 1, 1958, pp. 148-158.

7. Campanella, R.G. and Vaid, Y.P., "Triaxial and plane strain creep rupture of an undisturbed clay," Canadian Geotechnical Journal, Vol. 11, 1974, pp. 1-10.

8. Casagrande, A. and Wilson, S.D., "Effect of rate of loading on the strength of clays and shales at constant water content," Geotechnique, Vol. 2, 1950, pp. 251-263.

9. Crawford, C.B., "The influence of rate of strain on effective stresses in sensitive clay," Papers on Soils, ASTM STP No. 254, 1959, pp. 36-48.

10. Duncan, J.M. and Buchignani, A.L., "Failure of underwater slope in San Francisco," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 99, No. SM9, Proc. paper 10019, 1973, pp. 687-703.

11. Finn, W.D.L. and Snead, D.E., "Creep and creep rupture of an undisturbed sensitive clay," Proceedings, 8th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1.1, 1973, pp. 135-142.

12. Ladd, C.C., "Stress-strain modulus of clay in undrained shear," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 90, No. SM5, 1964, pp. 127-156.

13. Mitchel, J.K., "Fundamental aspects of thixotropy in soils," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 86, No. SM3, Proc. paper 2522, 1960, pp. 19-52.

14. Muryama, S. and Shibata, T., "Rheological properties of clays," Proceedings, 5th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, 1961, pp. 269-273.

15. Perloff, W.H. and Osterberg, J.O., "The effect of strain rate on the undrained shear strength of cohesive soils," Proceedings, 2nd Pan American Conference on Soil Mechanics and Foundation Engineering, Vol. 2, 1963, pp. 103-128.

16. Richardson, A.M. and Whitman, R.V., "Effect of strain rate upon undrained shear resistance of a saturated remolded fat clay," Geotechnique, Vol. 13, 1963, pp. 310-324.

17. Saito, M. and Uezawa, H., "Forecasting the time of occurrence of a slope failure," Proceedings, 5th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, 1961, pp. 315-318.

18. Taylor, D.W., "Fundamentals of Soil Mechanics," John Wiley and Sons, New York, 1948.

Appendix II - NOTATION

The following symbols are used in this paper:

$\sigma_1 - \sigma_3$	=	deviator stress
$(\sigma_1 - \sigma_3)_0$	=	initial deviator stress
σ'_1	=	major principal effective stress
σ'_3	=	minor principal effective stress
$(\sigma'_1 / \sigma'_3)_{max}$	=	maximum principal effective stress ratio
σ'_{1c}	=	consolidation pressure
$q = \dfrac{\sigma_1 - \sigma_3}{\sigma'_{1c}}$	=	normalised deviator stress
$q_m = \dfrac{(\sigma_1 - \sigma_3)_{max}}{\sigma_{1c}}$	=	normalised undrained strength
$q_0 = \dfrac{(\sigma_1 - \sigma_3)_0}{\sigma'_{1c}}$	=	normalised initial creep stress
ε	=	axial strain
$\dot{\varepsilon}$	=	axial strain rate