Creep behaviour of an undisturbed lightly overconsolidated clay

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To fill an important gap in the knowledge of creep phenomena, the creep behaviour of the intact, overconsolidated Saint-Alban clay has been investigated by means of drained and undrained triaxial tests as well as of odometer tests.

Creep deformations can be broken into volumetric and shear components. The development with time of both volumetric and shear strains can be represented by means of the phenomenological equation proposed by Singh and Mitchell in 1968. However, the stress function in that equation must be defined separately for each strain component and by reference to the limit state of the clay.

A general model of the time dependent behaviour of clays might be obtained by combining the concepts of limit state and isotaches, as implied in the YLIGHT model proposed by Tavenas and Leroueil in 1977 but the effect of overconsolidation on the shape of the isotaches requires further investigation.

Pour combler une lacune importante dans la connaissance des phénomènes de fluage, le comportement en fluage de l'argile intacte surconsolidée de Saint-Alban a été étudié au moyen d'essais triaxiaux drainés et non drainés et d'essais odométriques.

Les déformations de fluage peuvent être décomposées en partie isotrope et partie déviatoire. Le développement des déformations volumétriques et de cisaillement en fonction du temps peut être représenté par l'équation phénoménologique proposée par Singh et Mitchell en 1968. Cependant la fonction de contrainte dans cette équation doit être définie de façon distincte pour chaque composante de la déformation, et par référence à l'état limite de l'argile.

Un modèle général du comportement en fonction du temps de l'argile peut être obtenu en combinant les concepts d'isotache et d'état limite, tel que cela est sous-entendu dans le modèle YLIGHT proposé par Tavenas et Leroueil en 1977. Cependant l'effet de la surconsolidation sur la forme des isotaches doit être étudié plus avant.

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Introduction

The effects of time on the strength and deformation behaviour of soft clays have been the object of numerous investigations, in particular since 1960. Unfortunately these investigations have suffered from two fundamental weaknesses. First, they have followed the classical pattern of separating the problems of stability, investigated by means of strength tests, from the problems of settlement, investigated by means of odometer tests. As a result, two types of long term time effects have been separately defined and investigated: creep as related to strength problems and secondary consolidation as related to settlements, and practically no interconnection has been established in spite of the similarity of the phenomena. Second, the problem of creep has been dealt with essentially as a theoretical exercise aimed at the proposal of various rheological models and it has been poorly, if at all, related to *in situ* problems.

This last shortcoming may be easily evidenced. In all field situations partial or full drainage can develop; however, the majority of investigations, at least in North America, have been conceived with undrained creep tests. Excavated or natural slopes represent the most common situation where creep deformations occur and practically the only case where creep failure may develop as a result of a reduction of the shear strength with time. The clay in such slopes is necessarily in an intact, overconsolidated state, since it is submitted to stress release. In spite of this, only a few of the vast number of reported investigations have dealt with undisturbed, overconsolidated clays, and only one (Bishop and Lovenbury 1969) has included the analysis of creep behaviour during unloading. It is thus not surprising that the results of these investigations have found little application in practice.

As part of a research program on the behaviour of soft clays under embankments, the stress–strain–time behaviour of an undisturbed soft sensitive clay was investigated at Laval University. In a first step, a qualitative model (YLIGHT) of the clay behaviour was developed on the basis of the limit state concept by Tavenas and Leroueil (1977). This model, which integrates time effects, pointed out the necessity of a stringent consideration of the actual effective stress conditions in the analysis of time dependent phenomena. It also clearly indicated that a distinction between strength and deformation problems, and thus between creep and secondary consolidation, was mostly artificial. As a result, an investigation of time dependent phenomena in the intact Saint-Alban clay in both the overconsolidated and the normally consolidated state, and in drained as well as undrained conditions, was carried out following these principles.

It is the purpose of this paper, after a brief review of the few past publications pertinent to the analysis of the present data, to discuss the results of drained and undrained creep tests on the intact, overconsolidated Saint-Alban clay, and to develop a generalized description of time dependent phenomena in overconsolidated clays.

Important Aspects of the Present Knowledge of Time Dependent Phenomena in Clays

In spite of the artificial distinction between creep and secondary consolidation, the literature on the time dependent behaviour of clays provides some elements for the overall understanding and description of these phenomena.

Following the identification by Buisman (1936) of the existence of 'secular' settlements that would increase linearly with the logarithm of time, Taylor (1942) developed a conceptual description of time effects on the deformation and strength behaviour of clays that is still valid. Essentially he showed that any clay would present, not a unique relationship between its void ratio e and the applied effective stress σ_v', but rather a specific relationship for each possible duration of load application. Making the simple, classical assumption that the secular settlement would develop according to a function of the form

$$[1] \qquad \Delta e = C_\alpha \log (t_i + t)/t_i$$

where the coefficient of secondary consolidation C_α would be a constant, Taylor showed that the $e-\sigma_v'-t$ relationship would take the form of a set of parallel lines in the $e - \log \sigma_v'$ space. This principle has been confirmed experimentally by Crawford (1964), Bjerrum (1967), Sällfors (1975), and Tavenas and Leroueil (1977).

One of the important consequences of this phenomenon is the development with time of 'bonds' (Taylor 1942) or a 'reserve resistance' (Bjerrum 1967) in the aged clay, which is evidenced as a preconsolidation pressure σ_p' during the further loading of the clay consolidated under σ_{v0}'. When loading an overconsolidated, aged clay, the actual preconsolidation pressure will be a function, first of the age of the clay, and, second, of the duration of loading, decreasing linearly with the duration of loading (Crawford 1964; Tavenas and Leroueil 1977) or with the strain rate (Sällfors 1975).

Combining the concept of limit state with these time effects, Tavenas and Leroueil (1977) have shown that the entire limit state surface of a natural clay was age and rate dependent. Consequently they suggested that effects of age or strain rate would be proportionally similar on the preconsolidation pressure and on the strength characteristics of a natural clay. Their resulting YLIGHT model of clay behaviour clearly indicates that all aspects of time dependent phenomena, i.e., volumetric and shear deformations, strength variations and σ_p' effects are the result of a unique physical process and should therefore be investigated concurrently.

Many mathematical models have been developed to simulate this physical process. The 'secondary consolidation' approach to the problem has provided expressions for the development with time of the volumetric strains v that are also applicable to the axial strains ϵ_1 because of the particular features of the odometer test. In spite of the vast number of investigations since 1942, [1], which may also be written

$$[2] \qquad \varepsilon_1 = v = \frac{C_\alpha}{1 + e_0} \log \frac{t_i + t}{t_i}$$

is still the most commonly accepted expression. However, its use is complicated by the very limited amount of information on the variations of C_α with the applied stresses (Wahls 1962; Mesri and Godlewski 1977) and eventually with time.

On the other hand, the 'creep' approach has resulted in the proposition by Singh and Mitchell (1968) of an apparently general phenomenological equation for the variations of the axial strains with shear stresses and time, in the form of

$$[3] \qquad \dot{\epsilon}_1 = A e^{\bar{\alpha}\bar{q}} (t_i/t)^m$$

in which $\dot{\epsilon}_1$ is the axial strain rate, $\bar{q}$ the shear stress level, and A, $\bar{\alpha}$, and m, soil creep parameters. This expression was originally developed by Singh and Mitchell (1968) to apply to axial strains in both undrained and drained tests. In this later case, the expressions for the axial strains in the odometer test ([2] and in K_0 triaxial tests [3]) should be identical since the clay is submitted to the same stress conditions in the two types of tests. Indeed there is an obvious, yet generally unrecognized, similarity between [2], which can be rewritten

$$[4] \qquad \dot{\epsilon}_1 = \frac{C_\alpha}{1 + e_0} \frac{1}{t} = \dot{v}$$

and equation [3]. This implies that the creep parameters C_α, m, and $\bar{\alpha}$ are functions of the stress conditions.

Recently, Kavezajian and Mitchell (1977) have suggested that [3] was essentially applicable to undrained tests so that it would represent the variations of the deviatoric strains ϵ with time. As a result, they propose to analyze the creep deformations of a clay submitted to any stress condition in the normally consolidated state in terms of a volumetric strain component v that would comply with [2] and [4] and of a deviatoric strain component ϵ that could comply with [3]. This interesting suggestion was not supported by clear experimental evidence but it is certainly in line with the concepts resulting from the use of the limit state theory by Tavenas and Leroueil (1977).

In all these expressions, the strains vary with the logarithm of time. Therefore, their application requires the definition of an origin for the time scale. At present this definition is arbitrary, t_i being taken equal to 1 in [3] and to the time at the end of primary consolidation in [2]. To overcome this difficulty Suklje (1957) has postulated that the rate of volumetric deformation in the odometer is a unique function of the mean values of the void ratio e and the effective stress σ_v'. He defined the time dependent deformation behaviour of a clay in terms of a family of curves of constant rate of volumetric strain in the e–σ_v' plane, called 'isotaches'. The isotaches are equivalent to the 'equal duration of loading' lines defined by Taylor (1942) and Bjerrum (1967) but, by giving the strain rate as a unique function of the present state of e and σ_v' they resolve the problem of the definition of t_i. In a recent investigation Vaid and Campanella (1977) have applied essentially the same approach to shear deformations in undrained triaxial tests, assuming that "at a given value of strain ϵ (or structure), the shear stress q, is a function only of the instantaneous rate of strain $\dot{\epsilon}$, and is independent of the past strain rate history." Thus, the concept of isotaches proposed by Suklje (1957) could probably be enlarged to apply to all components of the strain field under all stress conditions. To this end, isotaches could be associated to limit state surfaces, a point on the isotache $\dot{\epsilon}$ in the e—σ_v' plane being enlarged to an isotache surface $\dot{\epsilon}$ in the e–q–p' space. According to Tavenas and Leroueil (1977), this isotache surface $\dot{\epsilon}$ should have the same shape as the limit state surface of the clay, being simply homothetic to it for different values of $\dot{\epsilon}$.

Experimental Technique

The soil used for this investigation is a marine silty clay from an experimental site in Saint-Alban, 80 km west of Quebec City in the St. Lawrence Valley. This clay, which has been the object of many investigations by the geotechnical group at Laval University, has been described in detail by Tavenas *et al.* (1974) and its main characteristics are summarized in Table 1. Although it has not been submitted to any significant geological preconsolidation, this clay has developed a high quasi-preconsolidation probably due mainly to aging and possibly to other factors.

Undisturbed samples of the Saint-Alban clay were obtained at different depths by means of a 20 cm diameter thin tube sampler equipped with an overcoring device developed at Laval University (Sarrailh 1975). In this way a high number of comparable test specimens could be obtained in a limited volume of soil, thus limiting the scatter of results usually associated with the variability of natural clays.

Equipment plays a major role in the successful performance of long duration triaxial tests. Following the identification of the causes of leakage that occurs in the classical triaxial cell and accessories, a special cell base with integrated back pressured burette was developed (Leroueil 1978), to eliminate the sources of 'mechanical' leakage through fittings, valves, tubes, etc. To reduce the leakage due to osmosis through the membrane, silicone oil, 200–350 centistokes grades, was used as a cell fluid. This resulted in a leak of pore water from the sample through the common rubber membranes towards the cell, which was calibrated at −0.05 cm³/week for cell pressures in the range of 0–50 kPa; for 5 cm diameter, 10 cm high samples, this leak would correspond to an error of the order of 0.25% for $\Delta V/V$ in a 10 week long test. Although such a leak is acceptable for drained tests where it can be accounted for, it results in the near impossibility of carrying out undrained tests with a duration in excess of 1 week. Indeed, when testing overconsolidated clays with a high modulus

TABLE 1. Geotechnical characteristics of the Saint-Alban clay

	3 m depth	5.7 m depth
Water content (%)	90	60
Liquid limit (%)	50	40
Plastic limit (%)	27	23
Plasticity index (%)	23	17
Clay content (%)	81	45
$(C_u)_{vane}/\sigma_{v0}'$	0.65	0.55
$(\sigma_p')_{od.}/\sigma_{v0}'$	2.25	2.20
$(\sigma_p')_{od.}$ (kPa)	50	80
Sensitivity by field vane	14	22
Salt content of the pore water (g/L)	0.7	0.3

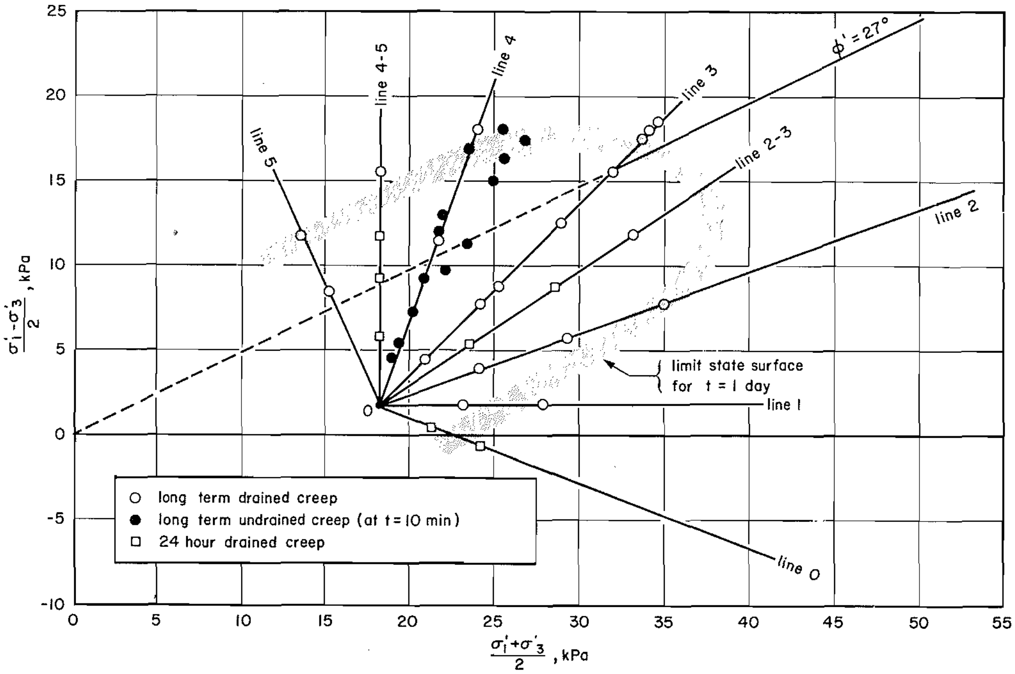

FIG. 1. Stress conditions for drained and undrained creep tests.

of compressibility, a small volume change results in large variations in the pore pressures and the applied effective stresses. As a result, undrained tests could not any more be considered as such after a duration of 3–5 days, and effective stresses equivalent to a drained condition were actually observed after about 2 weeks. Obviously, the problem would have been much less important and would have probably gone unnoticed if the clay had been tested in a normally consolidated state, when the corresponding low modulus of compressibility results in very limited changes in stresses due to small leaks.

All tests were carried out on samples 5.0 cm in diameter and 10 cm high. Cell pressures and back pressures were applied by means of a mercury pot system. Axial stresses were applied by means of dead weights carried by a counterbalanced frame resting on top of the cell piston. The test equipment was placed on vibration isolated tables with high inertia. The room temperature was maintained constant at 22 ± 0.5°C.

Investigated Stress Conditions

Tavenas and Leroueil (1977) have shown how the concept of limit state could be applied to represent the behaviour of natural, overconsolidated clays, and they suggested that time dependent phenomena should be analyzed by referring the effective stress conditions under which the phenomena may develop to the limit state of the intact clay. This approach was used in the present study to investigate the effect of stresses on the creep behaviour of the Saint-Alban clay.

The effective stress conditions at which creep tests were carried out are shown on Fig. 1. All tests were performed on samples obtained at 3.0 m depth; the limit state from 1 day duration tests of the intact clay at this depth is also shown on Fig. 1. In all cases the samples were first reconsolidated to the *in situ* stress condition, estimated at point 0 in Fig. 1, with a back pressure equivalent to the *in situ* hydrostatic pore pressure. Along line 3 and in the undrained tests, the final deviator stress was applied in one step. For tests on the other lines, the stresses were applied in increments lasting 24 h. Both drained and undrained tests were carried out over durations of 100 000 min, but, as already noted, undrained tests were affected by leakage and the results were considered to be acceptable only for the first 4000 min. The effective stress conditions in the undrained tests at $t = 10$ min are shown on Fig. 1. Vertical deformations and volume changes or pore pressures were measured at regular intervals. Corrections to the applied dead weights to maintain constant stresses were made when necessary depending on the observed changes in cross section area of the samples.

In a number of drained tests, the application of the creep stresses resulted in variations of the mean

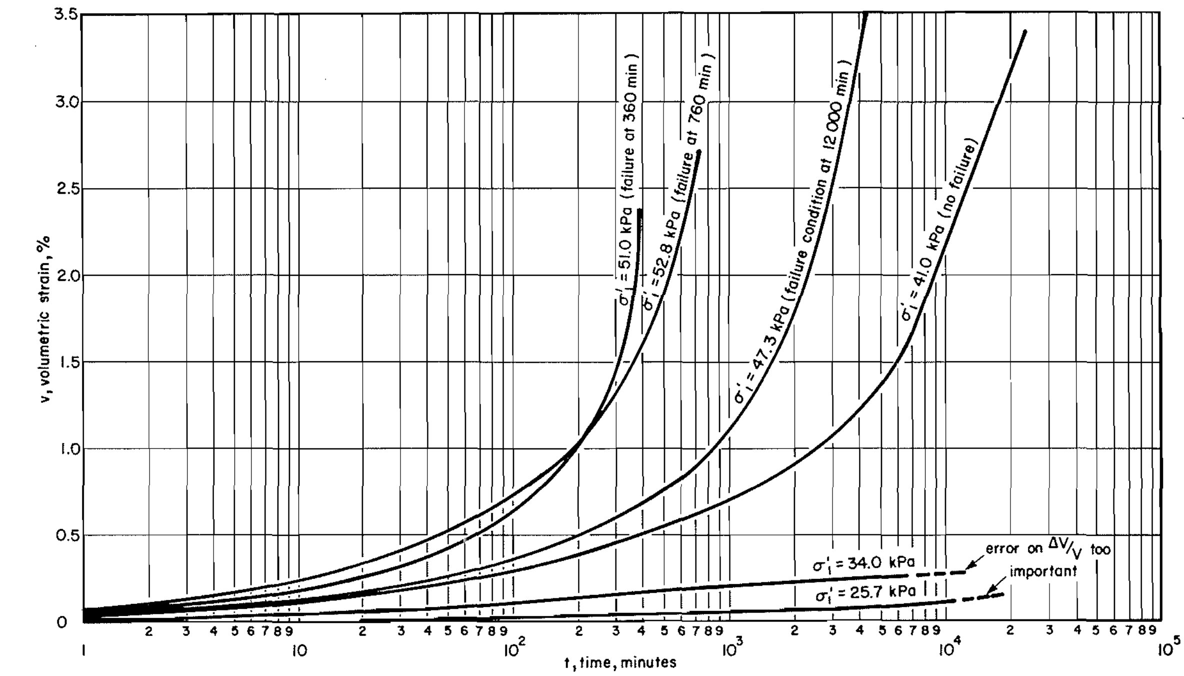

FIG. 2. Volumetric strain – time relationship for drained tests at $\sigma_3' = 16.5$ kPa performed along line 3 (Fig. 1).

normal effective stresses with consequent volume changes. However, the stepped stress application procedure was selected to maintain stress increment ratios of less than 0.3. In this case, according to various previous studies (e.g., Leonards and Girault 1961; Wahls 1962) the relative importance of primary consolidation is greatly diminished and the observed behaviour is essentially representative of secondary consolidation or creep. The results obtained in the present study confirm the validity of this principle.

Parallel to the triaxial test program, a series of long duration consolidation tests were carried out in the odometer. Samples from 3.0 m depth were initially reconsolidated to $P_o' = 22$ kPa and then loaded in one increment to vertical stresses of 28, 40, 45, 50, 54, 58, 63, 75, and 98 kPa, which were maintained for 100 000 min.

Development of Volumetric Strains with Time

As a result of the testing techniques used in the past, the development of volumetric strains with time has been investigated essentially in the odometer and it has been characterized by the coefficient of secondary consolidation C_α. Very few test results are available in the literature to evaluate the influence of the applied stress condition on the time dependency of volumetric strains. However, in view of the fact that long term deformation problems in the field are bound to be associated with partial or full drainage, i.e., with volume changes, and in order to be able to apply the approach suggested by Kavezajian and Mitchell (1977), it is necessary to develop a clear understanding of the influence of the stress conditions on the volumetric creep behaviour.

Drained Tests at $\sigma_3 = C^{st}$

The variations of volumetric strains with time in the creep tests along line 3 (Fig. 1) are shown on Fig. 2. Two types of behaviour may be observed: at low stress levels the volumetric strains remain small and after about 10 000 minutes the errors on v become of the same order of magnitude as the measured strains; at high stress levels the volume of the samples decreases rapidly as failure approaches; for the test at $\sigma_1' = 41$ kPa, large volume changes develop, a volumetric strain of 6% was observed at 60 000 minutes, but no sign of failure could be detected.

Using a 'five points' derivation technique, the volumetric strain rates $\dot{v}$ were determined as a function of time (Fig. 3). At low stress levels and in spite of some unavoidable scatter due to the small magnitude of the considered strain increments, a linear decrease of log $\dot{v}$ with log t can be observed.

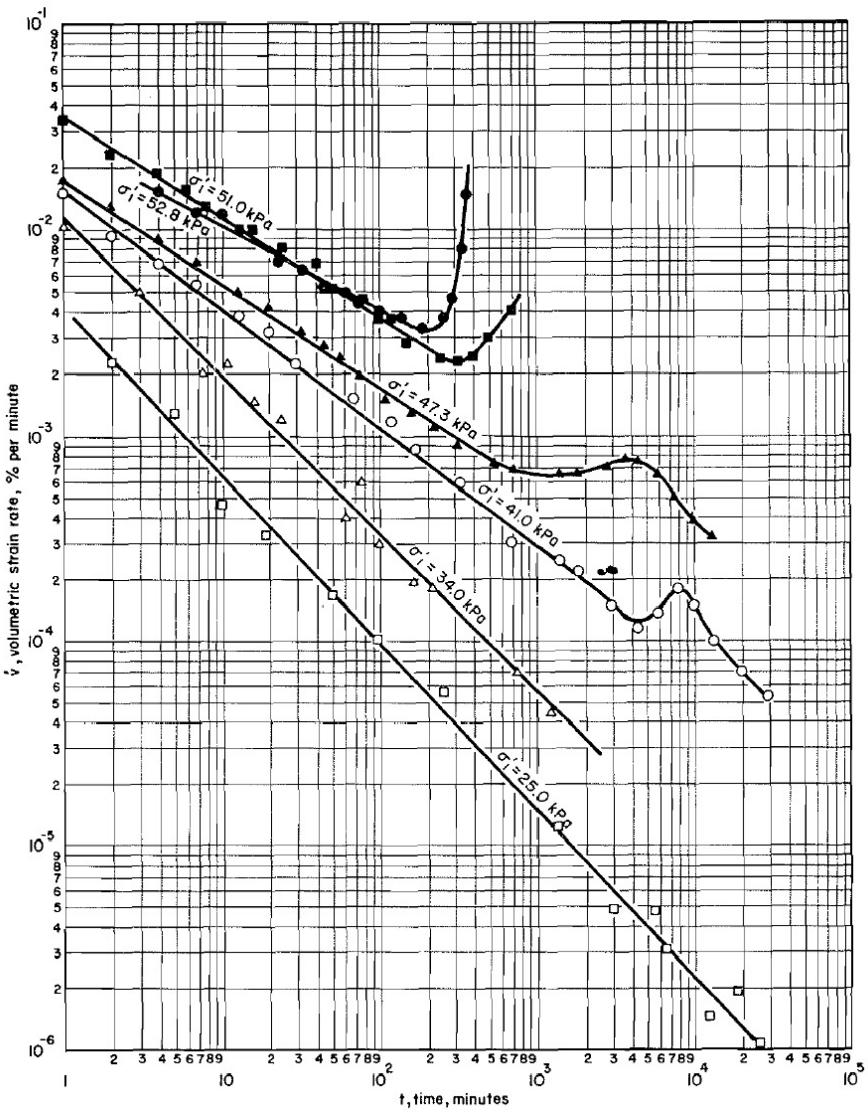

FIG. 3. Volumetric strain rate – time relationship for drained tests at $\sigma_3' = 16.5$ kPa performed along line 3 (Fig. 1).

Thus the volume changes of the clay are governed by an equation of the type:

$$\dot{v} = \beta\ (t_1/t)^m \quad [5]$$

The slope of the log $\dot{v}$ – log t lines represents the creep parameter m. According to the classical approach to volumetric creep [4], this parameter should be equal to 1.0. However, the test results indicate much lower values of m, which vary between 0.52 at high stress levels and 0.78 at low stress levels. The very low values of m for the tests with a duration of only a few hundred minutes could possibly be associated with a primary consolidation phenomenon, particularly since large volume changes occurred during these short periods (it might be noted that $m = 0.5$ represents the rate of volumetric strain in the early stages of development of Terzaghi's primary consolidation). On the other hand, at low stress levels, i.e. for low increases in mean normal stress, the perfect linearity of the log $\dot{v}$ – log t relationship confirms the negligible effect of primary consolidation.

At high stress levels, log $\dot{v}$ decreases linearly with log t initially, but a minimum strain rate is obtained, after which $\dot{v}$ increases rapidly to failure. This behaviour is similar to that observed by many

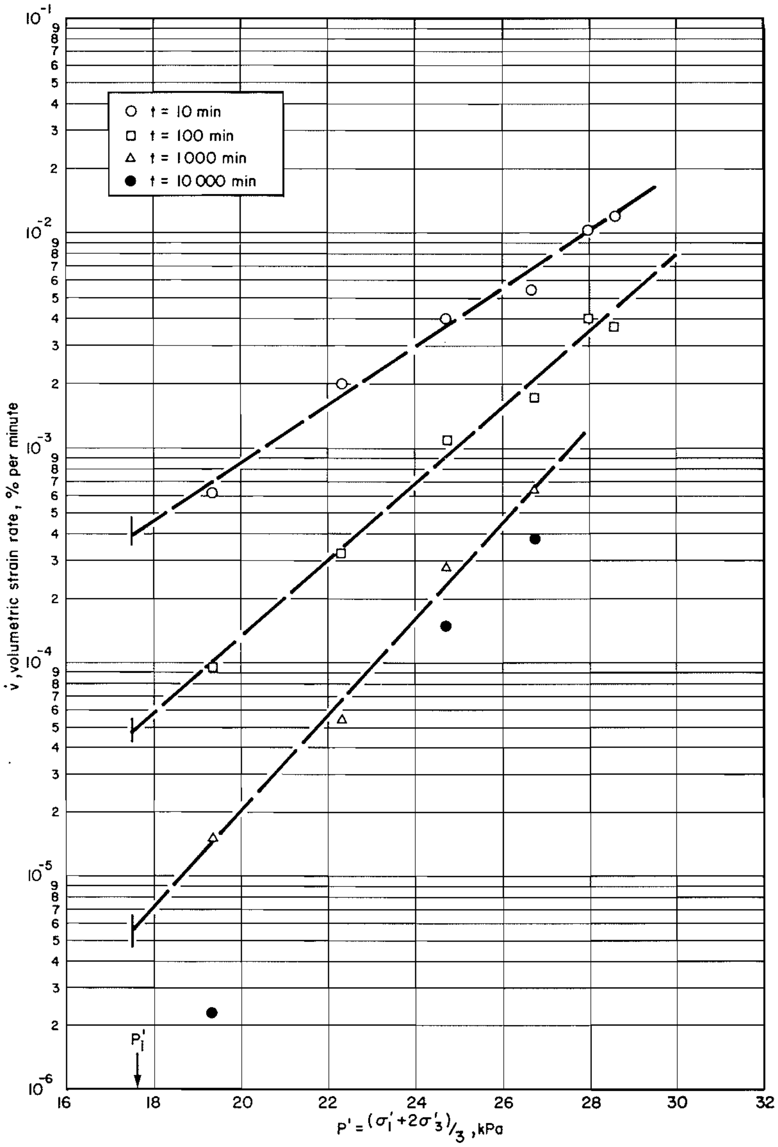

FIG. 4 Volumetric strain rate vs. mean normal effective stress in drained tests at $\sigma_3' = 16.5$ kPa performed along line 3 (Fig. 1).

investigators for the axial strain in undrained tests on normally consolidated clays (e.g., Campanella and Vaid 1974). The test at $\sigma_1' = 47.3$ kPa shows the same behaviour initially, but $\dot{v}$ decreases again after 4000 min. In this test the axial load was kept constant and the decrease in $\dot{v}$ corresponds to a reduction of σ_1' from 47.3 kPa at 2800 min to less than 46.5 kPa at 12 000 min, where large deformations and a near-failure condition were observed. Had the deviator stress been kept constant, it is likely that a true failure would have occurred earlier and in a brittle manner as for the tests at higher stresses. The test at $\sigma_1' = 41$ kPa shows a discontinuity in the decrease of log $\dot{v}$ with log t, but in this case σ_1' was kept constant; the observed variation of $\dot{v}$ is similar to that reported by Bishop and Lovenbury (1969) and must be associated with a particular behaviour of the clay structure under constant effective stresses.

In order to define in [5] the term β, which, by analogy with [3], should include a stress function, the variations of $\dot{v}$ with the mean normal effective stress p' have been plotted for various times t in Fig. 4. At any time, a linear relationship exists

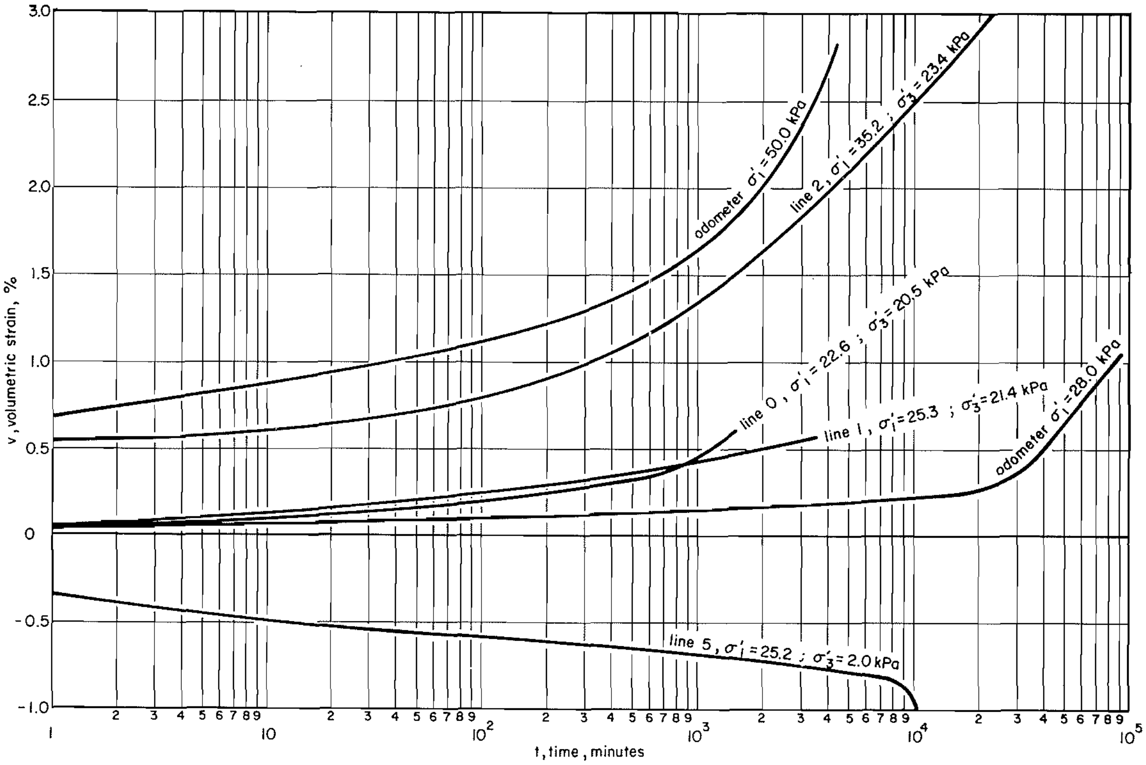

FIG. 5. Volumetric strain – time relationship for drained tests under various stress conditions.

between log $\dot{v}$ and p'. Considering the $\sigma_3' = C^{st}$ stress condition in all these tests, a similar linear relationship would also exist between log $\dot{v}$ and the shear stress so that [3], proposed by Singh and Mitchell (1968) for the description of axial strains and used by Kavezajian and Mitchell (1977) for deviatoric strains, can also be applied to volumetric strains. However, it should be noted that the creep parameter α is not a constant, as suggested by Singh and Mitchell (1968), but appears to be time dependent. In addition, since it is more logical to relate volumetric strains to p' than to the shear stress level, [3] should preferably be rewritten here as

$$[6] \qquad \dot{v} = \beta e^{\alpha(t)p'} (t_1/t)^m$$

Drained Tests under Various Stress Conditions

The variations of the volumetric strains with log t observed in four triaxial creep tests under various stress conditions and for two long term odometer tests are shown in Figure 5. The volumetric strain is obviously influenced by the mean normal effective stress p': in the test on line 5, at a value of p' about half the initial consolidation pressure, the specimen dilates continuously up to failure. In the tests on line 0 and 1 as well as in the odometer test at $\sigma_1' = 28$ kPa, little variation of p' occurred and limited volumetric strains developed with log t. On the other hand, the large volumetric strains observed on line 2 as well as in the odometer test at $\sigma_v' = 50$ kPa may be associated with both the magnitude of the variation of p' and the proximity of the limit state surface of the clay (Fig. 1).

The volumetric strain rates $\dot{v}$ computed for these tests are plotted against time in a log–log scale on Fig. 6. A primary consolidation phase is evident for the test on line 2 until about 200 min. Beyond this time, and at all times for the other tests, a linear decrease of log $\dot{v}$ with log t might be observed, even for the dilatant test on line 5. However, in this latter case, the volumetric strain rate starts to increase after 6000 min, a dilatant failure being observed at 10 000 min. The discontinuity in the log $\dot{v}$ – log t relationship observed for the test at $\sigma_1' = 41$ kPa (Fig. 3), occurs here in the odometer test; its cause remains to be established. Considering the observed linear log $\dot{v}$ – log t relationship observed here, [6] can be applied to describe the time dependency of volumetric strains in the overconsolidated Saint-Alban clay under

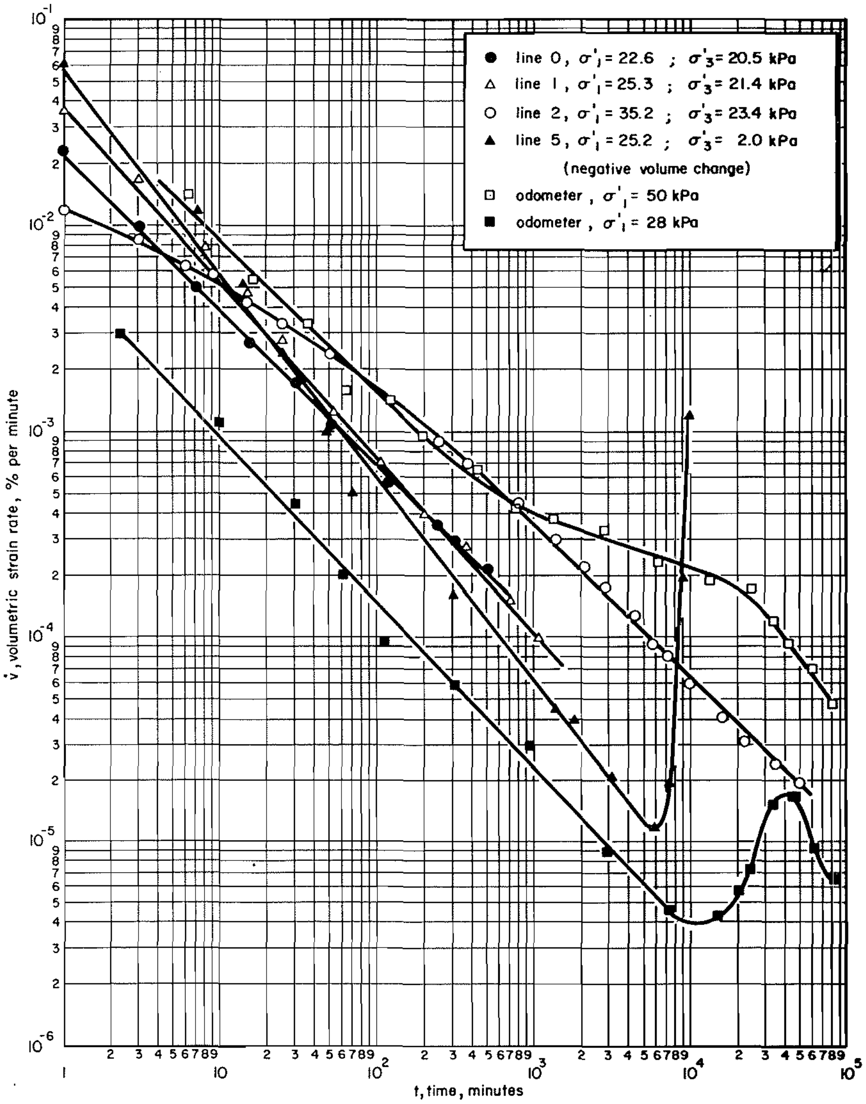

FIG. 6. Volumetric strain rate – time relationship for drained tests under various stress conditions.

all types of stress conditions, provided it is written in the more general form:

$$[7] \qquad \dot{v} = Bf(\sigma')\,(t_1/t)^m$$

The creep parameter m appears quite variable at first glance. The values observed for the different stress conditions are shown on Fig. 7. They vary between 0.52 and 0.93 with an average of 0.72 in the triaxial tests, and are of the order of 0.8 in the odometer tests. As shown on Fig. 7 there is no clear tendency for the variation of m with the stress condition and a constant m of the order of 0.7–0.8 could be considered representative of the behaviour of the overconsolidated clay.

In order to define the stress function $f(\sigma')$ in [7], a method similar to that used by Singh and Mitchell (1968) to derive [3] has been applied. The volumetric strain rates at $t = 100$ min have been plotted against various components of the stress field depending on the line of tests considered, and, as a result, the stress conditions producing equal volumetric strain rates have been plotted in the stress space, as shown in Fig. 8. The equations of this set of curves represent the stress function $f(\sigma')$. It should first be noted that a large area of the stress space, between lines 4 and 5, corresponds to very small or zero volume change so that no reliable measurement of $\dot{v}$ could be

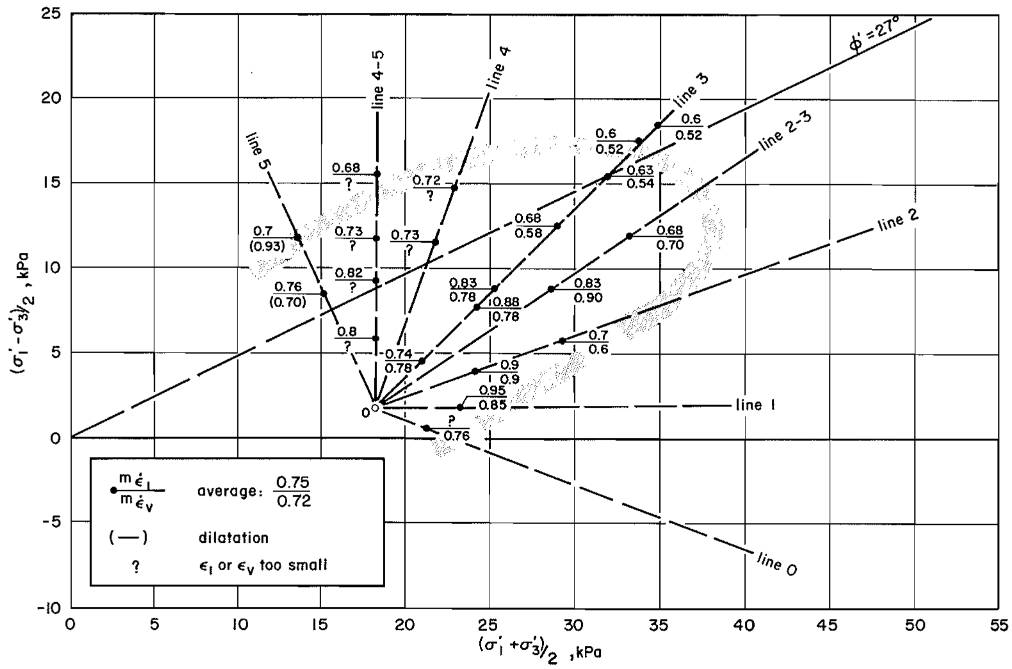

FIG. 7. Variations of the creep parameter m for volumetric and axial strains with the stress condition.

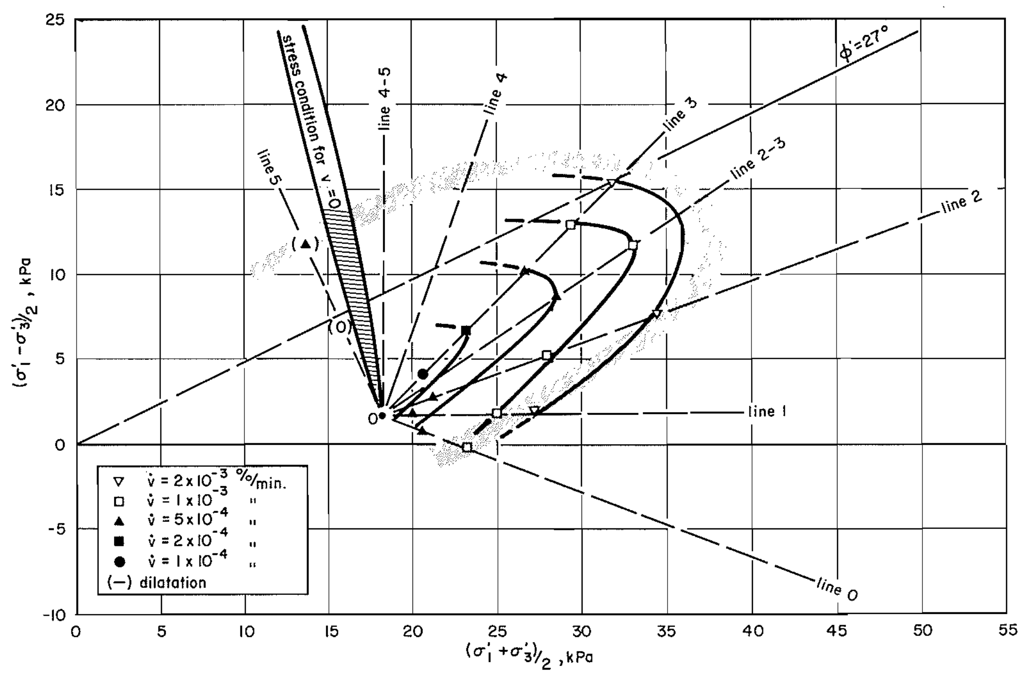

FIG. 8. Lines of equal volumetric strain rate at t = 100 min in the stress space for drained tests.

made. It is not clear if and how [7] might apply to such stress conditions, which correspond to a slight reduction in the mean normal effective stress p'. In the zone where volume changes are easily measured, i.e., between lines 0 and 3, the curves of equal volumetric strain rate are practically homothetic to each other as well as to the limit state surface of the clay. Therefore, the stress func-

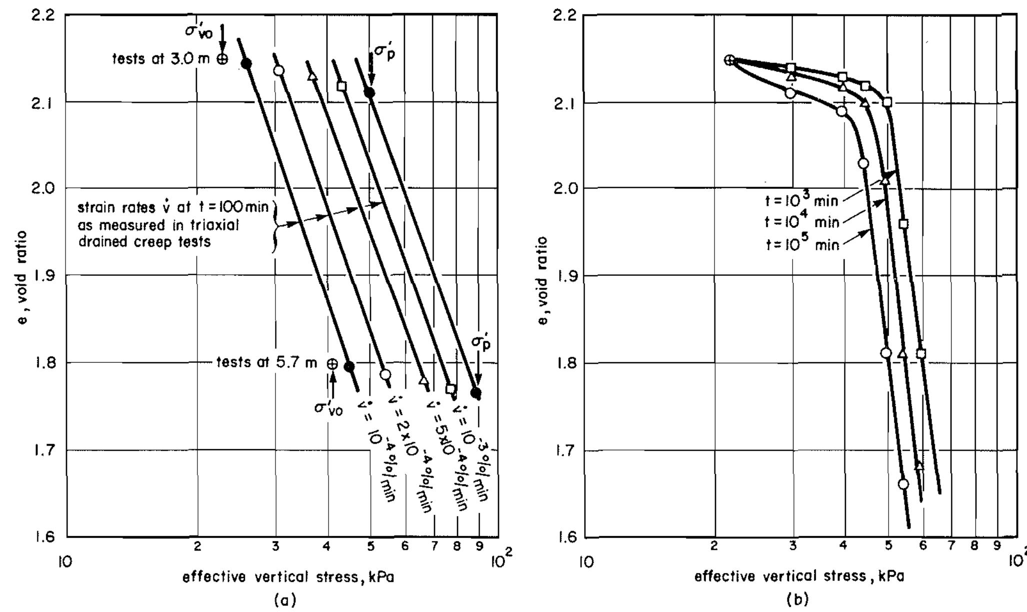

FIG. 9. Lines of equal volumetric strain rate and equal duration of loading in the $e - \log \sigma_v'$ plane for drained tests.

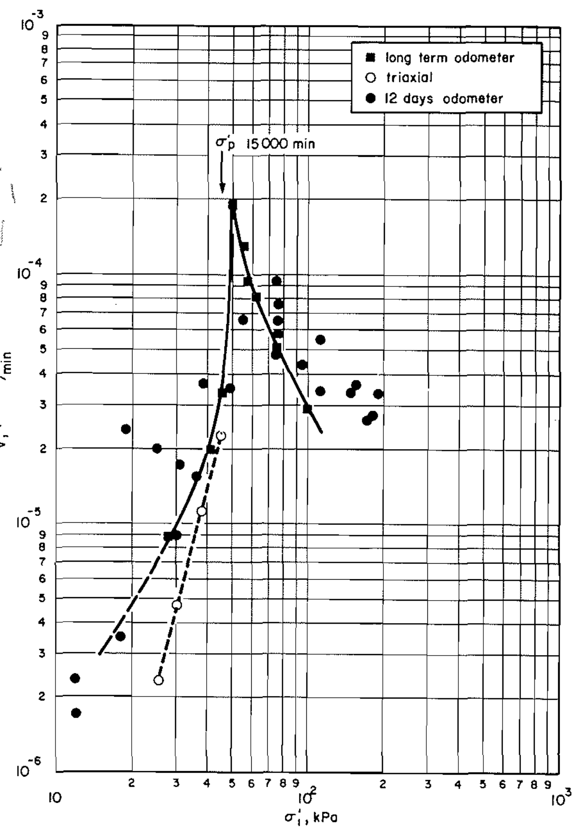

FIG. 10. Variations of the volumetric strain rate with σ_1' at t = 15 000 min.

tion $f(\sigma')$ should be derived from the equation of the limit state surface, and it should express the fact that the volumetric strain rate $\dot{v}$ for an overconsolidated clay at a void ratio e, under a stress condition (σ') is a function of the distance of this stress condition to the limit state surface of the clay at this void ratio.

An important consequence of this result is that the limit state surface is also a surface of equal volumetric strain rate. In other terms the classical coefficient C_α is a constant on the limit state. Combining this observation with the variations of C_α with the consolidation stress (Wahls 1962; Mesri and Godlewski 1977), i.e., with the position of the limit state in the stress space, a general formulation of the time dependent volumetric strains appears possible in both normally consolidated and overconsolidated clays.

It was suggested at the beginning of this paper that the concepts of limit state and of isotaches could eventually be associated to arrive at a general formulation of the time dependent behaviour of clays. The results presented in Fig. 8 provide a first element of justification. In order to assess the applicability of the concept of isotaches proposed by Suklje (1957), the relation between $\dot{v}$ and σ_1' was determined along the K_0 line. The results are plotted as a function of the corresponding void ratio (assuming a uniform void ratio e_0 = 2.15 for all tests at 3.0 m) in Fig. 9a. Also shown

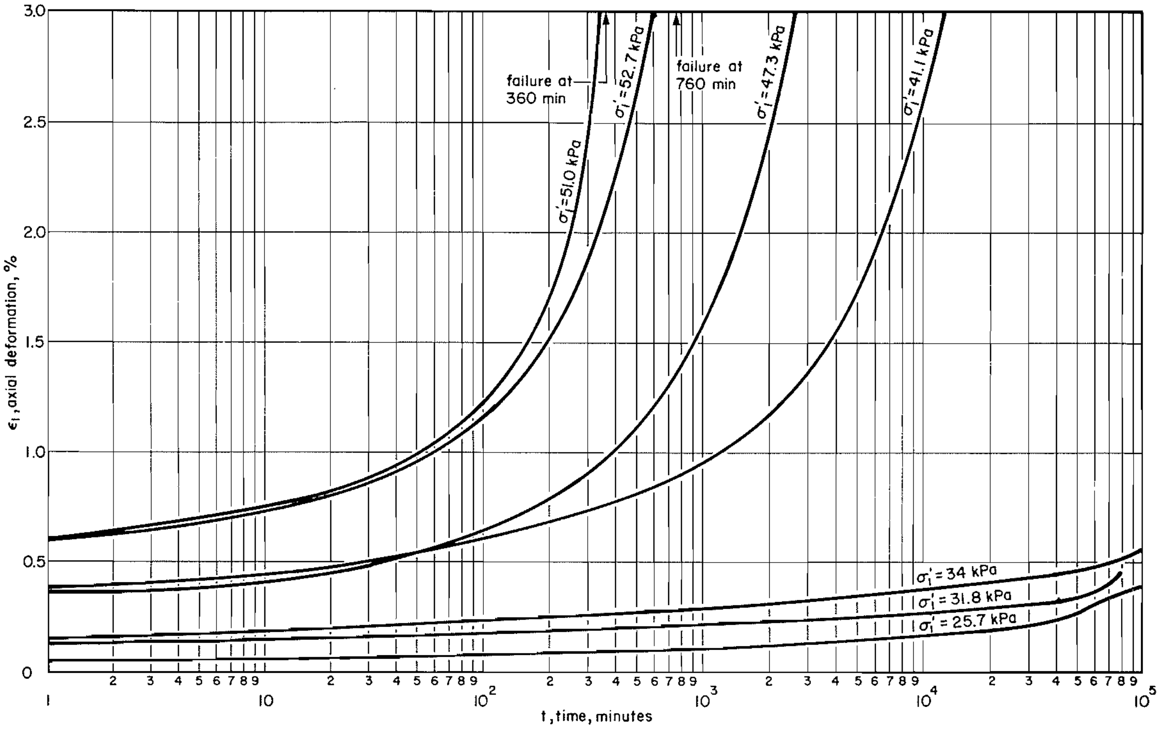

FIG. 11. Axial strain – time relationship for drained tests at $\sigma_3' = 16.5$ kPa performed along line 3 (Fig. 1).

on this figure are the results derived from a series of K_0 consolidation triaxial tests on samples from 5.7 m depth ($e_0 = 1.8$) on the same site. As can be seen, the lines joining the points of equal strain rates at 3.0 m and 5.7 m are practically parallel to each other as well as to the line joining the e–σ_p' results of odometer tests at the two depths.

These lines of equal strain rates apparently correspond to Suklje's isotaches. However, in Suklje's version of the Taylor–Bjerrum model the isotaches are identical to the equal duration of loading lines defined by Bjerrum (1967). Such lines of equal duration of loading have been defined by Tavenas and Leroueil (1977) from odometer tests on samples from the Saint-Alban clay at 3.0 m depth. As shown on Fig. 9*b*, the spacing of these lines is much closer than that of the lines of equal strain rate in Fig. 9*a*; this difference in spacing can be easily estimated by comparing lines having ratios of 10 either between durations of loading or between strain rates. The curves in Fig. 9*b* result essentially from the behaviour of specimens loaded to stresses in the vicinity of σ_p' or in the normally consolidated range, while the behaviour represented in Fig. 9*a* is essentially representative of the overconsolidated clay. Thus, it appears that the isotaches network is different depending on whether the clay is initially normally consolidated or overconsolidated; this influence of the state of consolidation on the shape of the isotaches has already been mentioned, but not demonstrated, by Suklje (1957). Based on the results of the present study an explanation of this phenomenon may be attempted.

According to the Taylor–Bjerrum model, at a given void ratio a linear relationship exists between log $\dot{v}$ and log t, the strain rate being constant and independent of the stress on the virgin compression line. However, in natural, sensitive clays, the strain rate is known to vary with the applied stress (Wahls 1962; Mesri and Godlewski 1977), the variations being more marked in highly structured clays. As for the Saint-Alban clay, the strain rates observed after 15 000 min in the tests that served to establish Fig. 9*b* are plotted on Fig. 10. The strong stress dependence of $\dot{v}$ is evident, as is the influence of the preconsolidation pressure σ_p', which corresponds approximately to the maximum strain rate. The results obtained from other long duration odometer tests are also shown on Fig. 10 and they exhibit the same trends. The shape of the log $\dot{v}$ – log σ_1' curve in the overconsolidated range might now be used to understand the behaviour

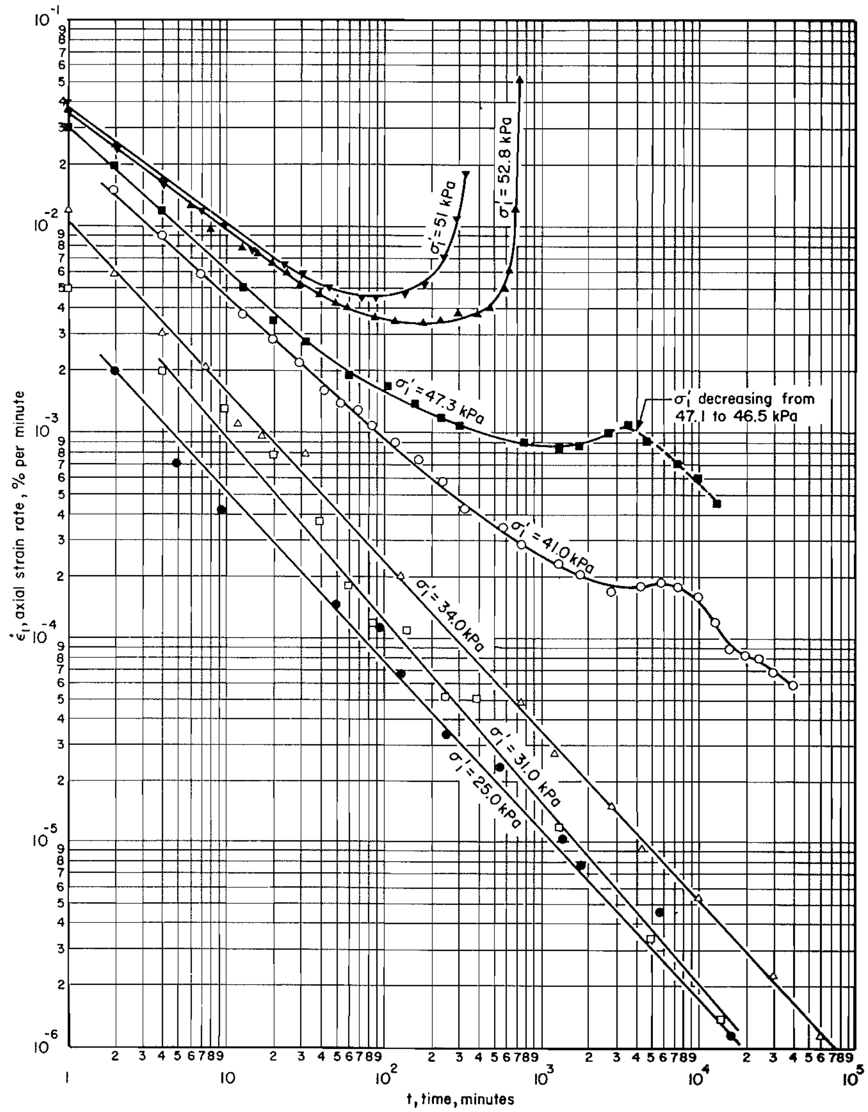

FIG. 12. Axial strain rate – time relationship for drained tests at $\sigma_3' = 16.5$ kPa performed along line 3 (Fig. 1).

represented in Fig. 9 *a* and *b*. In the vicinity of the preconsolidation pressure, the strain rate decreases very rapidly with σ_1', the steep slope of the log $\dot{v}$ – log σ_1' corresponding to the close spacing of the curves in Fig. 9*b*. However, for smaller stresses, the reduction of $\dot{v}$ becomes less pronounced, thus resulting in a wider spacing of the lines of equal strain rate in Fig. 9*a*. The strain rates observed in triaxial tests (extrapolated to 15 000 min, assuming $m = 0.75$) confirm this tendency as shown on Fig. 10. Considering now that the peak in the log $\dot{v}$ – log σ_1' curve that generates this phenomenon is essentially due to the presence of a marked structure in the overconsolidated clay, it is suggested that the Taylor–Bjerrum model does not apply in overconsolidated structured clays and, consequently, that Suklje's isotaches are discontinuous for $\sigma_1' = \sigma_p'$.

Development of Axial and Shear Strains with Time

As noted by Kavezajian and Mitchell (1977), the time dependency of strains developing in a clay submitted to any type of stress condition can be completely described by the separate consideration of volumetric strains and shear strains. The time dependency of volumetric strains and a possible method of expressing it by reference to the limit state of the clay has been discussed in the previous

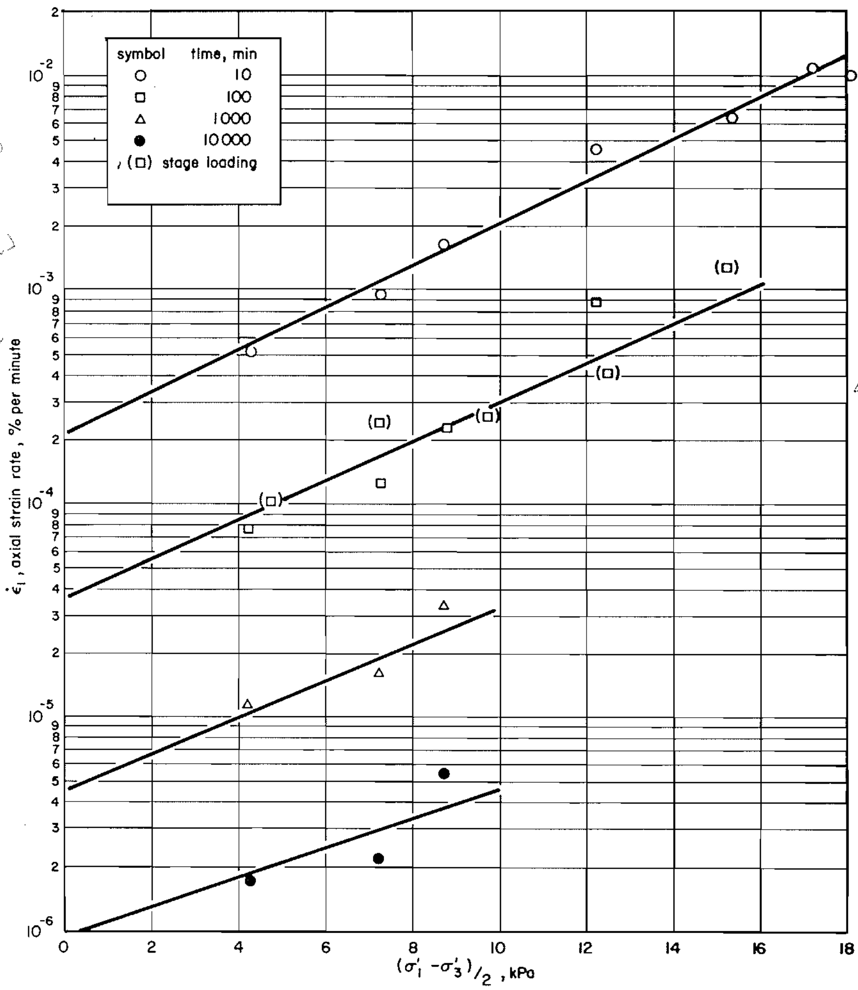

FIG. 13. Axial strain rate vs. shear stress for drained tests at $\sigma_3' = 16.5$ kPa performed along line 3 (Fig. 1).

section. The results of the present laboratory investigation may now be used to analyze the shear strain behaviour of the overconsolidated Saint-Alban clay.

Shear strains can be directly investigated by means of undrained triaxial tests since, in such tests, volumetric strains are equal to zero. However, as already discussed, truly undrained tests are nearly impossible to carry out on overconsolidated clays. In this case it appears preferable to use drained tests and to obtain the shear strains ϵ indirectly from the axial strains ϵ_1 by means of the relationship:

$$[8a] \qquad \epsilon = \epsilon_1 - \tfrac{1}{3}v$$

which can also be written in terms of strain rates:

$$[8b] \qquad \dot{\epsilon} = \dot{\epsilon}_1 - \tfrac{1}{3}\dot{v}$$

Axial Strains in Drained Tests at $\sigma_3 = C^{st}$

Figure 11 presents the development of axial strain with time in the series of drained tests along line 3 (Fig. 1). The shape of the ϵ_1 – log t curves are similar to those of the v – log t curves presented in Fig. 2 and the same groups of behaviour can be defined: at low stress levels the axial strains remain small; at high stress levels large deformations develop rapidly and a brittle failure was observed in the two tests at $\sigma_1' > 50$ kPa.

Figure 12 presents the variations of the logarithm of the axial strain rates with the logarithm of time. Again here there is a complete similarity with the data presented in Fig. 3. Thus the behaviour of the overconsolidated Saint-Alban clay conforms to an equation of the type:

$$[9] \qquad \dot{\epsilon}_1 = \beta(t^1/t)^m$$

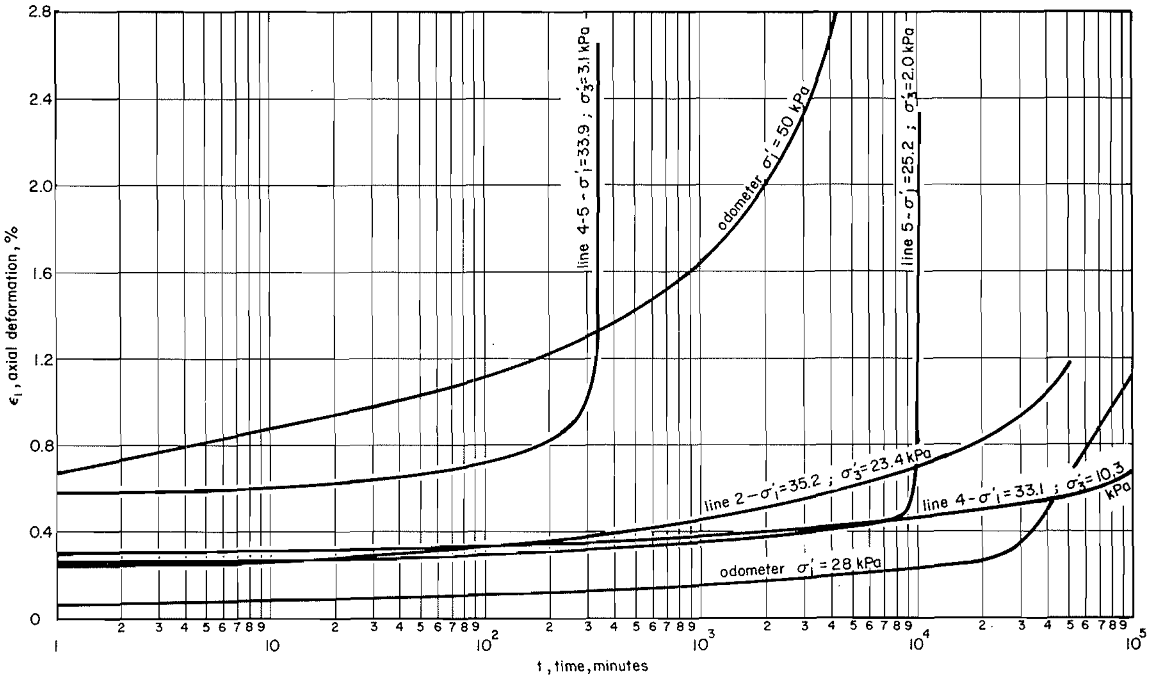

FIG. 14. Axial strain – time relationship for drained tests under various stress conditions.

as proposed by Singh and Mitchell (1968). The slope m of the log $\dot{\epsilon}_1$ – log t lines for $\sigma_1' < 35$ kPa is practically constant and of the order of 0.8. At higher stress levels, the m values are initially lower and the influence of the approaching failure already discussed for the volumetric strains is also evident here. The observed variation of m with the stress level is not consistent with the data presented by Singh and Mitchell (1968), but, as already noted, a primary consolidation process might have affected the results of the tests in which a large increase of the mean stress has been applied.

For different times varying between $t = 10$ and 10 000 min, the strain rate $\dot{\epsilon}_1$ observed in the different drained tests along line 3 has been plotted as a function of the corresponding shear stress in Fig. 13. At a given value of t, a linear relationship exists between log $\dot{\epsilon}_1$ and $q = \sigma_1' - \sigma_3'$, indicating that the behaviour of the overconsolidated Saint-Alban clay conforms to the general stress–strain–time function given by [3]. As noted by Singh and Mitchell (1968), the creep parameter α, which is the slope of the log $\dot{\epsilon}_1 - q$ lines, is practically a constant for the different values of t.

Axial Strains in Drained Tests at Various Stress Conditions

Figure 14 presents the increase in axial strain with the logarithm of time for four drained triaxial creep tests under different stress conditions and for two long term odometer tests. As for the volumetric strains, two types of behaviour can be identified: for stress conditions well inside the limit state surface of the clay (Fig. 1), such as for line 4 at $\sigma_1' = 33.1$ kPa and for the odometer test at $\sigma_v' =$ 28 kPa (Fig. 14), the axial strains increase more or less regularly with log t and remain small after 100 000 min; for stress conditions close to the limit state, such as for line 4.5 at $\sigma_3' = 3.1$ kPa and line 5 at $\sigma_2' = 2$ kPa and in the odometer test at $\sigma_v' = 50$ kPa, the axial strains become very important after a certain time, variable for each test, and failure conditions develop in the triaxial tests. It might be noted that the volume changes corresponding to these large axial strains were small and negative (i.e., dilatant) for the test on line 5, small and positive (i.e., contractant) for the test on line 4.5, and obviously large and positive for the odometer test. Similar trends were observed for all drained creep tests, depending on the position of the applied stress condition relative to the limit state surface of the clay.

Figure 15 presents a few typical variations of the axial strain rate with time. Again here a linear decrease of log $\dot{\epsilon}_1$ with increasing log t is observed. The values of the creep parameter m in [3] observed for the different stress conditions in drained tests are presented in Fig. 7. They vary between a

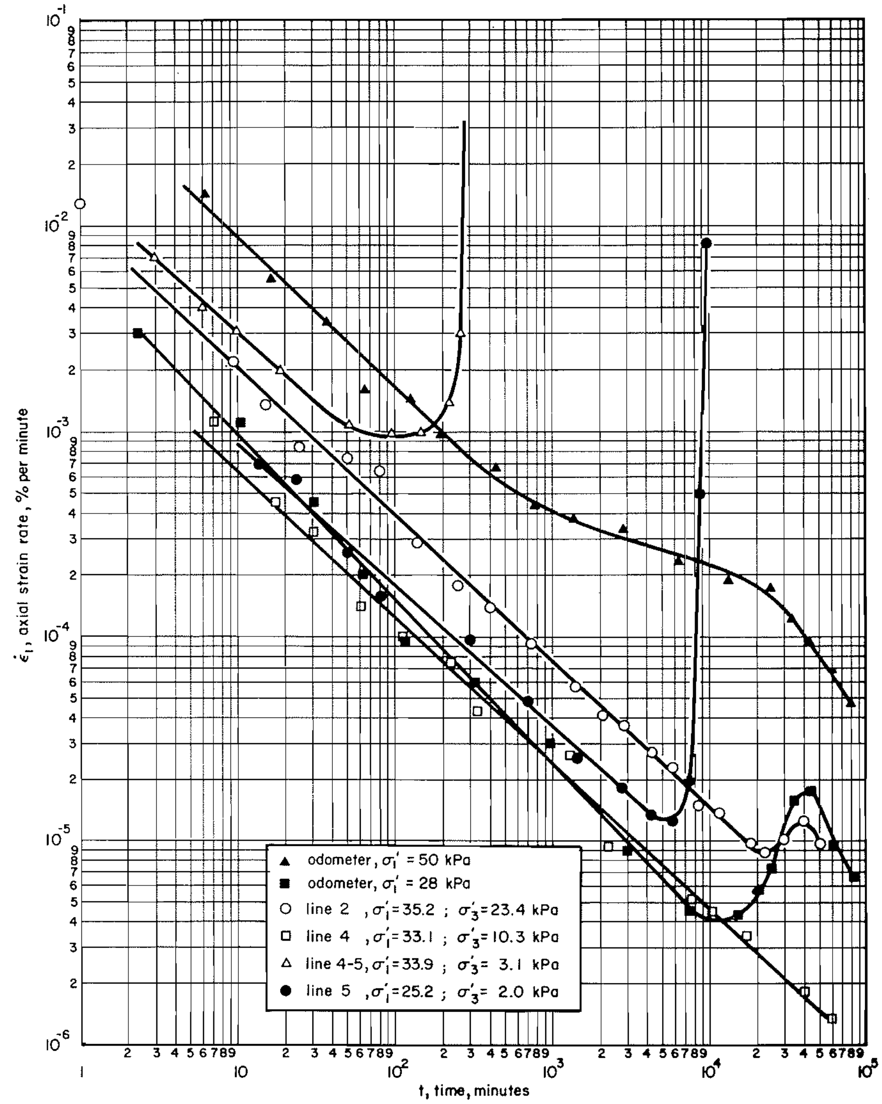

FIG. 15. Axial strain rate – time relationship for drained tests under various stress conditions.

minimum of 0.6 at high shear stresses on line 3 and a maximum of 0.95 on line 1. There may be a slight tendency for m to increase with the shear stress but, in view of the sensitivity of m to small errors, it can be concluded in first approximation that the creep parameter m for axial strain is constant and of the order of 0.76 $\pm$ 0.16, i.e., similar to that applicable to volumetric strains.

Therefore, an equation, similar to [3] proposed by Singh and Mitchell (1968), but taking the more general form of

$$[10] \qquad \dot{\epsilon}_1 = Ah(\sigma')\ (t_1/t)^m$$

appears to be representative of the axial creep under all types of stresses in the overconsolidated range. The stress function $h(\sigma')$, which was correctly formulated as $h(\sigma') = e^{\overline{\alpha q}}$ by Singh and Mitchell (1968) for tests at $\sigma_3 = C^{st}$ requires a more general definition. Analyzing the volumetric strain, it was shown that the similar stress function $f(\sigma')$ could best be defined by reference to the limit state of the clay. Using the same technique, the lines of equal axial strain rate at t = 100 min have been determined as shown in Fig. 16. The eventual, though not obvious, equations of this set of curves correspond to the stress function $h(\sigma')$. More data of this type are required before $h(\sigma')$ can be formulated, but at this stage, few simplified considera-

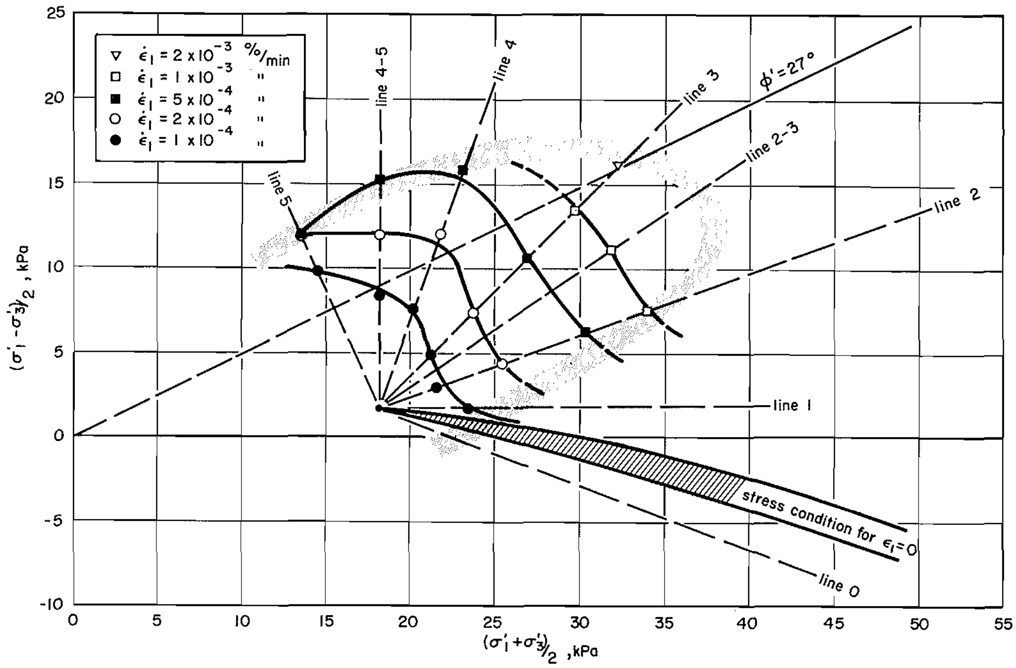

FIG. 16. Lines of equal axial strain rate at t = 100 min in the stress space for drained tests.

tions are in order. For mean normal effective stresses equal to or less than the initial consolidation stress, i.e., to the left of line 4, the axial strain rate appears to be essentially governed by the shear stress and the shear strength. For mean normal effective stresses in excess of the initial consolidation stress, i.e., to the right of line 4, the lines of equal vertical strain rate correspond roughly to lines of $\sigma_1' = C^{st}$. However, for shear stresses less than the initial value a zone of $\dot{\epsilon}_1 = 0$ may be defined, which will obviously correspond to asymptotic tendencies of $\dot{\epsilon}_1$. In any case, for all stress conditions between lines 1 and 4, the axial strain rate $\dot{\epsilon}_1$ could be expressed as a function of σ_1' in a manner similar to that proposed by Suklje (1957) as already discussed. However, and as for the volumetric strain rates presented in Fig. 8, the spacing of the $\dot{\epsilon}_1 = C^{st}$ lines in the stress space is much wider that what would be expected from the direct application of the Taylor–Bjerrum model (see Fig. 9).

Shear Strains in Drained and Undrained Tests

A series of 13 undrained triaxial creep tests, consolidated to the same initial effective stress condition 0 (Fig. 1) as the drained tests, was carried out on the same clay. The applied effective stress conditions at t = 10 min are shown on Fig. 1. Figure 17 presents the variations of log $\dot{\epsilon}$ = log $\dot{\epsilon}_1$ with log t observed in six of these tests (the values of σ_{10}' indicated correspond to the sum of the vertical consolidation pressure σ_1' at point 0 and the applied increment in total vertical stress σ_1). The linear decrease of log $\dot{\epsilon}_1$ = log ϵ with log t is identical to what has been reported for undrained tests on normally consolidated clays (e.g., Campanella and Vaid 1974) and is remarkably similar to the results of the drained tests (Fig. 12); the small effective stress variations already noted do not seem to modify the observed behaviour. At all stress levels the slope m of the log $\dot{\epsilon}_1$ – log t lines is constant and of the order of 0.78, i.e., close to the m values obtained in drained tests at low stress levels.

The variations of $\dot{\epsilon}_1 = \dot{\epsilon}$ with the shear stress at different times are shown on Fig. 18. There is a clear linear relation between log $\dot{\epsilon}_1$ = log $\dot{\epsilon}$ and the deviator but the slope $\bar{\alpha}$ is apparently smaller than that obtained in the drained tests. In addition, at a given stress level and a given time, the axial strain rates in the drained tests are greater than those in the undrained tests. This can be related to the contribution of the volumetric strain component in the drained tests. Indeed, as shown on Fig. 18, the shear strain rates obtained from the drained tests by combining, according to [8b], the axial and volumetric strain rates presented in Figs. 4 and 13 for t = 100 min, are in excellent agreement with

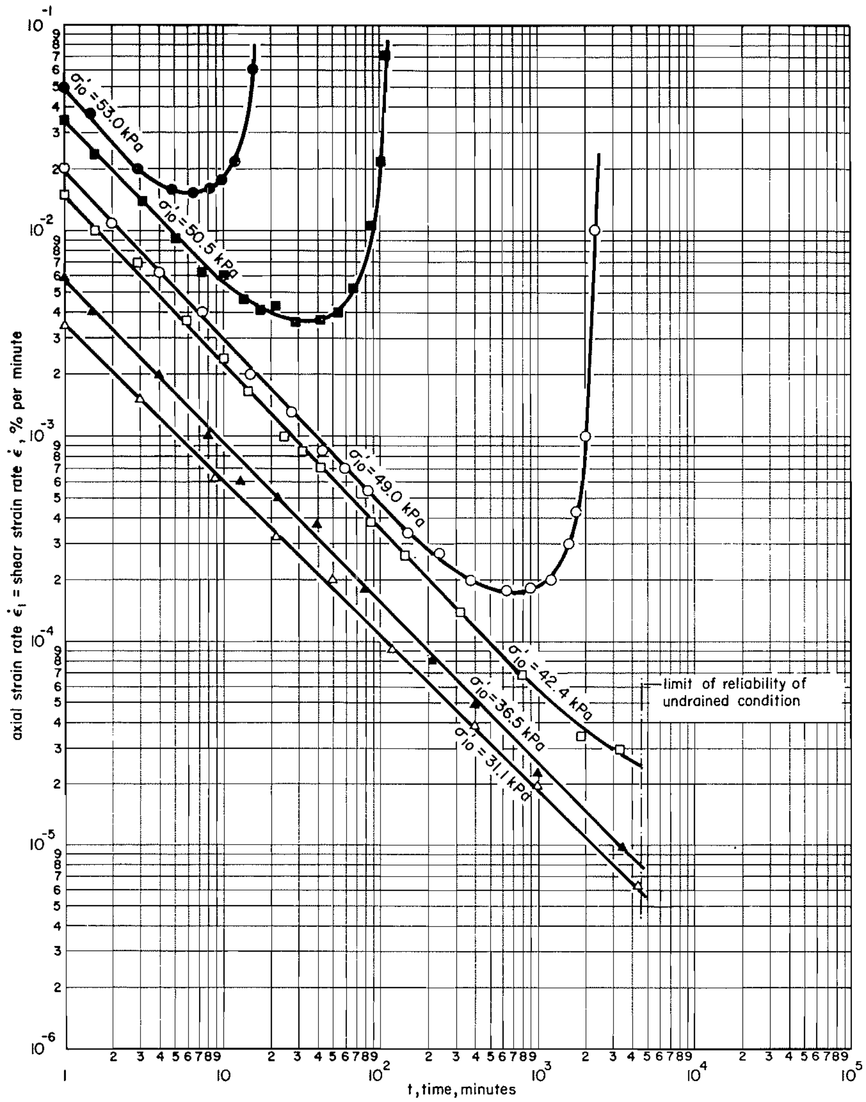

FIG. 17. Shear strain rate – time relationship for undrained tests at $\sigma_{30}' = 16.5$ kPa.

the results of the undrained tests. These results confirm the validity of the principle of separation in volumetric and shear strain components proposed by Kavezajian and Mitchell (1977).

The results of both the drained and undrained creep tests indicate that the development of shear strains with time in the overconsolidated Saint-Alban clay conforms to an equation of the form

[11] $\dot{\epsilon} = Ag(\sigma')(t_1/t)^m$

As already noted, the creep parameter m can, for all practical purposes, be assumed constant and identical for all components of strains, of the order of 0.7–0.8. In order to obtain some idea on the form of the stress function $g(\sigma')$, the results of the drained tests presented in Figs. 8 and 16 have been combined according to [8b] to obtain the form of the lines of equal shear rates at t = 100 min, as shown in Fig. 19. The equations of these lines represent the stress function $g(\sigma')$. As can be seen, at low mean normal effective stresses, to the left of line 4, the limit state surface appears to be a line of constant shear strain rate and the shear strain rate contours are homothetic to it. This behaviour is very similar to that observed for the volumetric strain rates in that portion of the stress space located below the Mohr–Coulomb line of the normally consolidated clay. The limit state surface

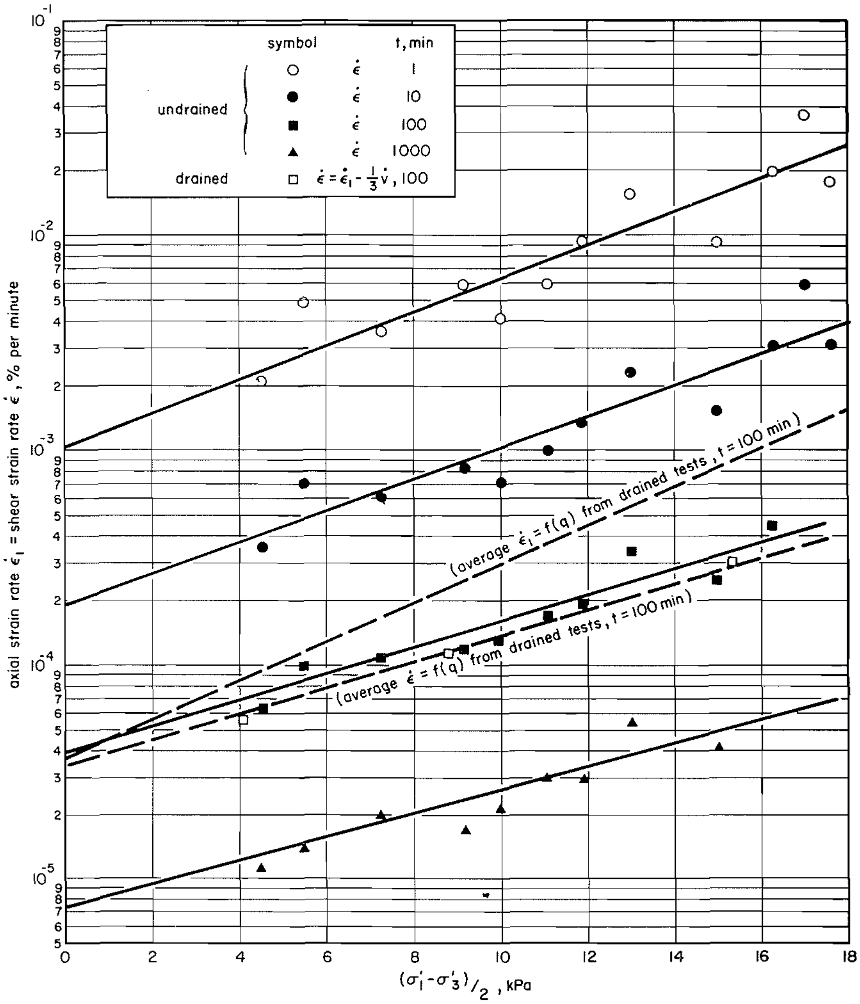

FIG. 18. Shear strain rate vs. shear stress for undrained and drained tests at $\sigma_{30}' = 16.5$ kPa.

would thus be a reference for both volumetric and shear strain; how the continuity is ensured in the vicinity of the Mohr–Coulomb line remains to be investigated and explained. At high mean normal effective stresses, to the right of line 2.3, the shear strain rate seems to be governed by the shear stress level, which is in agreement with the results obtained by Singh and Mitchell (1968) for tests in normally consolidated clays. There would thus be a continuity of the shear strain rates – shear stress relationship across the limit state surface of the clay. The transition between the two regimes of behaviour seems to occur more or less at constant mean normal effective stress, but further investigations are necessary to clarify this phenomenon.

Generalized Creep Behaviour of the Overconsolidated Saint-Alban Clay

Departing from the classical distinction between secondary consolidation and creep and from the limited stress conditions under which time dependent phenomena have been investigated in the past, the present investigation has considered the time dependent development of volumetric, axial, and shear strains in the undisturbed, overconsolidated Saint-Alban clay under a wide variety of stress conditions.

The first major result is that the phenomenological equation ([3]) initially proposed by Singh and Mitchell (1968) to represent the axial creep of normally consolidated clays in undrained conditions, can be generalized to represent the time dependency of all components of strains, in the form of [7] and [11]. The knowledge of the volumetric strain rates $\dot{v}$ and the shear strain rates $\dot{\epsilon}$ is sufficient to determine the time dependency of any component of the strain field, as noted by Kavezajian and Mitchell (1977).

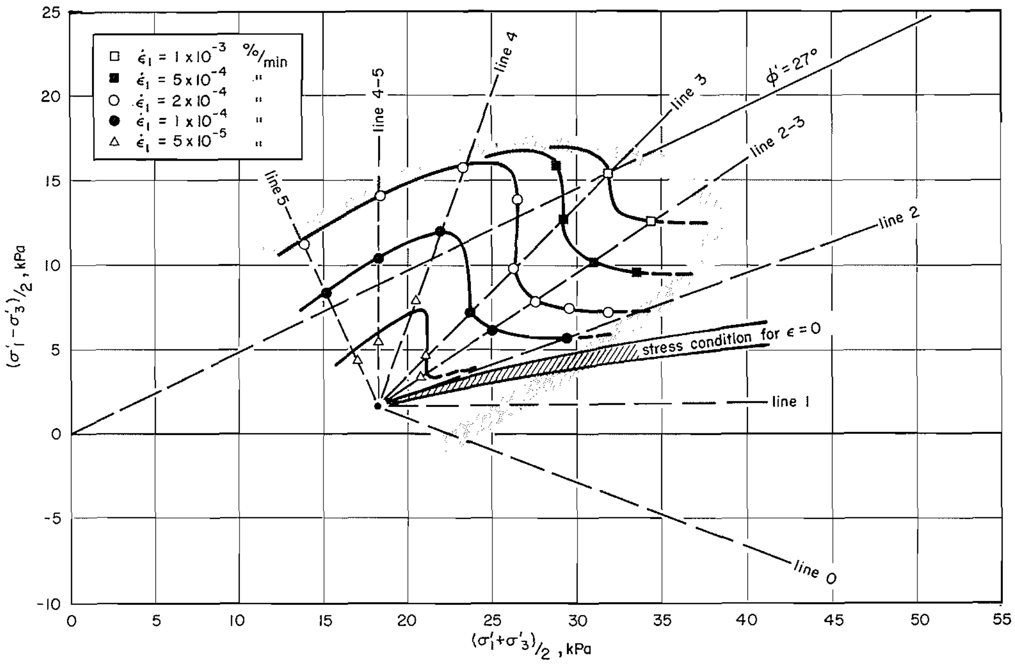

FIG. 19. Lines of equal shear strain rates at t = 100 min in the stress space for drained and undrained tests.

The stress functions $f(\sigma')$ and $g(\sigma')$ may best be defined by reference to the limit state surface of the clay, at least for certain stress conditions. In particular it was shown that the limit state corresponds to a surface of constant volumetric strain rate below the Mohr–Coulomb criterion, and to a surface of constant shear strain rate above this criterion. These results tend to confirm the hypothesis put forward at the beginning of this paper, that the concepts of limit state and of isotaches could be combined to produce a general model of the time dependent behaviour of clays.

A further confirmation of the validity of this hypothesis is obtained from the analysis of time effects on the limit state surface of the Saint-Alban clay. Combining the results of the present investigation with those presented by Tavenas and Leroueil (1977), the effect of time on the limit state surface has now been defined at five different stress conditions (Fig. 20*a*). It is entirely in agreement with the principles of the YLIGHT model. To investigate the possible effect of the stress condition on the rate of displacement of the limit state, the variations of σ_1' corresponding to the various stress conditions have been plotted against log t in Fig. 20*b*. In spite of a limited scatter, an average linear reduction of σ_1' with log t can be determined. Such a linear relationship would imply that the rate of displacement $\dot{\sigma}'$ of the limit state is of the form:

$$[12] \qquad \dot{\sigma}' = -\dot{a}/t$$

or, by comparison with [7], that the corresponding parameter m would be equal to 1, i.e., different from those observed for $\dot{v}$ and $\dot{\epsilon}$.

In discussing Figs. 8 and 9 it was noted that the spacing between the $\dot{v} = C^{st}$ lines in the stress space was much larger than what could be expected from the application of the Taylor–Bjerrum model. Comparing figures 8, 19, and 20, the same conclusion can be generalized, that the lines of equal volumetric and shear strain rates, although identical in shape, are much more widely spaced than the limit state surfaces at various times. Thus, and as already discussed, although the combination of the concept of limit state and isotaches appears possible, it will first be necessary to investigate the effect of overconsolidation on the shape of the isotaches before this combination can be used to completely describe the time dependent behaviour of clays.

Conclusion

It was the purpose of the present investigation on the creep behaviour of the undisturbed Saint-Alban clay, to fill one of the major gaps in the present knowledge of creep phenomena, by looking into the drained and undrained creep of overconsolidated clays, and to develop a general description of creep on the basis of the YLIGHT model proposed by Tavenas and Leroueil (1977).

The main conclusions are as follows:

1. As suggested by Kavezajian and Mitchell

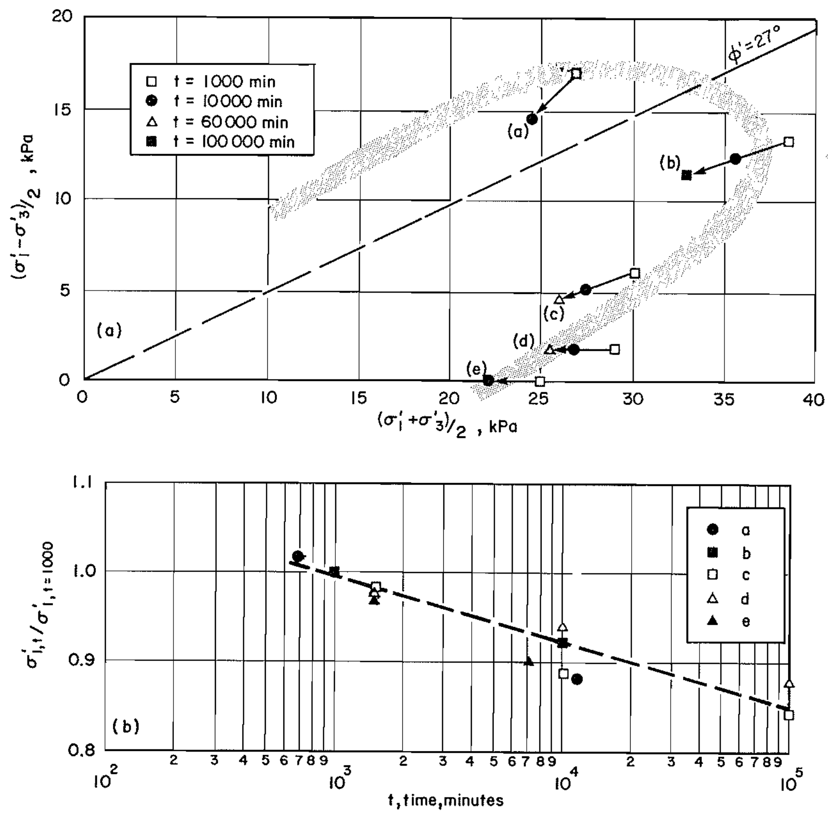

FIG. 20. Displacement of the limit state surface with time.

(1977), creep deformations can be investigated in terms of a volumetric strain component v and a deviatoric strain component ϵ.

2. The phenomenological equation proposed by Singh and Mitchell (1968) correctly describes all strain components during the creep of overconsolidated clays. It may be written in the two general forms given in [7] and [11].

3. In first approximation the creep parameter m for all stresses and drainage conditions can be assumed constant and of the order of 0.7–0.8 (average 0.76).

4. The stress function $f(\sigma')$ for volumetric strains should be expressed in terms of the limit state of the clay. The limit state surface is a surface of equal volumetric strain rate in the area of the stress space within the Mohr–Coulomb criterion of the normally consolidated clay. This result can be used to generate the description of creep in normally consolidated clays.

5. The stress function $g(\sigma')$ for shear strains should be expressed in terms of the limit state of the clay for mean normal effective stresses less than the initial state. It may be expressed with reference to the shear stress level, as proposed by Singh and Mitchell (1968) for mean normal effective stresses in excess of the initial state as well as for normally consolidated clays. At low effective stresses, the limit state surface is a surface of equal shear strain rate in the area of the stress space outside the Mohr–Coulomb criterion of the normally consolidated clay.

6. The basic hypothesis in the YLIGHT model proposed by Tavenas and Leroueil (1977), that the time dependent behaviour of an overconsolidated clay is completely described by the time dependent displacement of its limit state surface, is confirmed. The suggestion that the concept of isotaches (Suklje 1957) could be combined with that of limit state surfaces to provide a complete analytical description of time dependent deformations is also confirmed in principle. However, the effect of overconsolidation on the shape and spacing of the isotaches needs further investigation.

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