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A COMPREHENSIVE EXPERIMENTAL STUDY OF THE STRENGTH CHARACTERISTICS OF REMOULDED SPECIMENS OF KAOLIN

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SYNOPSIS

This paper summarises the data associated with the strength characteristics of remoulded specimens of kaolin tested in the conventional triaxial apparatus under stress controlled conditions. A detailed study of the effects of the miscellaneous test conditions such as end restraint, initial one-dimensional consolidation stress, subsequent isotropic consolidation stress and the load increment duration is made. All stress paths are classified into four groups depending on the increments of mean normal stress and deviator stress. The results of specimens subjected to these stress paths and the data from a series of miscellaneous tests in which there are several changes of direction of the imposed stress paths prior to failure are presented and discussed.

INTRODUCTION

The work presented in this paper is a continuation of that described by JAMES & BALASUBRAMANIAM (1971a) on the relationships of the peak stress envelopes and their relation to the critical state line. Before presenting the peak stress data for a very wide variety of stress paths the results of some tests specially devised to study the effects of the end restraint, the initial one-dimensional stress, the subsequent isotropic consolidation stress and the load increment duration on the observed peak stresses will be outlined. The properties of the kaolin tested and the testing procedure are described in detail by BALASUBRAMANIAM (1969). The stress parameters p and q are defined by:

$$p = (\sigma'_1 + 2\sigma'_3)/3 \quad \ldots\ldots\ldots\ldots (1)$$

$$q = (\sigma'_1 - \sigma'_3) \quad \ldots\ldots\ldots\ldots (2)$$

since $\sigma'_2 = \sigma'_3$ under the triaxial stress system.

THE EFFECTS OF MISCELLANEOUS TEST CONDITIONS ON THE OBSERVED PEAK STRESSES

End Restraint

To study the effect of the end restraint three specimens were prepared under

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(as nearly as possible) identical conditions, namely a one-dimensional consolidation stress to 22 lb/sq. in. followed by isotropic consolidation stress to 22 lb/sq. in. Each sample was then subjected to shear under fully drained (constant cell pressure) conditions, but the first sample had rough ends, the second conventional lubricated ends (ROWE & BARDEN, 1964) and the third enlarged ends. The conventional rough end was of a 1.5 in. diameter porous stone (3/16 in. thick UNI type 150 Kv) at the base. Lubricated ends were provided by a 3/16 in. thick highly polished brass disc covered with a thin layer of silicone grease. Drainage was permitted through a 1/4 in. diameter porosint disc (grade B) recessed into the centre of the polished brass base disc. The enlarged end used was 2 1/4 in. diameter with the dimensions of the porous stone the same as that used with the lubricated ends. The peak stress observed in these three tests, which were as nearly as possible identical except for the end restraints, gave virtually identical values of q_f/p_f, i.e. $0.768 \pm 2\%$ q_f was the maximum deviator stress and p_f was the mean normal stress corresponding to maximum deviator stress. If it is assumed that the cohesion is zero, the value of ϕ ranges from 19.2° to 20.0°. It would therefore appear that end restraint does not have a significant effect on the value of q_f/p_f for kaolin specimens with a height to diameter ratio of 2:1.

The Initial One Dimensional Consolidation Stress

To study the effect of the magnitude of the preliminary one-dimensional consolidation stress used in the preparation of samples from a slurry, three samples were prepared under one-dimensional stresses of 11, 22 and 55 lb/sq. in. These samples were then isotropically consolidated under 60 lb/sq. in. and subsequently sheared under fully drained conditions (constant cell pressure) with conventional lubricated ends. The value of q_f/p_f for tests on samples one-dimensionally consolidated to stresses of 11 and 22 lb/sq. in. were 0.72 and 0.75 respectively; these values are very similar to those presented in the previous subsection which corresponds to specimens sheared under different end conditions. However, the value of q_f/p_f for the specimen prepared under a one-dimensional stress of 55 lb/sq. in. was only 0.69: the Authors are unable to explain the premature failure of this sample. For practical purposes, however, the effect of the initial one-dimensional consolidation stress on the parameter q_f/p_f appears to be small.

Isotropic Consolidation Stress

Four samples were subjected to preliminary one-dimensional consolidation under a vertical stress of 22 lb/sq. in. and then isotropically consolidated to 30, 60, 90 and 120 lb/sq. in. respectively. They were subsequently sheared under fully drained conditions (constant cell pressure), giving peak stress ratios which decrease from 0.8 at 30 lb/sq. in. to 0.735 at 120 lb/sq. in. with a mean value of about 0.765 (the corresponding ϕ being 19.5°). Here again, the value of q_f/p_f appears to be unaffected to a first degree of approximation.

Load Increment Duration

Three identical specimens were prepared with preliminary one-dimensional consolidation under 22 lb/sq. in. followed by isotropic consolidation to 60 lb/sq. in. These samples were then subjected to shear with identical load increments, but on the first sample the duration of each increment was 12 hours, whereas for the other two specimens it was 24 and 48 hours respectively. The stress ratios q_f/p_f for these three intervals of time were 0.75, 0.76 and 0.77. The variation is less than ± 1.5%. The data associated with the peak stress conditions of all the tests presented in this section are summarised in tables published in a paper by BALASUBRAMANIAM (1969).

For all the tests presented in the subsequent sections, the following test conditions were ensured. All samples had conventional lubricated ends and were subjected to an identical one-dimensional stress of 22 lb/sq. in. The isotropic consolidation stresses were, for the majority of the samples, 30, 60 or 90 lb/sq. in. The duration of each of the stress increments during the shear phase of all tests was approximately the same and their magnitudes were proportional to the maximum isotropic stress used during sample preparation.

THE RELATIONSHIP BETWEEN PEAK STRESSES AND CHANGE IN VOLD RATIO OF SPECIMENS SHEARED FROM THE ISOTROPIC STRESS STATE

In this section, the peak stresses observed in 43 tests with widely differing stress paths will be presented and discussed. Each of these tests took 25 to 30 days to complete. In all, the Authors have carried out 100 tests of this duration, but in the other 57 they were mainly concerned with the stress-strain behaviour prior to failure. Some of these data will be presented later by JAMES & BALASUBRAMANIAM (1971b). All the specimens of the 43 tests discussed in the present section were one-dimensionally consolidated to 22 lb/sq. in.; 25 were then isotropically consolidated to 90 lb/in^2, 4 to 30 lb/in^2, 9 to 60 lb/sq. in. and the 5 remaining tests at miscellaneous cell pressures. Four of the tests on samples isotropically consolidated to 60 lb/sq. in. were extension tests which included an undrained test and tests with constant values of dq/dp of ∞, 3 and 1.5 respectively. All the other tests were compression tests, details of which will be given as each test is discussed below. The tests in the remaining subsections are divided for convenience into the following four types.

Type 1 — Tests were conducted on samples normally consolidated to an isotropic preconsolidation pressure of p_o and subsequently sheared under stress paths in which $p \leq p_o$, and for compression tests with $\Delta q \geq 0$ for $q > 0$. The full range of the paths of this type are illustrated in Fig. 1, in which point A represents the samples after normal consolidation under isotropic stress p_o. The path AP corresponds to constant effective pressure tests with $p = p_o$ throughout. The path AU represents an undrained test. The path AK corresponds to isotropic swelling. The region between paths AU and AK is generally only investigated in the laboratory by carrying out tests on heavily over-consolidated samples following paths of the Type AKJ or ABC. However, as it is important in all practical problems involving reduction of p, paths of the type AE were also investigated. For most practical problems involving normally consolidated clay, the void ratio of the clay will be decreasing as represented by the path AG.

Type 2 — This type of test is identical to Type 1 except that $p \geq p_o$ and $\Delta p \geq 0$. As shown in Fig. 2, the point A corresponds to samples after normal

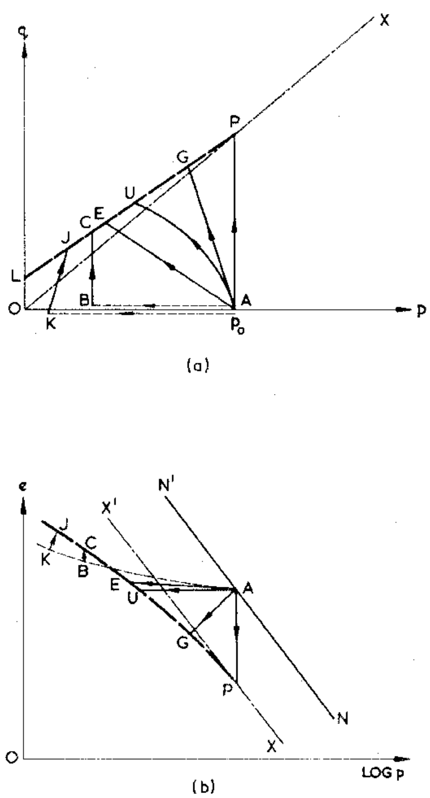


Fig. 1. The paths followed by specimens in Type 1 tests in the (q, p) **space and** $(e, \log p)$ **space.**

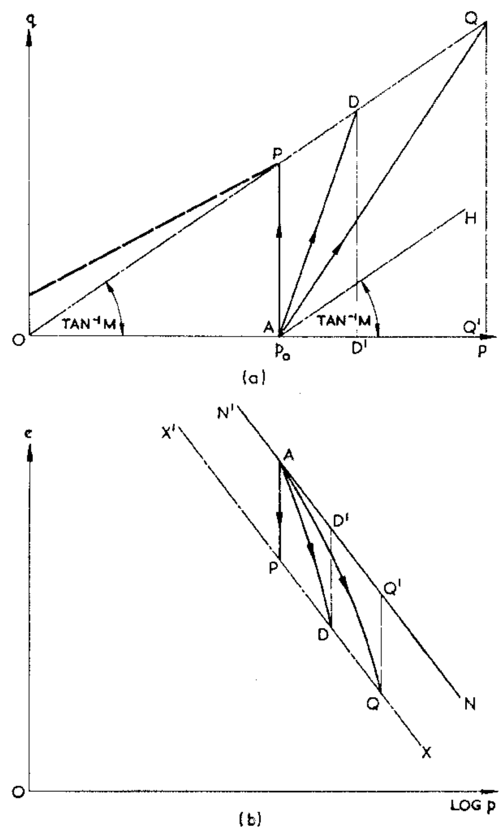


Fig. 2. The paths followed by specimens in Type 2 tests in the (q, p) **space and** $(e, \log p)$ **space.**

consolidation under the isotropic pressure p_o. The path AP again corresponds to a constant p test. The path AD represents a conventional drained test (with constant cell pressure so that $dq/dp = 3$) usually carried out in the laboratory. The path AQ corresponds to a test in which both the deviator stress and the cell pressure are increased. It is apparent for stress paths lying between the line AH (parallel to OQ, the critical state line) and the p axis in Fig. 2a that it is not possible for a specimen to reach the critical state. The points D' and Q' (Fig. 2b) on the normal consolidation line NN' correspond to points which have the same value of p as those of D and Q respectively. Since the critical state line XX' is assumed to be parallel to the line NN', the change in void ratio corresponding to state D from that of A along the path AD can be considered to be due to an isotropic consolidation phase AD' and the constant p shear phase $D'D$.

Type 3 — In this type of test, as shown in Fig. 3, after initial consolidation under isotropic stress p_o to the point A, the samles were subjected to the condition $\Delta p \leq 0$ during the initial phase of shear, and then to the condition $\Delta p \geq 0$, such that the specimens finally failed with $p > p_o$. At the point of reversal of Δp, the samples were in a lightly over-consolidated state. In a

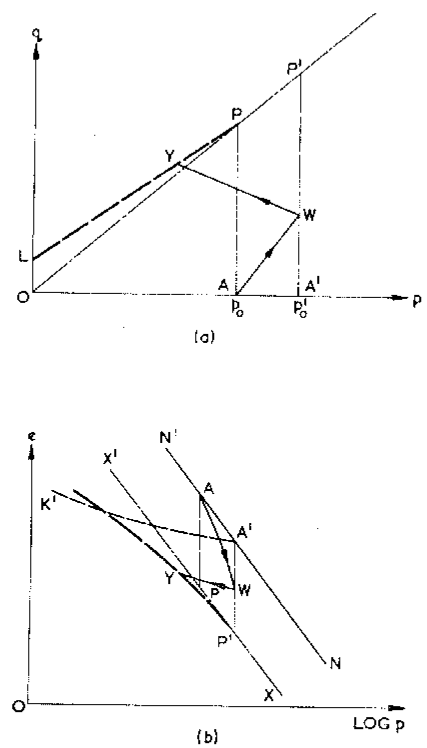


Fig. 3. The paths followed by specimens in Type 3 tests in the (q, p) space and $(e, \log p)$ space.

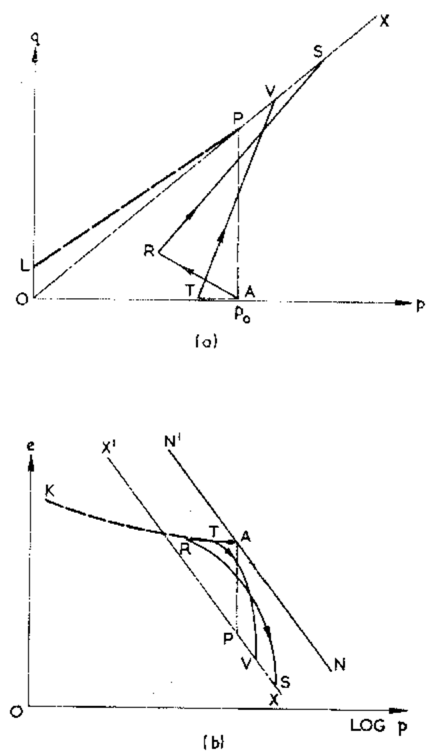


Fig. 4. The paths followed by speeimens in Type 4 tests in the (q, p) space and $(e, \log p)$ space.

sense, these samples are initially of Type 1, and then when p becomes greater than p_o they revert to Type 2 tests.

Type 4 — In this type of test the samples were initially sheared with $p > p_o$ corresponding to Type 2 tests as represented by *AW* in Fig. 4. Subsequently, and prior to failure, the value of p was reduced while the value of the deviator stress was continuously increased (path *WY*) until the peak stresses were reached at *Y*. During the second phase, it will be shown that the samples only behave as Type 1 tests provided the relevant value of p_o for stage *WY* is taken to be p'_o as shown in Fig. 4.

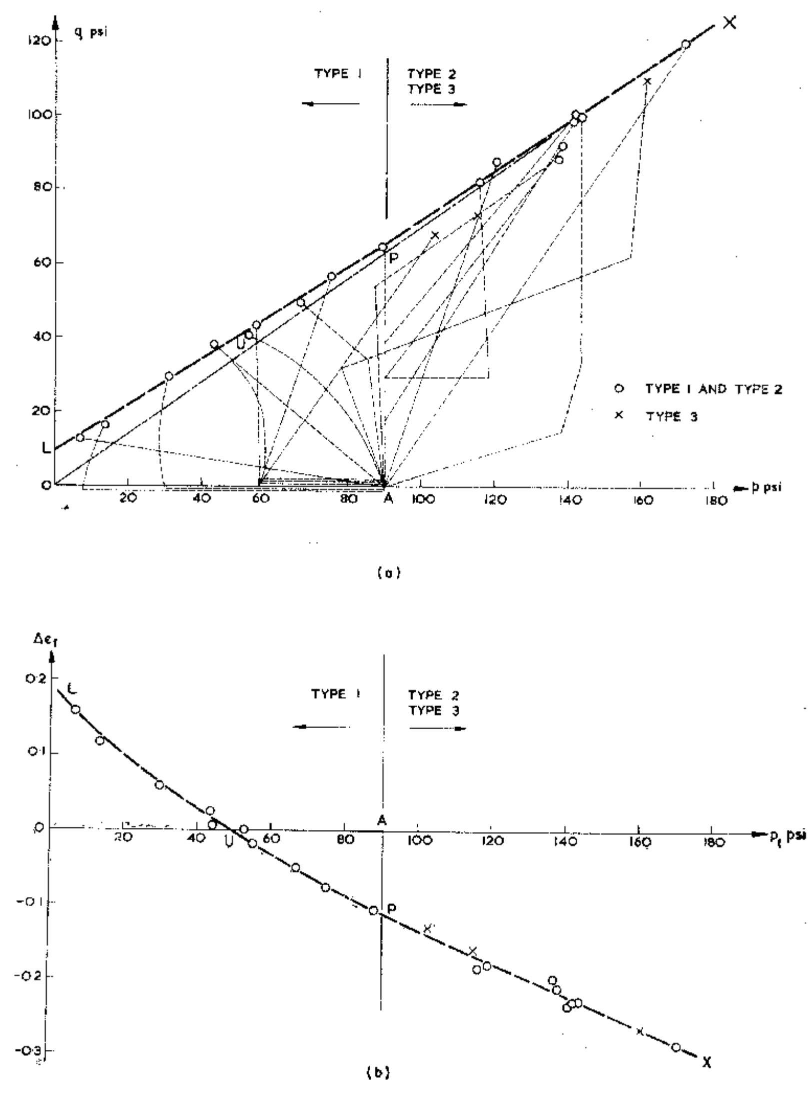


Fig. 5. The peak points of specimens sheared from 90 lb/sq. in. isotropic stress along Type 1, Type 2 and Type 3 stress paths.

COMPRESSION AND EXTENSION TESTS ON SPECIMENS SHEARED WITH DIFFERENT APPLIED STRESS PATHS

The conditions at peak deviator stress observed in all the Type 1, 2 and 3 tests carried out on samples initially isotropically consolidated to 90 lb/sq. in. are shown in Fig. 5 (a). The imposed stress paths are given in greater detail in the form of tables by BALASUBRAMANIAM (1969). The overall change in void ratio, Δe_f, throughout each test, as measured from a point A, are plotted against the value of p_f in Fig. 5 (b). The peak stress points for all three types of test lie on a unique curve. The results of five compression and four extension triaxial tests after isotropic consolidation under 60 lb/sq. in. are presented in Figs. 6 (a) and (b) in a manner similar to those already presented in Figs. 5 (a) and (b) for specimens sheared from 90 lb/sq. in. In these diagrams, the crosses represent the peak conditions in the extension tests while the circles refer to the compression tests. Furthermore, the curves and lines plotted are not the mean through the experimental points but have been scaled directly from Figs. 5 (a) and (b) (i.e. in the ratio of the initial isotropic stresses for each for a given change of void ratio, Δe_f). It is evident that the results of tests for samples prepared from 60 lb/sq. in. are geometrically identical to those obtained from samples prepared at 90 lb/sq. in. The corresponding data for four compression tests on samples initially consolidated to 30 lb/sq. in. and for five tests on samples consolidated to miscellaneous cell pressures revealed similar findings, details of which are given by BALASUBRAMANIAM (1969). The peak conditions of all tests are collected together and presented in Figs. 7 (a), (b) and (c) in the $(q_f/p_o, p_f/p_o)$, $(\Delta e_f, ln\,(p_f/p_o))$ and $(\Delta e_f, ln\,(q_f/p_o))$ plots

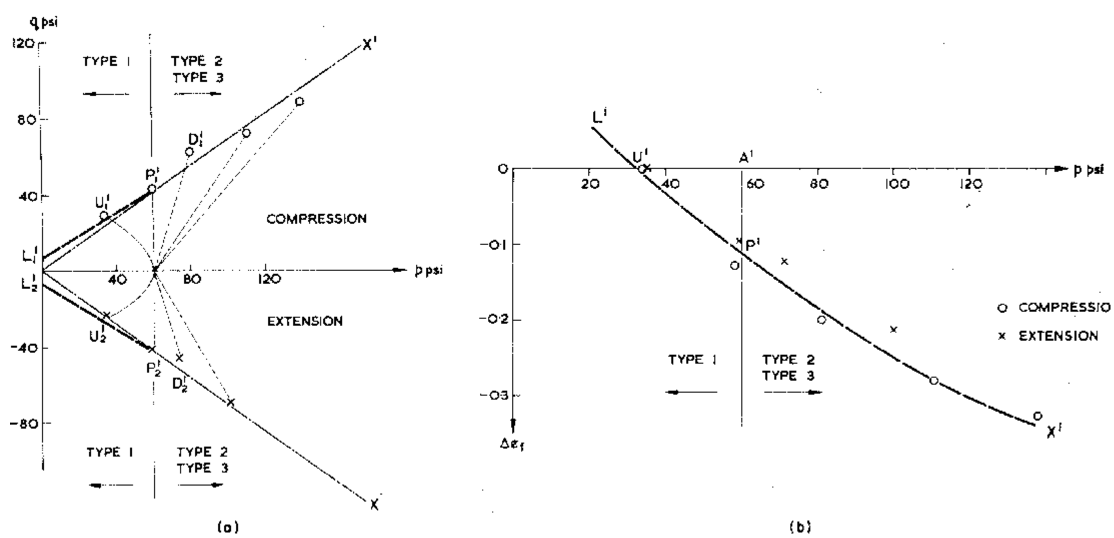


Fig. 6. The peak points of specimens sheared from 60 lb/sq. in. isotropic stress along Type 1, Type 2 and Type 3 stress paths.

respectively. It will be noticed that the point lettered Z in each of these plots refers to a Type 4 test which is considered in the next subsection. Based on these results, JAMES & BALASUBRAMANIAM (1971a) have shown that the peak conditions coincide with the critical state line (ROSCOE, SCHOFIELD & THURAIRAJAH, 1963) for $p_f/p_o \geq 1$, and is represented by the straight line portion PX of the curve LPX. The Authors have also shown that when $p_f/p_o < 1$ the peak conditions coincide with the curve LP, which represents a Hvorslev type curve.

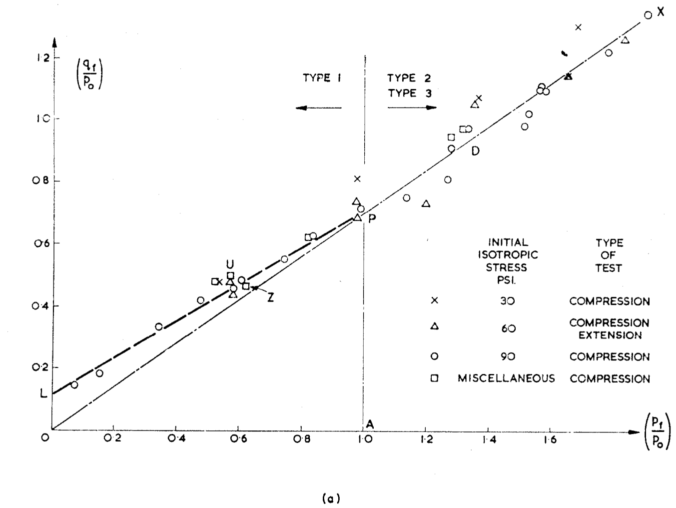
THE PEAK POINTS OF SPECIMENS IN TYPE 4 TESTS

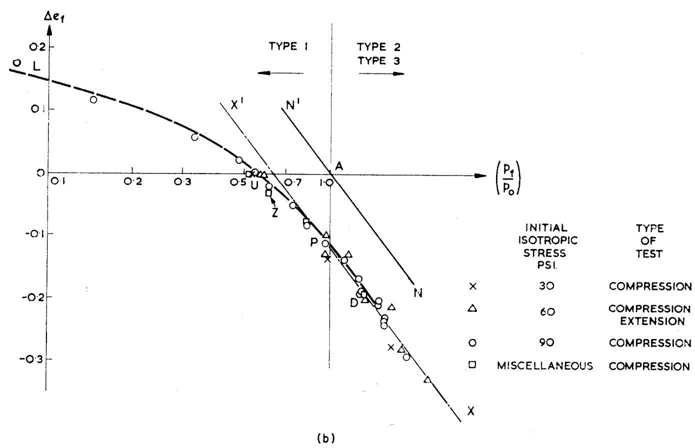
A typical stress path imposed in a Type 4 test is shown in Fig. 4. In this type of test, the mean normal stress p is increased for the initial phase of shear (path AW) and is decreased for the subsequent shear phase (path WY). The Authors have carried out only one such test (Test T_{12}). The path $ABCD$ followed by this specimen T_{12} is shown in the (q, p), $(\Delta e, \log p)$ and $(\Delta e, \log q)$ spaces in Figs. 8 (a), (b) and (c). The critical state line PX, and the Hvorslev envelopes LP and $L'P'$ corresponding to isotropic stresses of A (p_o = 90) and A' (p_o = 117.8 lb/sq. in.) are also shown in these figures. It is observed that the peak point D of this specimen lies closer to the envelope $L'P'$ than to the envelope LP. It is therefore concluded that the peak point of specimens subjected to a stress path of Type 4 (where $\Delta p > 0$ for the initial phase and $\Delta p < 0$ for the final phase) lies on the Hvorslev envelope corresponding to an isotropic stress p_o equivalent to the maximum p ever experienced by the specimen, provided that the specimen has undergone volumetric yielding during the phase in which Δp is less than zero.

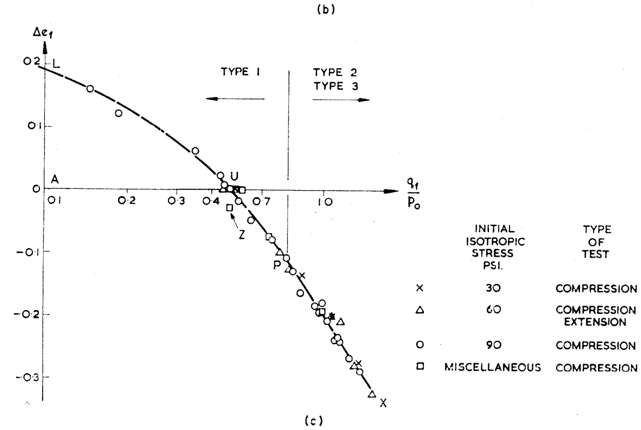
The peak point of the specimen T_{12} has already been plotted in Figs. 7 (a), (b) and (c) in the $(q_f/p_o, p_f/p_o)$, $(\Delta e_f, p_f/p_o)$ and $(\Delta e_f, q_f/p_o)$ spaces respectively. For this specimen, p_o and Δe_f are taken to be the isotropic stress corresponding to A', and the ordinate $A'C$, respectively in Fig. 8 (b).

THE PEAK POINTS OF SPECIMENS SUBJECTED TO STRESS PATHS THAT CAUSE ELASTIC VOLUMETRIC CHANGES AND CYCLES OF DEVIATOR STRESS

Figs. 9 (a) to 9 (d) illustrate the stress paths followed by the four specimens T_{17}, BR, BO and BS. These specimens were subjected to stress cycles in which both the deviator stress and the mean normal stress have been considerably reduced. The peak points of these four specimens are shown in Figs. 10 (a), (b) and (c) in relation to the peak stress envelope LPX originally shown







g. 7. The $(q_f/p_o, p_f/p_o)$, $(\Delta e_f, \ln (p_f/p_o))$ and $(\Delta e_f, \ln (q_f/p_o))$ characteristics of all specimens sheared along Type 1, Type 2 and Type 3 test paths.

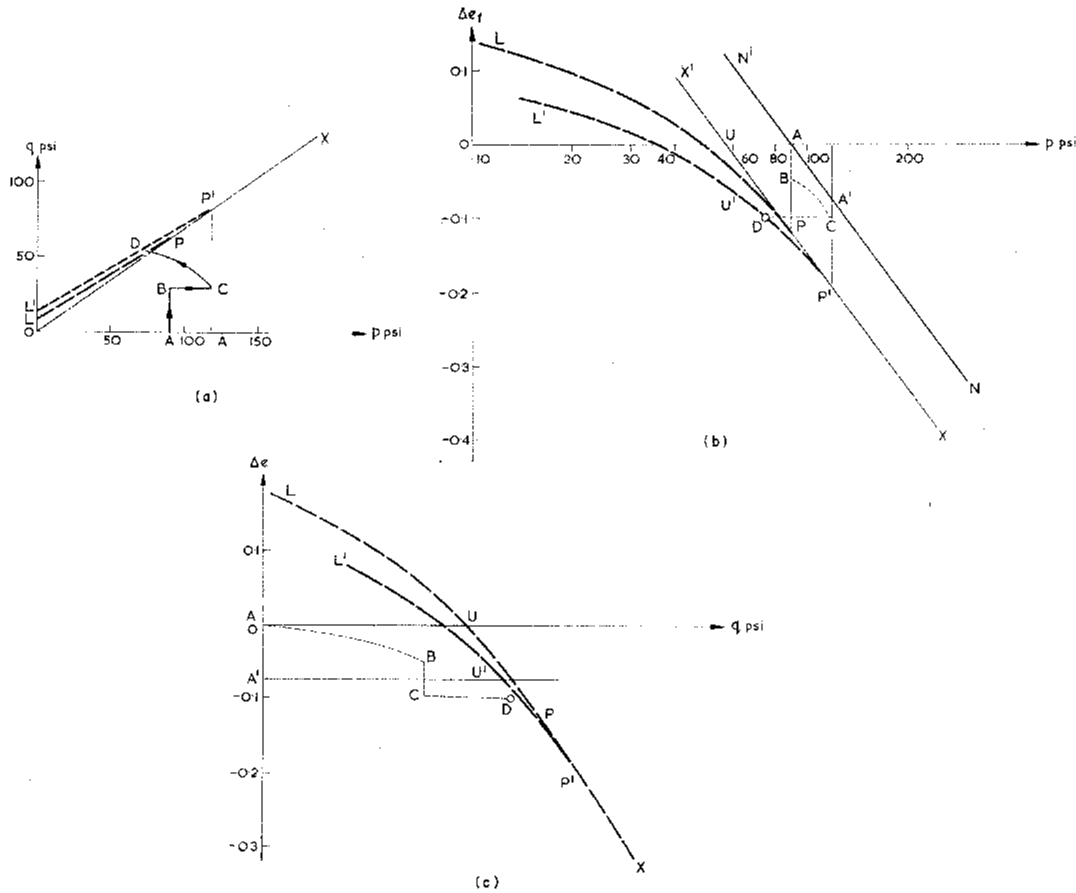


Fig. 8. The path followed by specimen T_{12} in (q, p), $(\Delta e, \log p)$ and $(\Delta e, \log q)$ spaces.

in Figs. 7 (a), (b) and (c). It can be seen that the peak points for all specimens lie approximately on the projection of the Hvorslev envelope *LP* in the stress plane of Fig. 10 (a). However, the peak points are found to deviate from the envelope *LP* in Figs. 10 (b) and (c), which entail the parameter Δe_f. At present the Authors have not sufficient information to explain these apparent deviations observed in the peak stress points of the samples subjected to stress cycles. Perhaps the envelope *LP* in Figs. 10 (b) and (c) is not unique. It is suggested that for specimens which have been subjected to a previous stress ratio η $(= q/p)$ as represented by *B* in Fig. 10 (b) with increasing deviator stress, and subsequently failed along stress paths which only cause elastic volumetric changes, the corresponding Hvorslev envelope may be of the form *L'P'* in Fig. 10 (b). The line *L'P'* is of the same slope as the asymptote *AL* and passes through *B*. The limiting positions of the envelope *L'P'* are *LP''* and *L''P*, corresponding to $((\Delta e)_\eta)_p$ being equal to zero and $(\Delta e_f)_p$ respectively. Using the unique envelope for q_f/p_o and p_f/p_o given by *LP* in Fig. 10 (b)

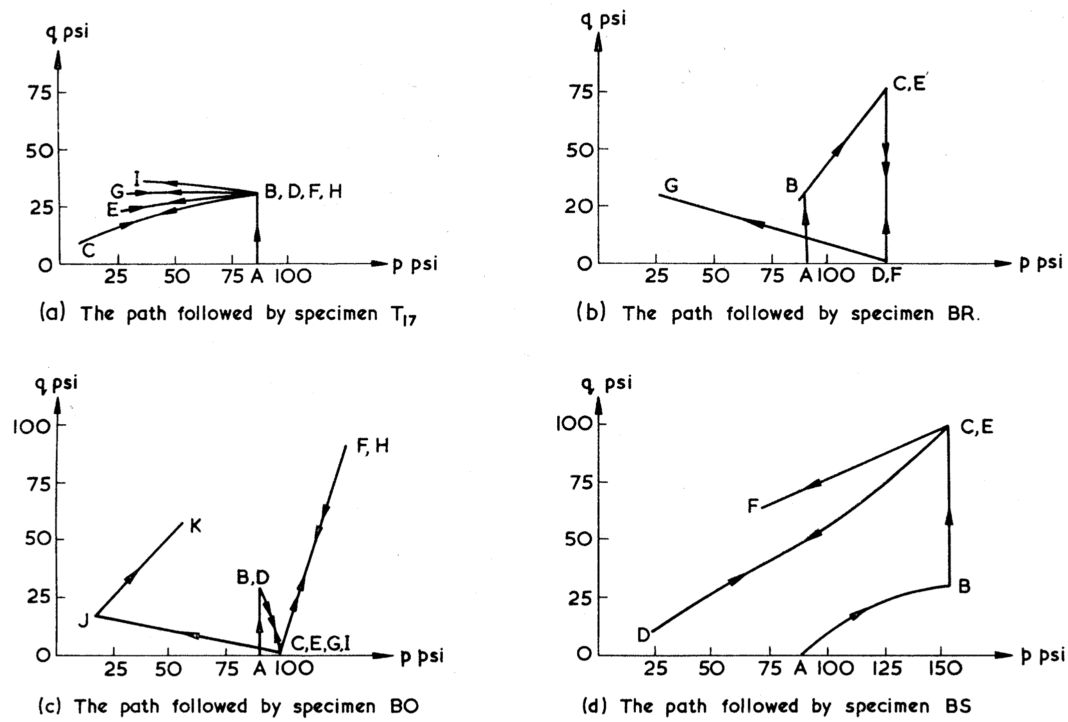


Fig. 9. The stress paths followed by specimens T_{17}, *BR*, *BO* and *BS* when subjected to stress reversals.

relating Δe_f and p_f/p_o, it is possible to obtain the projection in the $(\Delta e_f, q_f/p_o)$ space as represented by $L'P'$ in Fig. 10 (c). The apparent shift $(\Delta e_\eta)_p$ in Fig. 10(c) of the envelope $P'L'$ would appear to be a function of the plastic volumetric strain experienced by a specimen in a constant p test and, therefore:

$$(\Delta e_\eta)_p = f(\eta) \qquad \text{. . . . . (3)}$$

CONCLUSIONS

(1) The effects of stress history, such as the initial one-dimensional consolidation stress and the subsequent isotropic consolidation stress, on the peak stress conditions are studied in detail. It appears that the strength parameter q_f/p_f is independent of these factors to a first degree of approximation. It is also found to be independent of the end restraint and the load increment duration.

(2) The stress paths are classified into four groups depending on the increments of mean normal stress and the deviator stress. For the first three types of test, the peak stress conditions coincide with the conventional critical state conditions for values of $p_f/p_o \geq 1$. However, for values of $p_f/p_o < 1$, the peak stress points are found to lie on a Hvorslev type curve.

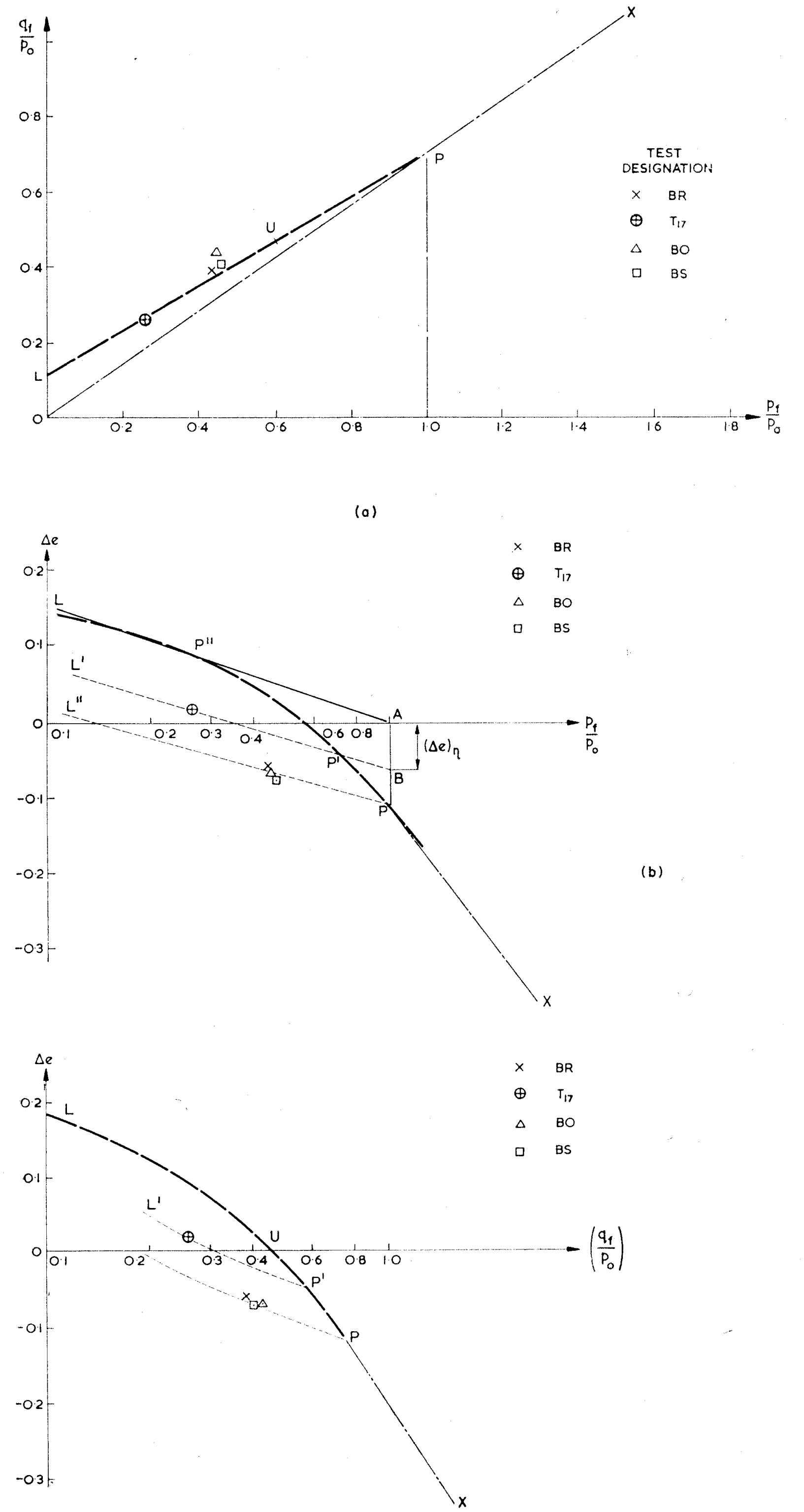


Fig. 10. **The $(q_f/p_o, p_f/p_o)$, $(\Delta e_f, \ln (p_f/p_o))$ and $(\Delta e_f, \ln (q_f/p_o))$ characteristics of specimens T_{17}, *BR*, *BO* and *BS* subjected to stress reversals.**

(3) The peak point of a specimen subjected to a stress path of Type 4 (where $\Delta p > 0$ for the initial phase and $\Delta p < 0$ for the final phase) lies on the Hvorslev envelope corresponding to an isotropic stress p_o equivalent to the maximum p ever experienced by the specimen, provided that the specimen has undergone volumetric yielding during the phase in which Δp is less than zero.

(4) The peak points of specimens subjected to stress paths that cause elastic volumetric changes and cycles of deviator stress appear to lie on a series of parallel curves starting from the original curve in the $(\Delta e_f, \ln (p_f/p_o))$ and $(\Delta e_f, \ln (q_f/p_o))$ spaces. Further experimental work is needed before a proper interpretation can be made of these parallel curves.

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