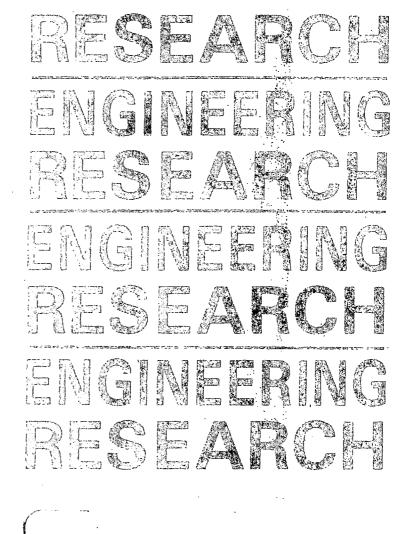


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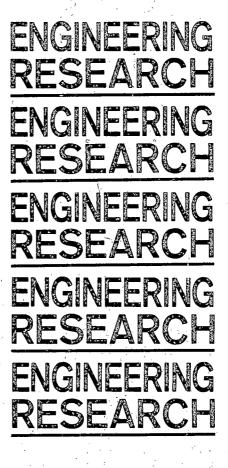


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SPECIAL REPORT BEHAVIOR OF GRANULAR MATERIALS UNDER TRIAXIAL COMPRESSION WITH PULSATING DEVIATOR STRESS

J. J. Marley and R. L. Handy Iowa Highway Research Board Project HR-131 Conducted by

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BEHAVIOR OF GRANULAR MATERIALS UNDER TRIAXIAL COMPRESSION WITH PULSATING DEVIATOR STRESS

J. J. Marley and R. L. Handy¹

ABS TRACT

Behavior of granular material subjected to repeated load triaxial compression tests is characterized by a model based on rate process theory. Starting with the Arrhenius equation from chemical kinetics, the relationship of temperature, shear stress, normal stress and volume change to deformation rate is developed. The proposed model equation includes these factors as a product of exponential terms. An empirical relationship between deformation and the cube root of the number of stress applications at constant temperature and normal stress is combined with the rate equation to yield an integrated relationship of temperature, deviator stress, confining pressure and number of deviator stress applications to axial strain.

The experimental program consists of 64 repeated load triaxial compression tests, 52 on untreated crushed stone and 12 on the same crushed stone material treated with 4% asphalt cement. Results were analyzed with multiple linear regression techniques and show substantial agreement with the model equations. Experimental results fit the rate equation somewhat better than the integrated equation when all variable quantities are considered.

The coefficient of shear temperature gives the activation enthalpy, which is about 4.7 kilocalories/mole for untreated material and

*Respectively, Instructor and Professor, Civil Engineering, Iowa State University. 39.4 kilocalories/mole for asphalt-treated material. This indicates the activation enthalpy is about that of the pore fluid. The proportionality coefficient of deviator stress may be used to measure flow unit volume. The volumes thus determined for untreated and asphalt=treated material are not substantially different. This may be coincidental since comparison with flow unit volumes reported by others indicates flow unit volume is related to gradation of untreated material. The flow unit volume of asphalt=treated material may relate to asphalt cement content.

The proposed model equations provide a more rational basis for further studies of factors affecting deformation of granular materials under stress similar to that in pavement subjected to transient traffic loads.

BEHAVIOR OF GRANULAR MATERIALS UNDER TRIAXIAL COMPRESSION WITH PULSATING DEVIATOR STRESS

J. J. Marley and R. L. Handy

INTRODUCTION

Solution of engineering problems involving soils or aggregates requires knowledge of the material properties, the nature of imposed stresses and other contemplated environmental changes, as well as response of the material to environmental changes. Among these requirements, the most easily determined is environmental changes. Considerable knowledge exists pertaining to material properties and response due to certain types of stresses and modes of stress applications.

One common mode of stress application about which little is known concerning response is the repeated application and removal of compressive and flexural stresses on highway or airfield pavements.

Without adequate knowledge to describe response to repeatedly applied stresses, solutions of pavement design problems have rested largely on empirical knowledge gained from in-service and full-scale test pavements. Because of an inability to control all environmental variables, results of such observations have been qualitative.

The objective of this study was to determine the nature of response of a crushed limestone aggregate subjected to repeatedly applied compressive stresses in a controlled laboratory environment, and thus determine those properties pertinent to behavior of materials subjected to this mode of stress application.

The study used a triaxial compression apparatus on compacted specimens of crushed limestone, either untreated or treated with asphalt cement as a stabilizing additive. The triaxial apparatus was designed to apply repeated uniaxial stress under controlled temperature conditions.

LITERATURE REVIEW

Studies of the shearing resistance of soils often assume that behavior of material is described by the Coulomb equation:

 $\tau' = C + P_n \tan \phi$

where

T is shear stress,

C is cohesion,

 \boldsymbol{P}_n is the stress normal to the shear stress, and

 ϕ is the angle of internal friction.

However, there are difficulties with this approach. Values of C and ϕ may not only be a function of the material but also of the type and conditions of the test by which they are determined. Since these parameters are dependent upon test conditions, their determination under conditions other than those corresponding to prototype conditions has limited value.

The Mohr-Coulomb theory describes material behavior at a failure condition where total rupture of the soil mass occurs. The Coulomb equation and the Mohr-Coulomb theory provide no information about deformation from application of stresses lower than the failure stresses, or about any cumulative effects of repeatedly applied subfailure stresses.

Since pavement design involves determination of a pavement structure that will sustain repeated application of many thousands of wheel loads with neither total rupture nor excessive deformation of the pavement structure, the Mohr-Coulomb theory is inadequate to describe behavior of materials under such stress.

(1)

The Coulomb parameters C and ϕ , as determined by conventional, controlled strain triaxial testing, have been qualitatively correlated to performance of in-service and full-scale test pavements with limited success.

Repeated load triaxial testing is a relatively recent approach in soil and highway engineering. While interesting aspects of material behavior under this type of loading have been reported by Havers and Yoder (1957), Haynes and Yoder (1963), Seed and Chan (1957, 1958), Seed <u>et al</u>. (1955), Seed <u>et al</u>. (1958), and Seed and McNeill (1956, 1957), little attempt has been made to describe observations other than phenomenologically, probably because there is no generally accepted behavioral model available by which the observations could be related.

Larew and Leonards (1962) observed that behavior of soil materials subjected to repeated loads appeared to be analogous to behavior of soil materials subjected to creep loading; that is, a time-dependent deformation under constant stress. This seems reasonable, considering that the number of applications of a repeatedly applied stress is a function of the frequency of load applications multiplied by elapsed time:

$$N = f \times t$$

(2)

where

N is number of load applications,

f is frequency of load applications, and

t is elapsed time.

From this simple relationship and since the number of load applications is a function of time, the behavior of material subjected to constant

stress may well be analogous to the behavior of material subjected to constant stress intermittently applied a number of times.

Recently, the theory of rate processes has been applied with considerable success to the time-dependent behavior of soils and highway pavement materials by Herrin and Jones (1963), Herrin <u>et al</u>. (1966), Christensen and Wu (1964), Mitchell (1964), Mitchell and Campanella (1964), Mitchell <u>et al</u>. (1968), Moavenzadeh and Stander (1966), Noble (1968), Secor and Monismith (1965) and Pagen (1965).

The potential for applying the rate process theory to processes as widely divergent as chemical reactions and shear deformation of particulate systems such as soil or mineral aggregates was recognized by the authors of an early definitive work on the rate process theory when they wrote: (Glasstone <u>et al.</u>, 1941, p. vii)

> ...the theory of absolute reaction rates is not merely a theory of the kinetics of chemical reactions; it is one that can, in principle, be applied to any process involving a rearrangement of matter, that is to say, any 'rate process'.

Application of the theory to creep behavior of metals has been known for some time and was investigated by Dorn (1957), Ree <u>et al</u>. (1963), Andrade (1951, 1957), and Schoeck (1957). Considerable data have been accumulated allowing many authors to hypothesize deformation mechanisms which agree with observed kinetic data. Attention has also been given to application of rate process theory to deformation of ice and snow by Barnes and Tabor (1966), Glen (1955), Glen (1953). Landauer (1955), Kingery (1960), Telford and Turner (1963) and Gold (1967). Hahn <u>et al</u>. (1967) applied the theory to plastic deformation of marble, Goughnour and Andersland (1968) to a sand-ice system, and Ree and Eyring (1955) and Andrade (1951) to generalized plastic solid systems.

Applicability of rate process theory to shearing deformation or viscosity of fluids has been known for some time and was treated in detail by Glasstone <u>et al</u>. (1941).

Applicability of rate process theory to behavior of metals subjected to intermittently applied stresses has been investigated by Caughey and Hoyt (1954), Smith and Houston (1954), Simmons and Cross (1954), Manson and Brown (1959), and Feltner and Sinclair (1963). They found that rate process theory adequately described the observed behavior, although they do not agree on the relationship between "static" and "cyclic" creep. The relationship between the amount and rate of deformation as observed by these investigators for materials subjected to constant stress and intermittent stress, apparently depends on the various stress levels, temperature conditions, and other test variables.

THEORY

If a material does not deform instantaneously under load, deformation of its mass requires an input of energy. In the particulate systems considered in this study, this energy must (1) break or deform any bonds (friction or cohesion) that exist between particles or groups of particles, and (2) change or rearrange the relative configuration of one particle or group of particles relative to another particle or group, if this rearrangement requires a change in volume of the material. This energy is released by the material system when the interparticle bonds reform, and particles and groups return to their initial configuration.

The deformation rate is a function of strength of interparticle bonds, relative configuration of the particles or groups, and rate of energy input into the system.

Chemical kinetic theory provides a means by which deformation rate, and those properties which affect deformation rate, can be related. The process rate theory cannot provide information about the state of the material before, during, or at completion of a reaction or rearrangement of material, but can provide information about the rate at which the reaction or rearrangement occurs. The state of the material before or during the reaction process affects the rate. Any such effect must be experimentally determined in order to develop an equation to adequately describe the rate process involved.

In any system of matter there are continuous movements. These movements are, in the absence of any external stress, nondirectional or randomly directed and result in no net movement of the material. Application of an external stress to such a system results in a net movement

in the direction of the imposed stress. This concept has been stated by Eyring (1967, p. 20):

> Electrical potentials, or other kinds of stress, applied to any system do not ordinarily initiate a new process but simply bias existing rates, thereby modifying the rate of passing to equilibrium.

Application of a stress alters the rate of, and gives direction to, an already existing process. This directional "biased" rate of passing to equilibrium is the concern of this study.

In chemical kinetics, the rate constant of chemical reactions is represented by the Arrhenius equation (Moore, 1962),

 $k = A \exp \frac{-E}{RT}$ (3)

where

k is the specific rate constant,

A is a pre-exponential multiplier, often called the Arrhenius

frequency factor,

 ${\bf E}_{a}$ is the activation energy of the process,

R is the universal gas constant, and

T is the absolute temperature at which the reaction occurs.

Equation (3) is generally accepted as an adequate representation of the temperature dependence of any rate process, as Glasstone <u>et al</u>. (1941, p. 1) stated:

> ...it is now generally accepted that a relationship of this kind represents the temperature dependence of the specific rates of most chemical reactions, and even of certain physical processes....

Energy Concepts

For this study, resistance of a soil to shear deformation is assumed to result from an energy barrier for bonding units in the material. This energy barrier results from two factors mentioned previously; <u>viz</u>., bonds between particles or groups of particles, and other resistance to rearrangement of particles or groups of particles. This energy barrier is the so-called activation energy. The number of bonding units having enough energy to surmount the energy barrier, i.e. the number of bonding units with energies greater than the activation energy of the material, is given by the Maxwell-Boltzman distribution law. The rate of bonding units passing over the energy barrier is proportional to the number of bonding units with energy greater than, or equal to, the activation energy.

The number of bonding units which pass over the energy barrier per unit time is a measure of the deformation rate of the material and may be expressed as

$$\varepsilon = K \exp - \frac{\Delta F^*}{kT}$$

where

 $\dot{\epsilon}$ is deformation rate,

K is a proportionality constant,

 ΔF^* is the activation free energy of the material,

k is the Boltzman constant, and

T is the absolute temperature at which the deformation occurs.

(4)

The energy barrier with no externally applied stresses is illustrated in Fig. 1 by the solid line.

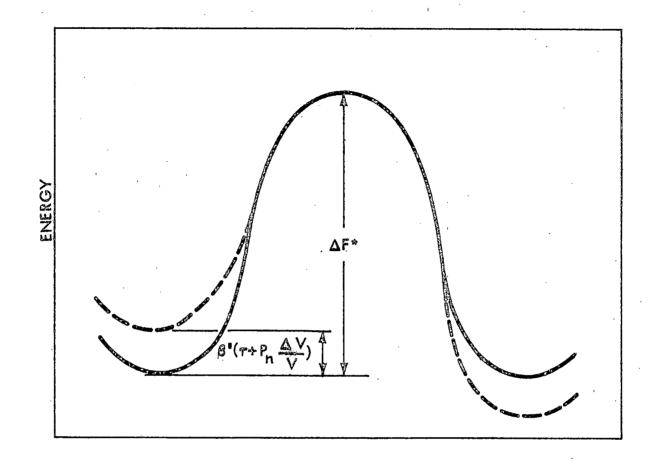


Fig. 1. Energy barrier for deformation, with and without shear stress.

The applied stresses in a triaxial compression test are illustrated in Fig. 2, σ_1 being the major principal stress and σ_3 the minor principal stress. Considering the stresses acting on an element of the material such as element A in Fig. 2a, and expanded in Fig. 2b, the imposed stresses are resolved into normal and tangential stress components, designated P_n and τ , respectively.

The work done in deforming this element of soil from configuration 1 shown with solid lines in Fig. 2b to configuration 2 (dashed lines), consists of breaking interparticle bonds and changing the volume of the element against the normal stress P_n . The work done in breaking one interparticle bond is the stress on the bond multiplied by the volume of

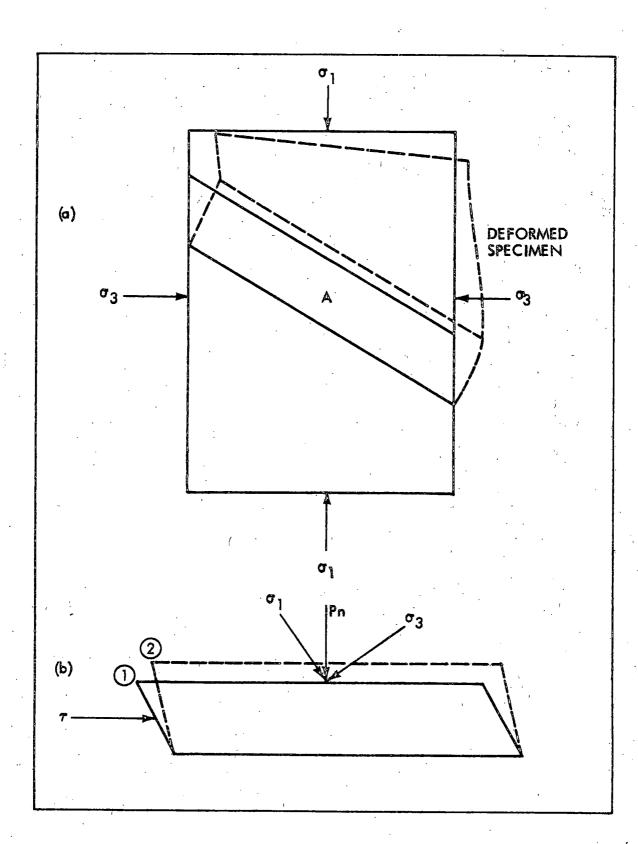


Fig. 2. Applied stresses in triaxial shear testing.

the bonding unit. The stress on the bond is τ and, designating the volume of a bonding unit as β' , the energy required to break one interparticle bond is - $\beta'\tau$, which is the energy acquired by the bonding unit in exceeding the energy barrier. The work required to change the volume of material from configuration 1 to 2 is $P_n(V_2 - V_1)$ or $P_n\Delta V$, representing the total volume change work done on this element. The volume change work done on the element per unit volume of bonds is the volume change work done on the element multiplied by the ratio of the volume of a bonding unit to the total volume of the element or $B'Pn \Delta V/V$. The total work required to deform the element is then $-\beta'\tau + B'Pn \Delta V/V$ or $\beta'(-\tau + P_n \Delta V/V)$.

The height of the energy barrier designated as ΔF^* in Fig. 1 is changed by an amount $\beta'(-\tau + P_n \Delta V/V)$ when an external stress is applied to the system as shown by the dashed lines in Fig. 1. The effect of the term $P_n \Delta V/V$ depends on the nature of the volume change of the material. If the volume must be increased, $\beta' P_n \Delta V/V$ represents energy that must be surmounted by the bonding unit, and the activation energy is increased by this amount. If volume is decreased by deformation, $\beta' P_n \Delta V/V$ represents energy acquired by the bonding unit, and activation energy is decreased by this amount. Since an increase in volume was considered in this derivation, the effects of shear stress and volume change on activation energy are of opposite sign.

Introducing the relationship from thermodynamics that

(5)

$$\Delta F^* = \Delta H^* - T \Delta S^*$$

where

 ΔH^* is the activation enthalpy,

 ΔS^* is the activation entropy, and

other terms are as previously defined,

and considering the further subdivision of ΔF^* when an external shear stress is applied as developed above,

$$\Delta F^* = \Delta H^* - T \Delta S^* - \beta' \tau + \beta' P_n \frac{\Delta V}{V} .$$
 (6)

Substituting Eq. (6) into Eq. (4),

$$\dot{\epsilon} = K \exp - \frac{\Delta H^*}{kT} \exp \frac{\Delta S^*}{k} \exp \frac{\beta' T}{kT} \exp - \frac{\beta'}{kT} P_n \frac{\Delta V}{V}$$
 (7)

If it is now assumed that ΔS^* is independent of temperature, this term may be included in the pre-exponential coefficient, and further, setting $\beta = \beta'/kT$, Eq. (7) becomes

$$\hat{\epsilon} = K' \exp - \frac{\Delta H^*}{kT} \exp \beta \tau \exp - \beta P_n \frac{\Delta V}{V}$$
 (8)

Soil Structure

The relationship expressed by Eq. (8) indicates the deformation rate is independent of total deformation (other than that represented by volume change) and time, since neither quantity appears on the right side. However, in deriving Eq. (8) it has been assumed that any change in structure is completely represented by volume change. Also, timedependence of deformation rate is implicit in Eq. (8) since volume change is time-dependent.

Time-dependence of deformation rate presents a problem in applying Eq. (8) to shear deformation of soils. In order to determine the effect of varying τ on deformation rate, the rate at constant τ must be constant, or the functional relationship between time and deformation rate must be known.

Since constancy of the deformation rate can be assured by determining the rate when its derivative is zero ($\ddot{e} = 0$), this seems to be a much simpler criterion for determining a meaningful deformation rate than attempting to determine a functional relationship between deformation rate and time. However, since none of the terms on the right side of Eq. (8) can be zero and the derivative of exp - $\beta P_n \Delta V/V$ is generally not zero, this equation inadequately represents the deformation rate of soils unless some further relationships are known.

Since there is experimental evidence that deformation rate is a function of deformation (or time), this relationship should be included in Eq. (8) so that

$$\dot{\epsilon} = K' \exp{-\frac{\Delta H^*}{kT}} \exp{\beta \tau} \exp{-\beta P_n \frac{\Delta V}{V}} \cdot f(\epsilon)$$
 (9)

where $f(\epsilon)$ is an unknown function of deformation.

Both $f(\varepsilon)$ and $\Delta V/V$ are measures of the rearrangement of the material during deformation or, combined, represent a change in structure of the material during deformation. Representing these combined effects by a single factor S, an unknown function describing the dependence of deformation rate on any changes in structure during deformation, Eq. (9) becomes

$$\dot{\epsilon} = K' \exp{-\frac{\Delta H^*}{kT}} \exp{\beta \tau} \cdot S.$$
 (10)

Equation (10) expresses a relationship among deformation rate, activation enthalpy, shear stress and structure; the structure factor

S is an unknown function, and this equation is of little value unless the effect of this function can be determined or eliminated. Since the structure function is probably a complex function, the possibility of eliminating its effects will be considered.

One possibility is to consider the relationships of strain rate and other variables at a condition of constant structure in each specimen tested. Under these conditions, the effect of structure would be constant and could be included in the pre-exponential coefficient.

With introduction of constant structure, Eq. (10) is a useful relationship if two conditions are met when the equation is applied: (1) that $\ddot{e} = 0$ and (2) that a constant structure exists. But a means of insuring constant structure is necessary.

It is assumed that initial structure of specimens prepared in the same manner is essentially constant (or normally distributed about some mean value of the structure parameter), and that each specimen, as it is deformed under differing test conditions, could attain another value of the structure parameter which is identical in all specimens. The structure at any time after the start of a test is a function of time, shear stress, temperature, and normal stress or

$$S = f(\tau, P_n, T, t).$$
 (11)

There are other functional relationships of structure that could be considered. For instance, t could be replaced by deformation, ϵ , but the variables chosen are obvious independent variables assumed for development of the theory.

Differentiating Eq. (11) at constant temperature and normal stress,

$$dS = \left(\frac{\partial S}{\partial \tau}\right)_{T, P_{n}, t} d\tau + \left(\frac{\partial S}{\partial t}\right)_{T, P_{n}, \tau} dt.$$
(12)

Introducing the condition that when the structure function is constant, dS = 0, and setting the right side of Eq. (12) equal to zero, gives

$$\left(\frac{\partial S}{\partial \tau}\right)_{\mathrm{T},\mathrm{P}_{\mathrm{n}},\mathrm{t}} \left(\frac{\partial \tau}{\partial t}\right)_{\mathrm{T},\mathrm{P}_{\mathrm{n}},\mathrm{S}} + \left(\frac{\partial S}{\partial t}\right)_{\mathrm{T},\mathrm{P}_{\mathrm{n}},\mathrm{\tau}} = 0.$$
(13)

Again differentiating Eq. (11) but at constant temperature and shear stress gives

$$dS = \left(\frac{\partial S}{\partial P_n}\right)_{T, \tau, t} dP_n + \left(\frac{\partial S}{\partial t}\right)_{T, \tau, P_n} dt, \qquad (14)$$

and setting the right side of this equation equal to zero gives

$$\left(\frac{\partial S}{\partial P_{n}}\right)_{T, \tau, t} \left(\frac{\partial P_{n}}{\partial t}\right)_{T, \tau, S} + \left(\frac{\partial S}{\partial t}\right)_{T, \tau, P_{n}} = 0.$$
(15)

Differentiating Eq. (10) with respect to time at constant temperature, shear stress and normal stress,

$$\tilde{\epsilon} = K' \exp - \frac{\Delta H^*}{kT} \exp \beta \tau \left(\frac{\partial S}{\partial t}\right)_{T, \tau, P_n}$$
 (16)

Where $\ddot{\varepsilon} = 0$, the right side of Eq. (16) must be zero. Since the only term on the right side of this equation which can be zero is $(\partial S/\partial t)_{T, \tau, P_n}$, this term must be zero when $\ddot{\varepsilon} = 0$. Thus, when one necessary condition for valid application of Eq. (10) is met, $(\partial S/\partial t)_{T, \tau, P_n}$ is also zero.

Substituting this relationship into Eqs. (13) and (15), when $\ddot{e} = 0$,

$$\left(\frac{\partial S}{\partial \tau}\right)_{T,P_{n},t}$$
, $\left(\frac{\partial T}{\partial t}\right)_{t,P_{n},S} = 0$, and $\left(\frac{\partial S}{\partial P_{n}}\right)_{T,\tau,t}$, $\left(\frac{\partial P_{n}}{\partial t}\right)_{T,\tau,S} = 0$,

if the structure remains constant. These conditions may be satisfied if either the products are zero or if one of the terms in either equation is zero.

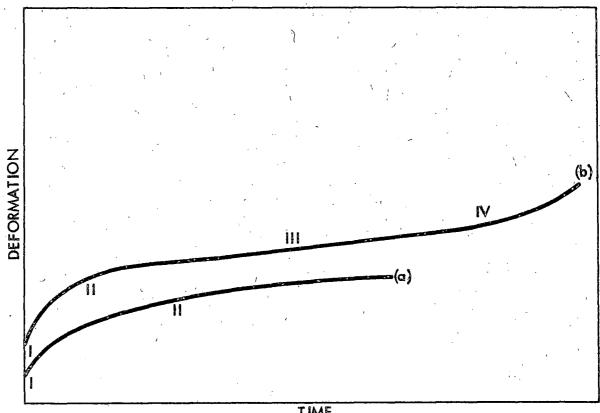
Generally, neither $(\partial \tau / \partial t)_{T, P_n, S}$ nor $(\partial P_n / \partial t)_{T, \tau, S}$ are zero. If they were, no relationship would be indicated between τ and t or \boldsymbol{P}_n and t, which is contrary to experimental evidence. If the relationships between τ and t or $P_{_{\rm D}}$ and t had maximum or minimum values, the partial derivatives would be zero at that point. However, for these relationships to have maximum or minimum values, the value of the structure function at a low value of τ or Pn must be duplicated at a higher value of τ or P_n . At an intermediate value of τ or P_n , the value of the structure function would be either greater or less than that occurring at higher or lower values of τ or P_n . Since it seems unreasonable to expect this to occur, it is unlikely either $(\partial \tau / \partial t)_{T, P_n, S}$ or $(\partial P_n / \partial t)_{T, \tau, S}$ have zero values. If neither have zero values, then $(\partial S/\partial \tau)_{T,P_{r},t}$ and $(\partial S/\partial P_n)_{T,\tau,t}$ must be zero whenever $(\partial S/\partial t)_{T,\tau,P_n}$ and $(\partial S/\partial \tau)_{T,P_n,t}$ or $(\partial S/\partial P_n)_{T, \tau, t}$ are zero at any point of inflection, which means that at points of inflection the structure remains constant when t, τ , or P_n is varied.

The relationship for constant structure has been developed for constant temperature. However, the same reasoning would lead to the possibility of $(\partial T/\partial t)_{T, P_n, S}$ having a zero value and result in conclusions similar to those above.

Failure Criteria and Deformation

Use of $\ddot{e} = 0$ as a criterion for applying the rate equation to determine the effect of stress on deformation rate is common in creep testing of metals (Dorn, 1957; Schoeck, 1957). The deformation rate used by these researchers is the rate in a secondary creep portion of the

time-deformation curve where the deformation rate is constant. Timedeformation relationships are usually considered to consist of several. different stages, as shown in Fig. 3. Stage I is the instantaneous



TIME

Fig. 3. Generalized deformation versus time relationships.

deformation which occurs when the load is applied. Stage II is transient creep in which the deformation rate decreases and may terminate under low stresses as shown in curve (a) of Fig. 3. Stage III represents steady-state creep characterized by constant rate of deformation, and stage IV is tertiary creep characterized by accelerating deformation and leads to rupture as shown in curve (b) of Fig. 3.

Some researchers (Noble, 1968; Singh and Mitchell, 1968) have found that steady-state creep seldom occurs for any significant time in soils

tested in direct or triaxial shear. However, in creep tests exhibiting a transient creep zone and a tertiary creep zone, there is a point of inflection in the time-deformation curve where the second derivative of deformation with respect to time is zero, even though there may be no evidence of a significant period of steady-state creep.

Failure criteria have been proposed by Schmidt (1962b) as the point at which strain acceleration becomes positive (i.e. where $\ddot{e} > 0$), and by Hughes (1967) as the point of inflection on the strain repetition curves for repetitive loading of asphaltic concrete. The Hughes criterion is identical to the $\ddot{e} = 0$ criterion and, if the material exhibits no secondary creep, the Schmidt criterion is also essentially the same. Noble (1968) also proposed the criterion of $\ddot{e} = 0$ for determining a meaningful deformation rate in applying the rate equation to soil deformation.

Conditions under which the rate equation is applicable to soil deformation, as developed above for constant structure, are consistent with any of the proposed failure criteria. Equation (10) may now be written

$$\dot{\epsilon} = K'' \exp - \frac{\Delta H^*}{kT} \exp \beta \tau$$
 (17)

where K" is a coefficient that includes the proportionality constant, the entropy of activation, and the effect of structure.

Equation (17) describes the effects of shear stress and temperature on deformation rate at a point defined as incipient rupture. However, in many engineering applications, incipient rupture is not a satisfactory failure criterion since deformations detrimental to the intended use of

the engineering structure may occur before rupture. One such application is to highway and airfield pavements where the pavement may exhibit deformations detrimental to its function before rupture of the pavement mass.

Therefore, it is desirable to be able to relate the amount of deformation to shear stress, normal stress and temperature. To do this, the functional relationship between deformation and time in the transient creep portion of the time-deformation curve is needed. Considerable work has been done on this aspect of the behavior of metals, and a functional relationship has been proposed by Andrade (1951):

$$\epsilon - \epsilon_{o} = bt^{1/3}$$
 (18)

where

€ is total deformation,

 ε_{o} is instantaneous (elastic) deformation which occurs with application of the stress,

(19)

(20)

b is a proportionality constant, and

t is elapsed time after application of the stress.

Differentiating this equation,

$$\dot{\mathbf{e}} = \frac{\mathbf{b}}{3} \mathbf{t}^{-2/3}, \qquad \qquad$$

and solving for t from Eq. (18),

$$t = \frac{(\epsilon - \epsilon_0)^3}{b^3}.$$

Substituting the relationship for t in Eq. (20) into Eq. (19) gives

$$\dot{\epsilon} = \frac{b}{3} \left[\frac{\left(\epsilon - \epsilon_{0}\right)^{3}}{b^{3}} \right]^{-2/3} = \frac{b^{3}}{3} \frac{1}{\left(\epsilon - \epsilon_{0}\right)^{2}} .$$
(21)

If ε_{o} is very small compared to ε , its effect can be neglected and

$$\dot{\epsilon} = \frac{b^3}{3} \frac{1}{\epsilon^2} . \tag{22}$$

There are now two equations for deformation rate, one derived from theoretical principles and the other an empirically proposed relationship which later will be shown to be consistent with results of this study.

If $1/\epsilon^2$ is the unknown function of deformation in Eq. (9) and the coefficient b^3 of Eq. (22) is represented by the other terms on the right side of Eq. (9), the rate equation becomes

$$\dot{\epsilon} = \frac{K'}{3} \exp - \frac{\Delta H^*}{kT} \exp \beta \tau \exp - \beta P_n \frac{\Delta V}{V} \cdot \frac{1}{\epsilon^2} .$$
(23)

In this form, the rate equation is more complex than Eq. (17) and as such is a less desirable form for evaluating the ΔH^* and β . However, by separating variables and integrating this equation, a relationship between total deformation and other variables results:

$$\epsilon^{3} = K' \exp - \frac{\Delta H^{*}}{kT} \exp \beta \tau \exp - \beta P_{n} \frac{\Delta V}{V} \cdot t.$$
 (24)

Because of its empirical nature and the assumptions used in its derivation, the validity of Eq. (23) can only be ascertained by experimental evidence. Inclusion of several interdependent variables in the equation poses the question whether the correct functional relationship among them is stated in Eq. (23). For example, the effect due to $\Delta V/V$ in Eq. (9) may be included in $1/e^2$ in Eq. (22) rather than in b³ as was assumed in Eq. (23).

Implications of Eq. (23) may be further examined to determine if it implies conditions contrary to any basic laws. One such condition is the relationship between total deformation and volume change when $\varepsilon = 0$.

The time derivative of Eq. (23) at constant τ , P_n, and T, since K', T and τ are independent of time, is:

$$\ddot{\epsilon} = \frac{K'}{3} \exp - \frac{\Delta H^{*}}{kT} \exp \beta \tau \frac{d}{dt} (\exp - \beta P_n \frac{\Delta V}{V} \cdot \frac{1}{\frac{2}{\epsilon}})$$

$$\ddot{\epsilon} = \frac{K'}{3} \exp - \frac{\Delta H^{*}}{kT} \exp \beta \tau (-\beta P_n \exp - \beta P_n \frac{\Delta V}{V} \cdot \frac{1}{\frac{2}{\epsilon}} \frac{d \Delta V/V}{dt}$$

$$+ \frac{-2}{\frac{2}{\epsilon^3}} \exp - \beta P_n \frac{\Delta V}{V} \frac{d\epsilon}{dt})$$

$$\ddot{\epsilon} = \frac{K'}{3} \exp - \frac{\Delta H^{*}}{kT} \exp \beta \tau \exp - \beta P_n \frac{\Delta V}{V} \cdot \frac{1}{\frac{2}{\epsilon}} (-\beta P_n \frac{d \Delta V/V}{dt} - \frac{2}{\epsilon} \frac{d\epsilon}{dt}) \quad (25a)$$

or

$$\dot{\varepsilon} = \dot{\varepsilon} (-\beta P_n \frac{d \Delta V/V}{dt} - \frac{2}{\varepsilon} \frac{d \varepsilon}{dt}).$$
 (25b)

Setting $\ddot{\varepsilon} = 0$,

$$\dot{\varepsilon}$$
 (- $\beta P_n \frac{d \Delta V/V}{dt} - \frac{2}{\varepsilon} \frac{d\varepsilon}{dt}$) = 0.

Neglecting the solution when $\dot{\varepsilon} = 0$, which occurs only when no shear stress is applied,

$$-\beta P_n \frac{d \Delta V/V}{dt} = \frac{2}{\varepsilon} \frac{d\varepsilon}{dt} .$$
 (26)

at the point of inflection.

Since increasing volume has been considered positive throughout the derivation, Eq. (26) shows that slope of the volume change-time curve must be negative, and the slope must equal - $2/\beta P_n \varepsilon d\varepsilon/dt$ at the point of inflection.

Other investigators (Best and Hoover, 1966; Ferguson and Hoover, 1968) have proposed a failure criterion based on volume change measurements in constant rate-of-deformation triaxial compression tests. The condition they chose to indicate failure was "...the minimum volume condition, or some point near this condition...."

It would be desirable to compare this failure criterion with that proposed in this investigation, especially since Eq. (26) indicates the $\varepsilon = 0$ criterion is related to rate of volume change. The minimum volume criterion implies a zero rate of volume change (d $\Delta V/V/dt = 0$). But this relationship cannot be substituted into Eq. (26) because in constant rate-of-deformation testing, τ is not independent of time as it is in constant load tests. Therefore, it is not possible to make a direct comparison of these two failure criteria. It is significant, however, that both are related to rate of volume change, one requiring rate of volume change to be negative, the other specifying a zero rate of volume change.

Verification of any relationship between these failure criteria awaits further understanding of material behavior mechanisms under different test conditions. This discussion has indicated the empirical relationship of Eq. (23) is not, nor does it imply conditions, contrary to any basic principles or the energy barrier concept of shear strength.

Consolidation Pressure

As stated before, a relationship similar to Eq. (17) is desirable for evaluating ΔH^* and β . These parameters can be evaluated from that equation if all other variables affecting deformation rate or the value of these parameters are held constant.

Experimentally, however, deformation rate also varies with normal stress P_n , temperature of consolidation T_c (distinct from the temperature at which deformation occurs, designated T_s), and consolidation pressure P_c .

The effect of normal stress on deformation rate has been shown in Eq. (8), which also includes part of the time-dependent structure changes that occur during deformation. However, at the point of inflection, the structure is constant for any normal stress. The effect of normal pressure can be separated from the pre-exponential coefficient of Eq. (17) without changing the fact that the point of inflection represents a point where effect of structure is constant.

$$\dot{\epsilon} = C''' \exp - \frac{\Delta H^*}{kT} \exp \beta \tau \exp - \beta P_n \frac{\Delta V}{V}$$
 (27)

The coefficient C"' in Eq. (27) represents, in addition to the proportionality constant and the entropy of activation, resistance to deformation due to structure changes, other than that due to $P_n \Delta V/V$. As such, C"' is a quantity which varies with $P_n \Delta V/V$. A constant value of these effects can be evaluated by extrapolating Eq. (27) to zero P_n .

The effect due to consolidation pressure can be envisioned by considering frictional resistance of solids proposed by Bowden and Tabor (1950). The actual area of contact between solids is very small compared to the total area. The area of contact is related to applied load on the contact area. When compared to molecular dimensions, the surfaces of solids are relatively rough and the load is carried by the highest points of irregularity on the surfaces. The stresses at such contacts cause elastic and plastic deformations of the material until the contact area is large enough to carry the load.

If the applied load causes plastic deformations, bonds may form between the solid surfaces. If release of the load allows elastic rebound sufficient to break any bonds that may have formed, no permanent adhesion between solid particles results. This probably occurs in granular materials and there is no frictional resistance under zero normal load. However, in clays, bonds probably form between adsorbed water layers adjacent to the surface (rather than between atoms of the particle surfaces). These bonds are not all broken when the load is released. This effect would also be present in granular materials containing some clay or clay-size particles. In granular materials containing no clay particles, the consolidating pressure may have an effect since the greater the normal load, the greater the plastic deformations of the irregular solid surfaces. This would bring the surfaces closer to each other, allowing more bonds to form between the adsorbed water on these surfaces. Since plastic deformation of the irregular solid surface is itself time-dependent, the formation of such bonds would also be time-dependent. A consolidating pressure, applied for some period of time would affect the number of bonds between particles. These bonds between larger particles of a granular system would probably be broken by elastic rebound if consolidation pressure were released. If this occurred before application of shear stress, the effect of consolidation pressure on deformation rate would be negligible. Since the materials used in this investigation contained some clay particles and the consolidation pressure was not released before application of shear stress, the effect of consolidation pressure must be included in the rate equation.

The effect of consolidation pressure on activation energy can be represented by - $\gamma' P_c$, where γ' represents the decrease in volume of an average flow unit due to application of consolidation pressure.

Consolidation Temperature

The effect of consolidation temperature on deformation rate was previously reported by Noble (1968) and was assumed to cause an exponential variation in deformation rate. Noble's experimental data fit that assumption.

Campenella and Mitchell (1968) have shown that increasing consolidation temperature causes a decrease in void ratio for any consolidating pressure. The increase in amount of consolidation is probably due to decreasing viscosity of water with increasing consolidation temperature. The decreased void ratio also indicates water content is less, making the remaining adsorbed water layers thinner and bringing particle surfaces closer to each other. This allows more bonds to form between these thinner adsorbed water layers than between thicker layers resulting from lower consolidation temperatures.

If the increased number of bonds per degree of consolidation temperature is represented by α' , the effect of consolidation temperature can be represented by - $\alpha'T_c$.

Setting $\gamma = \gamma'/kT$ and $\alpha = \alpha'/kT$, the rate equation becomes

$$\hat{\epsilon} = C'' \exp - \frac{\Delta H^{*}}{kT_{s}} \exp \beta \tau \exp - \beta P_{n} \frac{\Delta V}{V} \exp - \gamma P_{c} \exp - \alpha T_{c}$$
 (28)

where

C" is the same as C"' but with the effects of T and P c c separated.

These effects of consolidation temperature and pressure change the height of the energy barrier of the material. Increased consolidation pressure increases the number of bonds, as does higher consolidation temperature, thus reducing the flow unit size, β' . Including these effects in the rate equation allows comparison of the parameter β among material specimens subjected to different values of P and T.

Model Equation

Information from triaxial shear test data is more readily expressed in terms of principal and/or deviator stresses rather than shear and normal stresses. The major principal stress applied to a circular section of the cylindrical specimen, i.e. perpendicular to the longitudinal axis, is the confining pressure in the triaxial cell plus the deviator stress applied through the loading piston, if the effect of cell pressure on the loading piston is neglected. This can be described in the equation

$$\sigma_1 = p + \frac{L}{A}$$

where

 σ_1 is major principal stress,

p is cell pressure,

L is applied force on the loading piston, and

A is the cross-sectional area of the specimen on which the load is applied.

(29)

(30)

The minor principal stress, or the stress on any plane perpendicular to the major principal stress, is simply the cell/pressure, or

From Mohr stress theory, the maximum shear stress in the specimen is

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \tag{31}$$

and the stress normal to the maximum shear stress is

$$\mathbf{P}_{n} = \frac{\sigma_{1} + \sigma_{3}}{2} \,. \tag{32}$$

Substituting the relationships from Eqs. (29) and (30) into Eqs. (31) and (32),

$$\tau = \frac{L}{2A}$$
(33)

and

$$P_n = \frac{L}{2A} + p.$$
 (34)

The consolidation pressure on any plane in the specimen equals the cell pressure since the specimen is isotropically stressed during consolidation in a triaxial cell, or

$$\mathbf{P}_{c} = \mathbf{p}.$$
 (35)

Substituting the relationships from Eqs. (33), (34) and (35) into Eq. (28) and combining terms,

$$\dot{\epsilon} = C'' \exp - \frac{\Delta H^{\star}}{kT_s} \exp \frac{\beta L}{2A} (1 - \Delta V/V) \exp - (\beta \Delta V/V + Y) \exp - \alpha T_c$$
. (36)

The effect of $\Delta V/V$ on the term $\beta L/2A$ (1 - $\Delta V/V$) can be neglected since the value of $\Delta V/V$ is small compared to 1, usually less than 0.02.

Because of the nature of the triaxial test and the experimental techniques used in this investigation, the effects of P_c and P_n on deformation rate are inextricably interrelated. The effect of variation of the pre-exponential coefficient due to structural changes and the effects of ($\beta \Delta V/V + \gamma$) can be combined into a new linear coefficient of

cell pressure, p. This coefficient, designated μ , is theoretically a variable quantity dependent on ΔV and probably on other quantities as well. But analysis of experimental data indicates that considering μ constant does not introduce serious error.

Substituting these approximations into Eq. (36) gives the relationship

$$\dot{\epsilon} = C' \exp - \frac{\Delta H^*}{kT_c} \exp \frac{\beta L}{2A} \exp - \mu p \exp - \alpha T_c$$
, (37)

which is the model equation proposed for deformation of materials.

From Eq. (34) the normal stress on the shear plane is greater than the consolidation pressure. This increase in normal stress during shear could also affect the number of bonds. However, formation of bonds is time-dependent and, since deviator stress was repetitively applied and released, there was probably insufficient time for permanent bonds to form due to increased P_n . If any bonds were formed, they were probably broken by elastic rebound as the deviator stress was released.

Application of deviator stress, thus increasing normal stress, would also cause elastic deformation of the particles. Since elastic deformation would occur on the surface irregularities, the amount of volume change necessary for the material to deform would increase, i.e. increased microdilation. The necessary increase in volume change has been included in the $\Delta V/V$ term, but ΔV is a function of P_n. Because of this interdependence and the relationship between normal stress and consolidation stress, these effects have been combined into an experimentally determined coefficient μ in Eq. (37).

Equation (37) can be used to evaluate the parameters which characterize the material. If information about total deformation or the time to reach a given total deformation is desired, Eq. (24) must be used. Substituting the relationships for shear and normal stress into Eq. (24), neglecting the effect of $\Delta V/V$ on β as before, and including the effects of consolidation temperature and pressure, the relationship for total strain becomes

$$e^{3} = M'' \exp - \frac{\Delta H^{*}}{kT_{s}} \exp \frac{\beta L}{2A} \exp - \mu p \exp - \alpha T_{c} \cdot t.$$
 (38)

Solving this equation for t,

$$t = \frac{\epsilon^3}{M''} \exp \frac{\Delta H^*}{kT_s} \exp - \frac{\beta L}{2A} \exp \mu p \exp \alpha T_c .$$
 (39)

Equation (39) can be evaluated for t at any constant ϵ , by writing

$$t_{\epsilon} = M' \exp \frac{\Delta H^*}{kT_s} \exp - \frac{\beta L}{2A} \exp \mu p \exp \alpha T_c$$
 (40)

where the coefficient M' represents the effect of all quantities affecting the time to reach a total deformation ϵ which are not otherwise included in Eq. (40). To use Eq. (40) in this form, the quantities not specifically considered, i.e. total strain, must be held constant.

In development of the theory to this point, the rate of deformation considered has been the time rate of shear deformation. Shear deformations in a triaxial compression test cannot be measured because of the inability to control either the shear plane or thickness of the shear zone. It is assumed the shear deformations are proportional to axial deformations, conveniently expressed as a percentage of the initial specimen height. The number of applications of deviator stress were measured rather than time. Therefore, time, when used as a variable, can be replaced by the number of applications divided by the frequency of applications as shown in Eq. (2). The deformation rate then becomes the rate of axial deformation per application of deviator stress if the frequency of application is included in the pre-exponential coefficient. Frequency of application was held constant throughout this investigation. Dimensionally, this rate of deformation is in units of percent per application. Likewise, the time to reach a given deformation in Eq. (40) can be replaced by N/r and the constant frequency included in that pre-exponential coefficient.

These exponential relationships can be conveniently expressed by taking logarithms of both sides of the equations. Equation (37) then becomes

$$\ln \dot{\epsilon} = \ln C - \frac{\Delta H^*}{kT_s} + \frac{\beta L}{2A} - \mu p - \alpha T_c , \qquad (41)$$

and Eq. (40) becomes

$$\ln N_{e} = \ln M + \frac{\Delta H^{*}}{kT_{e}} - \frac{\beta L}{2A} + \mu p + \alpha T_{c}, \qquad (42)$$

where the coefficients C and M include, in addition to those factors already stated, the proportionality constants for the relationships between shear and axial deformations, the frequency of load applications, and the conversion of strain to percent strain.

Equations (41) and (42) are the basic relationships evaluated in this investigation. Their development has been based on rate process theory and consideration of those factors known to affect deformation rate. As will be demonstrated, they are in substantial agreement with observed experimental results.

EXPERIMENTAL PROGRAM

Material Properties

The granular material used in the experimental program was a crushed dolomite obtained from a quarry near Garner, Hancock County, Iowa. The material was approved by the Iowa State Highway Commission for rolled stone bases and was tested in the condition as received from the quarry stockpile.

Material properties, as determined by standard procedures, are summarized in Table 1.

The granular material was tested both with and without stabilizing additives. The stabilizing agent was a 120-150 penetration grade asphalt cement meeting specifications of the Iowa State Highway Commission (1964) for petroleum asphalt. Table 1. Material properties.

1

Textural composition (%)	
Gravel (> 2.00 mm) Sand (2.0 mm - 0.074 mm) Silt (0.074 mm - 0.005 mm) Clay (< 0.005 mm) Colloids (< 0.001 mm)	61.6 26.0 10.2 2.2 1.4
Atterberg limits	Nonplastic
Mineralogical composition (by x-ray diffraction)	Calcite Dolomite with small amounts of Quartz Mica Kaolinite
Calcite/Dolomite ratio (by x-ray diffraction peak intensity)	1.16:1
Moisture-density relationships	
Standard AASHO-ASTM density (pcf) Standard AASHO-ASTM optimum moisture content (%) Modified AASHO-ASTM density (pcf) Modified AASHO-ASTM optimum moisture content (%)	147.6
Specific gravity (of minus No. 10 sieve fraction)	2.83
Textural classification	Gravelly sandy loam
AASHO classification	A-1-a

Specimen Preparation

All specimens were prepared by vibratory compaction procedures found by previous studies (Hoover, 1967) to be more suitable than other methods. Each specimen was compacted in a 4-in. diameter by 8-in. high cylindrical mold attached to a Syntron Electric Vibrator table. A constant frequency of 3600 cpm, amplitude of 0.368 mm, surcharge weight of 35 lb, a compaction period of two min, is the combination of factors capable of producing standard AASHO density with minimum degradation (Hoover, 1967) and were used throughout the experiment.

Untreated specimens were prepared by obtaining sufficient air-dry material for a 4-in. diameter by 8-in. high cylindrical specimen; distilled water was added to obtain optimum moisture content. The granular material and water were mixed by hand to reduce degradation of the material, after which the mixture was allowed to stand in a moist atmosphere for 10 min. After standing, the material was again hand mixed and two moisture samples of 100 to 125 g each were removed. The material was placed in the mold in three equal layers, each layer being rodded 25 times with a 5/8-in. diameter tapered point steel rod.

After compaction, the height of each specimen was measured while still in the mold. The specimen was then extruded with a hydraulic jack, wrapped in two layers of Saran wrap and aluminum foil and the ends sealed. The specimens were then encased in a plastic sleeve to prevent deformation of the specimen under its own weight and stored at 75°F and 100% relative humidity until tested.

The asphalt-treated specimens were prepared by obtaining sufficient aggregate and asphalt cement for the desired asphalt content (nominally 4% by weight of the aggregate) for each specimen. The aggregate, asphalt cement, mixing bowl and mold were heated to 250°F. The aggregate and asphalt were then mixed in a mechanical mixer (Hobart Model S-601) for two min. The mixture was again heated and maintained until temperature of the mix reached 250°F. The aggregate-asphalt mixture was then placed in a preheated mold and compacted in the same manner as the untreated specimens.

The asphalt content of each specimen was determined by actual weight of asphalt cement added to the aggregate.

After compaction, the specimens were extruded from the mold and allowed to cool to room temperature. They were then weighed, measured and stored at room temperature and humidity until tested.

Triaxial Compression Apparatus

The repetitive-load triaxial compression apparatus was designed by the Iowa State University Soil Research Laboratory and fabricated by the ISU Engineering Shop and Soil Research Laboratory (Figs. 4 and 5).

The axial loading system, program control center, timer, counter and necessary control valves and pressure switches were manufactured by Enerpac. The hydraulic actuator had a capacity of 17,000 lbs at 10,000 psi fluid pressure.

Applied axial load was measured by a Dillon Series 200, 10,000 lbs capacity lead cell and Dillon Type B meter readout. The meter readout was calibrated to read directly in pounds, each scale division representing 50 lbs.

The timer, which controlled the time a preset load was held on the specimen, had a range from about 0.05 sec to 1.0 sec. The counter was capable of recording one million applications of load.

Positive and negative pore water pressures were measured with a 0-100 psi pressure transducer (N. 4-312-0001) manufactured by Consolidated Electrodynamics and read by a Daytronic Corporation Model 300D Amplifier-Indicator with a Type 93 strain gage input module. The indicator was calibrated to read directly in pounds-per-square-inch with an arbitrary zero reference taken at atmospheric pressure. On the 10% scale, each division on the indicator represented 0.1 psi.

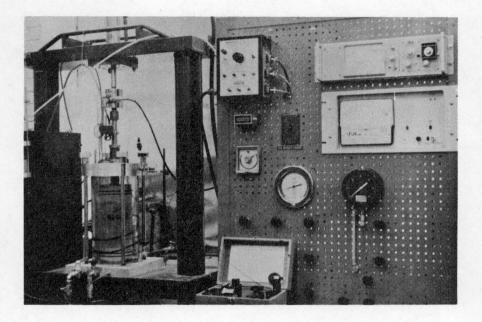


Figure 4. Repetitive load triaxial compression apparatus and control panel

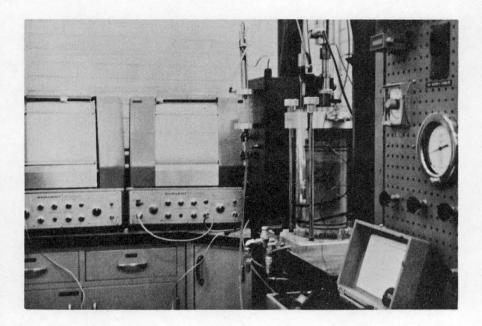


Figure 5. Repetitive load triaxial compression apparatus and strip chart recorders

Volume change was measured with a device developed at the Soil Research Laboratory which incorporates a linear variable differential transformer (LVDT). This device is capable of measurement precision near 0.03 cu in. Vertical deformations of the specimens were measured by a dial extensometer (0.001 in. per division) and simultaneously by an LVDT which was capable of 0.003 in. precision. Both the LVDT used in deflection measurement and that used in the volume change device were manufactured by Schaevitz Engineering.

The volume change, deflection, pore pressure and axial load measurement devices were designed such that all measurements could be continuously recorded on strip-chart recorders.

Temperature control of the specimens was achieved by a controlled temperature water bath consisting of a 0.7 cu ft insulated glass jar heated by an immersion heater and immersed light bulbs equipped with rheostats. The light bulbs operated intermittently by an immersion controller, while the immersion heater operated continuously. Temperature of the test specimen and water in the triaxial cell were controlled by circulating water from the controlled temperature bath through a closed coil in the triaxial cell. Temperature of the cell water was measured by submerged thermocouple wires led through a sealed connection in the triaxial cell cap and connected to a potentiometer calibrated to read directly in degrees Centigrade. Temperature control of the specimen with variations less than one degree Centigrade were possible with this arrangement.

Test Procedure

When ready for testing, a specimen was measured before being placed in the triaxial cell. Saturated corundum porous stones, each 1/2-in. thick, were placed at the top and bottom of the specimen. Specimen, cap, stones and base were sealed in a 0.025-in. thick seamless rubber membrane. The removable heating coil was placed around the specimen and the cell was filled with water.

Water from the controlled temperature bath was circulated through the closed heating coil until the thermocouple readout indicated the desired consolidation temperature. Because the measured temperature was that of the water in the cell rather than that of the specimen, the consolidation temperature was maintained for one hour to insure constant temperature throughout the system before applying consolidating pressure.

In all tests shear temperature was equal to or less than the consolidation temperature. This was necessary since any increase in temperature above consolidation temperature would result in further consolidation, and shear strength would increase as a result of additional consolidation. To determine the effect of shear temperature separate from consolidation temperature, the specimens in each test series were consolidated at a temperature equal to the highest shear temperature used in the respective test series.

After one hour at the consolidation temperature, the consolidating pressure was applied and volume change, pore pressure and deflection measurements were recorded. A uniform consolidation period of 36 min was used for each specimen. With this consolidation period, all specimens reached virtually a constant volume condition.

If shear temperature was to equal consolidation temperature, the specimen drain was closed and the repetitive load process initiated immediately after consolidation. If a shear temperature lower than consolidation temperature was necessary, the specimen was cooled to the desired shear temperature. A minimum equilibration period of one hour was again used at this point in the test procedure. Cooling the specimen to the desired shear temperature after consolidating at a higher temperature was a step which introduced some uncontrollable variation in the specimen, the effects of which will be discussed later.

After equilibrating at the shear temperature, the specimen drain was closed and the repetitive load process initiated. The specimens were subjected to repeated applications of a preset deviator stress until axial deformation reached about 15% of the initial specimen height or until a minimum of 10,000 applications of the stress had been sustained, which ever occurred first.

During repeated loading, pore pressure, volume change and deflection were continuously recorded on the strip-chart recorders. The number of applications were periodically recorded on the strip-charts, thus relating pore pressure, volume change and deflection to the number of stress applications. Since deviator stress and shear temperature were held constant throughout the test on any one specimen, these were monitored on their respective readouts to insure that they did remain constant.

The dwell time, or time that the deviator stress was maintained on the specimen during one stress application, was maintained constant at 1 sec throughout the entire experimental program. The rise and decay times of the stress pulse, plus the "dead" time, consumed a combined total

39.

time of about 1 sec so the frequency of stress application was 30 to 33 applications per minute.

Computations necessary for analysis of data from this study were done primarily with facilities of the Computation Center, Iowa State University, using programs especially developed by the Soil Research Laboratory.

Discussion of Procedure

Despite efforts to standardize all procedures described above, some scatter of results was observed. In a complex testing program, the large number of variable quantities comprise many potential sources of experimental error. Much of the scatter in results reflects these random errors.

However, one source of error which may be systematic involves those changes that occur in the specimen when it is cooled after consolidation at a higher temperature.

More consolidation takes place at higher than at lower temperatures due to lower viscosity of water. When consolidation is complete, it is impossible to lower the temperature in the triaxial cell while maintaining the same conditions of pore pressure, moisture content and saturation. This is due to the coefficient of volumetric expansion of water being 10 times that of mineral matter. Thus, as the specimen was cooled, negative pressure occurred in the pore water as the water contracted more than the mineral matter. If the specimen is cooled with the specimen drain closed, negative pore pressures will develop, the magnitude depending on the temperature differential. If the specimen is cooled with the specimen drain open, negative pore pressure will not build up, but the moisture or air content will be changed, depending on whether the specimen drain is connected to a water reservoir. When the drain is not connected to a water reservoir, the degree of saturation and moisture distribution in the specimen will be changed since air could enter the specimen only from one end.

All methods described above were tried in an attempt to determine a method that would give consistent results. Cooling the specimens with the drain open to a water reservoir was finally adopted. It was thought changes in moisture content due to cooling would not significantly affect results. However, analysis of data subsequently obtained indicated these changes in moisture content affect deformation rate. These effects will be further discussed in the analysis of results section.

Testing Program

Laboratory tests performed in this investigation were all isotropically consolidated, undrained, repetitive-load triaxial compression tests. For simplicity in discussing the results of these tests, they have been classified into series and groups according to the triaxial cell pressure and consolidation temperature as shown in Table 2. Each test consisted of two stages: a consolidation phase in which the specimen was isotropically consolidated under a cell pressure equal to the confining pressure during shear; and a triaxial shear phase during which a deviator stress was repeatedly applied and released. Each test group consisted of several specimens differing only in the level of repeatedly applied deviator stress.

Serie s	Group	P _c , psi	т _с , ^о с	T _s , ^o C
A	5A `	5	25	25
	10A	10	25	25
	15A	15	25	25
	20A	20	25	25
B1	25B1	10	60	25
	40B1	10	60	40
	60B1	10	60	60
В2	25B2	20	60	25
	40B2	20	60	40
	60B2	20	60	60
6 ·	25C	10	. 60	× 25
	40C	10	60	40
	60C	10	60	60

Table 2. Test series and groups.

In Table 2, P_c is consolidation pressure and T_c and T_s are consolidation and shear temperature, respectively. Test series A consisted of all untreated specimens consolidated and sheared at 25°C. Test groups in series A designate the consolidation pressure for that group. Test series Bl and B2 consolidated at 60°C, series Bl having been consolidated and sheared under 10 psi pressure and series B2 under 20 psi pressure. Test series C consisted of asphalt-treated specimens, all consolidated at 60°C and sheared under 10 psi pressure. The test groups in series B1, B2, and C indicate the shear temperature.

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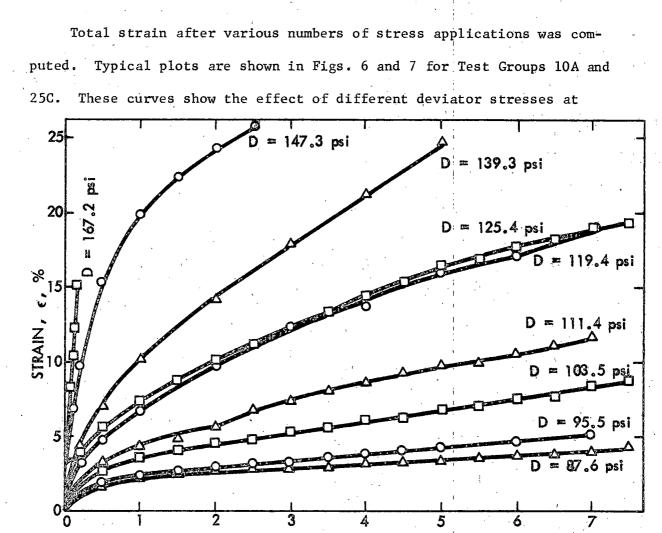
RESULTS AND ANALYSIS

Methods of Analysis

Small variations in materials, specimen preparation, and testing procedure were reflected in the behavior of each specimen. Since each test and/or group or series of tests contained a reasonable number of data points and the equations describing material behavior, Eqs. (18), (41), and (42), consist of linear relationships or combinations of linear relationships, the data could be treated by least squares fitting. All data were so treated. Statistical tests, where appropriate, were made on the quantities computed to help interpret the results.

Because of the number of tests and the number of individual data points obtained for each test, it was not practical to include all primary data from all tests in either tabular or graphic form, but tables of observed quantities and representative graphs have been included for each type of analysis.

Since pore pressure does not appear in any of the equations proposed to describe material behavior, no attempt has been made to describe the effect of pore pressure on deformation rate. This does not mean pore pressure does not affect material behavior, but rather pore pressure does not independently affect material behavior. Any such effect has been included in other quantities. Pore pressure measurements and deflection measurements made with the dial gauge extensometer were useful for observing general behavior of the specimen at any stage during a test.



Strain-Stress Application Relationships

Fig. 6. Strain versus deviator stress applications curves, Group 10A.

DEVIATOR STRESS APPLICATIONS, N x 10-3"

fixed levels of other variables. The shape of these curves is essentially the same as those published by other researchers for soils and other materials if the number of applications were replaced by time on the abscissa.

To test applicability of Eq. (18) to deformation of material, plots of strain versus the cube root of the number of applications were made and are shown in Figs. 8 and 9. Least squares regression analysis of

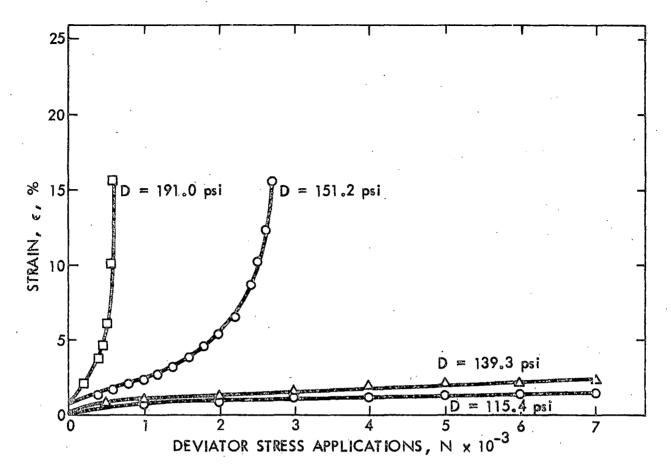


Fig. 7. Strain versus deviator stress applications curves, Group 25C.

all 64 tests are shown in Tables 3 through 15. Deviator stress, equal to L/A in Eq. (33), is denoted D; ϵ is the axial strain; and N is the number of applications of the designated deviator stress. Columns headed ϵ_0 and b indicate values of intercept and slope computed in the regression analysis and, below each value, its standard error. The column headed r is the correlation coefficient of the regression. These analyses do not represent the entire strain versus stress application curve; only the transient portion of the creep curve is represented (stage II of Fig. 3).

Computed values of b in Tables 3 through 15 reflect the changing value of deviator stress. Apparently volume change, in the range of strain considered here, is also a linear function of deviator stress,

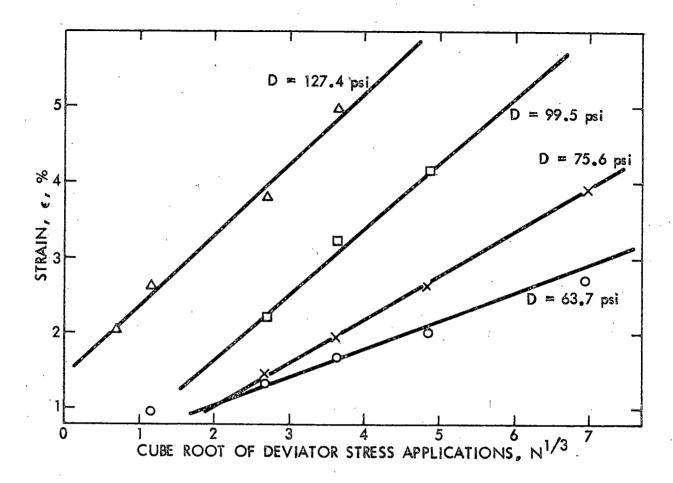


Fig. 8. Strain versus cube root of deviator stress applications relationships, Group 5A.

so this effect is included in the computed value of b. At strain values above those listed in Tables 3 through 15, volume change has an effect independent of, or not linearly related to, deviator stress and the strain application relationship cannot be represented beyond these values by Eq. (18).

Values of the intercept, ϵ_0 , in Tables 3 through 15, indicate no systematic relationship to the level of deviator stress but appear to be distributed about zero. Of the 64 regression analyses, there are 30 negative values of the intercept and 34 positive values. About one-half the values of ϵ_0 are not statistically significant at a significance level of 0.05.

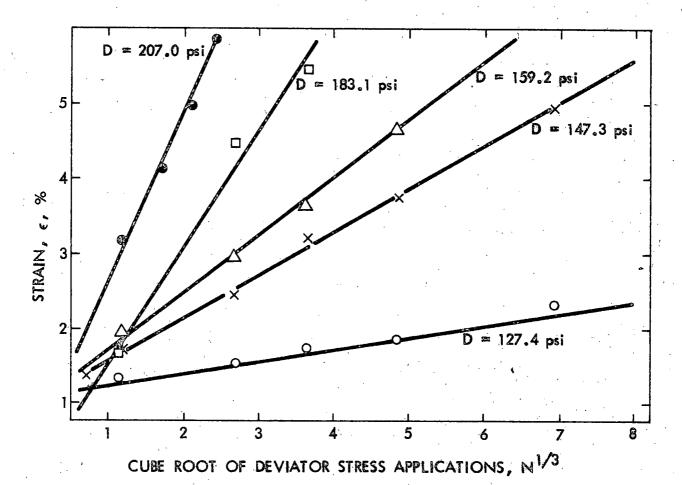


Fig. 9. Strain versus cube root of deviator stress applications relationships, Group 15A.

Because of this apparent random variation in the computed values of ϵ_0 , the assumption in Eq. (22) that elastic deformation is small compared to total deformation seems justified. Computed values of ϵ_0 are thought to represent experimental variation in apparatus and procedure. Some obvious potential sources of error include imperfect contacts between various elements of the loading mechanism and variable seating of porous stones on the ends of the specimen when the repetitive load process was initiated.

	e		1/2	Regres:	sion analy: versus N ^{1/1}	sis,
D, psi	ε, %	N.	N ^{1/3}	€ _o , s _e	b, s _e	r
63.7	0.94	10	2.154	- 0.099	0.377	0.997
,	1.28	50	3.684			
	1.66	100	4.642	0.088	0.009	
	2.00	200	5.848			
	2.72	500	7.937			
	3.58	1000	10.000			
	4.11	1500	11.447			
	4.64	2000	12.599			
•	5.13	2 500	13.572			
	5.39	3000	14.422			
	5.73	3500	15.183			
75.6	1.46	50	3.684	- 0.746	0.582	0.998
	1.91	100	4.642			
	2.62	200	5.848	0.117	0.021	
	3.91	500	7.937	, ,		
99.5	2.17	50	3.684	- 0.991	0.880	0.999
	3.21	100	4.642	,		
	4.14	200 (5.848	0.187	0.032	•
	5.97	500	7.937			
119.4	1.83	5	1.710	- 0.592	0.303	0.993
	2.06	10	2.154			
	4.00	_. 50	3.684	0.358	0.110	
127.4	2.05	5	1.710	0.462	0.950	0.995
	2.61	10	2.154			
	3.80	50	3.684	0.207	0.063	
	4.96	100	4.642			

Table 3. Strain-stress applications, Group 5A.

۰ ۰			1/3	Regres ε	sion analys versus N ^{1/1}	sis, 3
D, psi	e, %	N	N ^{1/3}	€o, ^s e	b, s _e	, r
87.6	1.03	10	2.154	0.734	0.152	0.996
,	1.41	50	3.684		ł	
×	1.45	100	4.642	0.046	0.066	
	1.60	200	5.848		• • • • •	•. •
	1.91	500	7.937		. 1	
	2.32	1000	10.000			
	2.44	1500	11.447			•
	2.60	2000	12.599			
	2.82	2500	13.572 ⁾	Ç		
	2.98	3000	14.423	· ,		
	3.09	3500	15.183	د .		
95.5	0.75	5	1.170	0.389	0.187	0.999
	0.81	10	2.154	1	·	
	1.07	50	3.684	0.021	0.003	
÷	1.24	100	4.642			
	1.45	200	5.848	3		
	1.85	50 0	7 .9 37			,
	2.25	1000	10.000			•
·	2.53	1,500	11.447			· ·
	2.79	2000	12.599			
103.5	1.42	50	3.684	0.010	0.360	0.998
	1.64	100	4.462			
	2.09	200	5.848	0.082	0.009	1
	2.77	500	7.937	, ,		
· 1	3.74	1000	10.000			
	4.04	1500	11.447			
	4.57	2000	12.599	· ·		1
	4.91	2 500	13.572			
111.4	0.75	5	1.710	- 0.252	0.460	0.998
	0.78	10	2.154	·	Р	
	1.27	, ' 50	3.684	0.082	0.011	,
	1.75	100	4.642	,		
	2.42	200	5.848			
	3.39	、 500	7.937			
	4.36	1000	10.000		Ň	
	5.00	1500	11.447		,	`
	5.63	2000	12.5 99)	,	
119.4	1.10	10	2.154	- 0.052	0.632	0.993
	2.41	50	3.684			
	3.03	100	4.642	0.228	0.044	
,	3.72	~200	5.848			
	4.82	500	7.937	1		

Table 4. Strain-stress applications, Group 10A.

			1/2		sion analy <u>versus N</u> 1/	
D, psi	e, %	N	N ^{1/3}	€ _o , s _e	b, s _e	r .
125.4	1.58 2.43	10 50	2.154 3.684	0.185	0.625	0.998
	3.04 3.89	100 200	4.642 5.848	0.115	0.027	
139.3	1.58 2.53	10 50	2.154 3.684	0.031	0.703	0.996
	3.35	100	4.642	0.234	0.064	
147.3	2.43 5.51	10 50	2.154 3.684	- 1.424	1.827	0.997
	6.93	100	4.642	0.515	0.141	
159.2	2.21 2.49	5 10	1.710 2.154	- 0.065	1.264	′0 . 981
	3.25 3.74	19 25	2.668 2.924	0.431	0.179	
167.2	1.45 1.94	1	1.000	- 0.287	1.790	0.999
	2.87	2 5 10	1.710	0.068	0.032	
	4.10 4.55	15 20	2.466 2.714			
	4.92	25	2.924			

·		·			sion analys versus N1/3	
D, psi	ε, %	N	N ^{1/3}	€o, ^s e	b, s _e	r
127.4	1.33	10	2.154	0.886	0.181	0.995
	1.52	50	3.684	0.056	0.000	
	1.75 1.86	100 200	4.642 5.848	0.056	0.009	
	2.32	500	7.937			
	2.74	1000	10.000			
127.4	1.88	50	3.684	1.276	0.163	0.992
	2.07	100	4.642			
	2.26	200	. 5.848	0.082	0.010	
	2.45	500	7.937			1
	2.92	1000	10.000			
'	3.20	1500	11.447			
147.3	1.38	5	1.710	0.448	0.570	0.999
	1.71	10	2.154			
	2.49	50	3.684	0.063	0.013	
	3.20	100	4.642			
	3.76	200	5.848			-
	4.95	500	7.937			
159.2	10	2.154		0.181	0.770	0.998
	2.98	50	3.684			
	3.63	100	4.642	0.137	0.026	
	4.65	200	5.848			
	6.38	500	7.937		· ·	. •
183.1	1.66	10	2.154	- 1.548	1.544	0.997
i	4.46	50	3.684	0 010		
	5.44	100	4.642	0.310	0.063	
	7.41 8.84	200 300	5.848 6.694			
:	0.04	200	0.094			
191.0	1.75	5	1.710	0.274	0.864	0.999
	2.14	10	2.154			
	3.46	50	3.684	0.013	0.005	
207.0	3.15	10	2.154	- 1.872	2.256	0.997
	4.13	20	2.714			
	4.98	30	3.107	0.247	0.073	
	5.85	40	3.420			
	6.42	50	3.684			
	6.98 7.52	60 70	3.915 4 121			
	7.52	70	4.121			

Table 5. Strain-stress applications, Group 15A.

			1/3	6	sion analy versus N ^{1/}	sis, 3
D, psi	ε, %	N	N ^{1/3}	€o, se	b, s _e	r
151.2	1.66	10	2.154	0.859	0.453	0.999
	2,67	50	3.684			
	3.00	100	4.642	0.066	0.005	
	3.65	200	5.848			
	4.26	500	7.937			
	5.46	1000	10.000	ı		
	6.07	1500	11.447			
	6.59	2000	12.599			
	6.97	2500	13.572			
	7.35	3000	14.423			
	7.76	3500	15.183	4		
1	8.03	4000	15.874			
	8.25	4500	16.510			
	8.59	5000	17.100			
	8.97	5500	17.652			
191.0	1.48	5	1.710	0.598	0.602	0.997
	1.94	10	2.154			
	2.89	50	3.684	0.107	0.022	
	3.53	100	4.642		•	
ſ	4.06	200	5.848			
	5.32	500	7.937			
207.0	3.44	50	3.684	- 0.648	1.098	0.999
	4.47	100	4.642		-	
	5.65	200	5.848	0.185	0.032	
	8.13	500	7.937	-		
222.9	1.43	5	1.710	- 0.449	1.101	0.999
	1.95	10	2.154	·		
	3.56	50	3.684	0:058	0.018	
	4.69	100	4.642			
230.8	1.60	1	1.000	- 0.172	1.651	0.999
	2.57	5	1.710			
	3.28	10	2.154	0.101	0.038	•
	4.29	20	2.714			
	4.92	30	3.107			
	5.53	40	3.420			
	5 .9 7′	-50	3.684			J

Table 6. Strain-stress applications, Group 20A.

١		,	1/3	Regres: €	sion analys versus N ^{1/1}	sis, 3
D, psi	ε, %	N	N ^{1/3}	€o, ^S e	b, s _e	r
127.4	1.71	_ 50	3.684	0.908	0.206	0.999
	1.86	100	4.642			
	2.05	200	5.848	0.035	0.003	•
	2.54	500	7.937			
	3.07	1000	10.000			
	3.19	1500	11.447			
	3.44	2000	12.599			
	3.68	2 500	13.572			
	3.91	3000	14.225			
	4.02	3500	15.183	`		
	4.16	4000	15.874			
	4.29	4500	16.510			
	4.42	5000	17.100			
	4.56	5500	17.652			
	4.67	6000	18.171			
143.3	2.46	50	3.684	- 1.883	1.179	0.999
	3.60	100	4.642			
	5.01	200	5.848	0.031	0.006	
163.2	4.07	50	3.684	1.462	0.700	0.999
	4.68	100	4.642			
	5.54	200	5.848	0.075	0.013	
	6.64	400	7.368			
191.0	3.32	10	2.154	- 0.520	1.772	0.998
	4.24	20	2.714			
	5.02	30	3.107	0.264	0.098	
207.0	2.08	5	1.710	- 0.591	1.533	0.998
	2.65	10	2.154			
	3.52	·20	2.714	0.174	0.070	
	4.22	30	3.107			

Table 7. Strain-stress applications, Group 25B1.

			1/0	Regress e v	sion analys versus N ^{1/2}	sis, }
D, psi	ε, %	N	N ^{1/3}	^e o, ^s e	b, s _e	r
111.4	1.83	100	4.642	0.901	0.193	0.998
	2.02	- 200	5.848			
	2.40	500	7.937	0.050	0.006	
	2.82	1000	10.000			
	3.14	1500	11.447			
127.4	2.16	50	3.684	0.770	0.376	0.998
	2.47	100	4.642			
	3.02	200	5.848	0.091	0.016	
	3.74	500	7.937			
143.3	3.26	50	3.684	0.716	0.695	0.999
	3.99	100	4.642			•
	4.75	200	5.848	0.081	0.014	
	6.24	500	7.937			
179.1	2.11	10	2.154	- 0.776	1.325	0.999
	4.03	50	3.684			
	5.42	100	4.642	0.195	0.053	:
191.0	2.54	10	2.154	- 0.874	1.552	0.997
	4.67	50	3.684	0.442	0.121	
	6.44	100	4.642			
207.0	1.46	1	1.000	0.179	1.259	0.998
	1.76	2	1.260			
	2.29	- 5	1.710	0.077	0.048	
	2.92	10	2.154			

Table 8. Strain-stress applications, Group 40B1.

			1 / 2	Regress c	sion analys versus N ^{1/1}	sis, }
D, psi	ε, %	N	N ^{1/3}	e, se	b, s _e	r
127.4	1.71	10	2.154	1.038	0.335	0.993
	2.36	50	3.684			
	2.59	100	4.642	0.116	0.027	
	2.97	200	5.848			
127.4	1.65	10	2.154	0.981	0.310	0.997
	2.10	50	3.684			
	2.47	100	4.642	0.070	0.016	
	2.77	200	5.848	ı		
143.3	2.35	50	3.684	0.819	0.411	0.998
	2.70	100	4.642			
	3.24	200	5.848	0.118	0.024	
163.2	4.24	. 50	3.648	0.598	1.012	0.998
	5.41	100	4.642			
	6.5 4	200	5.848	0.245	0.046	
	7.32	300	6.694			
207.0	2.78	5	1.710	- 0.072	1.666	0.997
	3.54	10	2.154			
	3.96	15	2.466	0.196	0.085	
	4.49	20	2.714			·

Table 9. Strain-stress applications, Group 60B1.

			Regression analysis, ε versus N ^{1/3}			
D, psi	ε, %	Ň	N ^{1/3}	€ _o , s _e	b, s _e	r
183.1	2.41 2.94	50 100	3.684 4.642	0.873	0.431	0.998
,	3.40 4.28	200 500	5.848 7.937	• 0.113	0.020	
199.0	2.56 3.16	50 100	3.684 4.642	- 0.362	0.779	0.995
	4.23	200	5.848	0.011	0.074	
199.0	2.49 3.10	50 100	3.684 4.642	0.108	0.646	0.999
	3.87	200	5.848	0.355	0.002	
238.8	3.84 5.01	50 100	3.684 4.642	- 0.771	1.248	0.999
	6.52 8.44	200 400	5.848 7.368	0.036	0.007	

Table 10. Strain-stress applications, Group 25B2.

Table 11. Strain-stress applications, Group 40B2.

			1/2	Regression analysis, ε versus N ^{1/3}		
D, psi	€, %	N	N ^{1/3}	°o, se	b, s _e	r
199.0	2.17	50 100	3.684 4.642	0.878	0.352	0.999
	2.94	200	5.848	0.018	0.004	
238.8	3.15 3.87	50 100	3.684 4.642	0.297	0.771	0.999
	4.81	200	5.8:48	0.047	0.010	ī

			1/2	Regression analysis, c versus N ^{1/3}			
D, psi	ε, %	N	N ^{1/3}	€ <mark>, s</mark> e	b, s _e	r	
183.1	2.27	50 100	3.684 4.642	0.604	0.454	0.999	
	3.25	200	5.848	0.047	0.010		
199.0	2.41 2.87	50 100	3.684 4.642	0.638	0.478 —	-	
238.8	3.31 4.15	50 100	3.684 4.642	0.572	0.757	0.999	
	5.02 6.12	200 400	5.848 7.368	0.122	0.022		

Table 12. Strain-stress applications, Group 60B2.

Table 13. Strain-stress applications, Group 25C.

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			N ^{1/3}	Regres:	sion analy: versus N ^{1/}	sis, 3
D, psi	e, %	N		€ <mark>o, s</mark> e	b, s _e	r
115.4	0.56 0.75	50 100	3.684 4.642	0.315	0.080	0.953
ų	0.78 0.93	200 500	5.848 7.937		0.018	
139.3	0.55 0.63	50 100	3.684 4.642	0.270	0.080	0.985
	0.78 0.88	200 500	5.848 7.937	0.057	0.010	
151.2	0.76 0.95	50 100	3.684 4.642	0.176	0.121	0.909
	1.15	200	5.848	0.007	0.033	
191.0	0.55 1.00	10 50	2.154 3.684	- 0.175	0.331	0.99 5
	1.34	100	4.642	0.113	0.031	

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	ε, %		1/2	Regression analysis, <u>c versus N^{1/3}</u>			
D, psi		N	N ^{1/3}	°,.s _e	b, s _e	. r	
99.5	1.22 1.54	50 100	3.684 4.642	- 0.206	0.381	0.998	
	2.04	200	5.848	0.108	0.023		
111.4	1.33	50	3.684	- 1.292	0.706	0.999	
	1.96 2.85	100 200	4.642 5.848	0.119	0.025		
119.4	1.11 1.41	50 100	3.684 4.642	- 0.379	0.397	0.994	
	1.97	200	5.848	0.205	0.043		
135.3	0.95 1.84	10 50	2.154 3.684	0.109	0.431	0.988	
,	2.57	100	5.848	0.275	0.066		

Table 14. Strain-stress applications, Group 40C.

Table 15. Strain-stress applications, Group 60C.

			1/2	Regression analysis, c versus N ^{1/3}				
D, psi	ε, %	N	N ^{1/3}	€ _o , s _e	b, s _e	r		
79.6	1.00 1.86	100 200	4.642 5.848	- 1.977	0.649	0.999		
	3.16	500	7.937	0.157	0.025			
91.5	1.41 2.09	50 100	3.684 4.642	- 2.064	0.900	0.992		
	2.92 5.22	200 500	5.848 7.937	0.450	0.078			
99. 5	2.36, 4.10	50 100	3.684 4.642	- 5.029	1.993	0.997		
	5.63	150	5.313	0.595	0.129			
111.4	1.26 1.72	5 10	1.710 2.154	- 2.903	2.278	0.975		
	3.02 4.46	20 30	2.714 3.107	0.896	0.361			

Deviator Stress-Application Relationships

The number of applications at which each specimen reached total strains of 2% and 5% were computed and plotted on a semi-logarithmic scale versus the applied deviator stress for each test group. All other variables were constant. Typical examples are shown in Figs. 10 and 11. Regression analyses for all 13 groups of tests are shown in Tables 16 through 19, where the column headings are as previously defined.

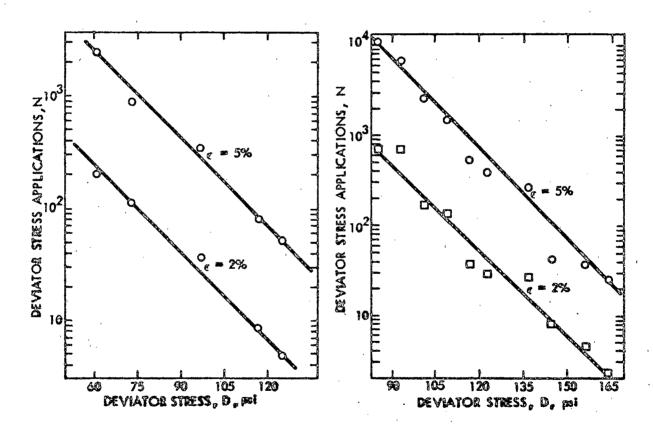


Fig. 10. Variation in number of stress applications for 2% and 5% strain with deviator stress, Group 5A.

Fig. 11. Variation in number of stress applications for 2% and 5% strain with deviator stress, Group 10A.

				- <u></u>	Regression 2%	analysi	s, 1n N _s ver	<u>sue D</u>	
				Intercept,	$\beta/2 \times 10^2$,	r	Intercept,	$\beta/2 \times 10^2$,	r
Group	D, psi	N, 2%	N, 5%	e e	. 8 e		se e	8 e	
5A	63.7	200	2423	9.116	5.807	0.995	11.415	5.834	0.995
	75.6	113	877						,
	99.5	37	340	0.346	0.345		0.354	0.353	•
	119.4	8.6	81						
	127.4	4.9	52						
10A	87.6	698	10791	12.892	7.245	0 .9 83	13.752	7.862	0.986
	95.5	689	6728'						
	103.5	17 9	2593	0.619	0.483		0.595	0.464	
	111.4	137	1502						
	119.4	37	546						
	125.4	30	391						
	139.3	28	265						
	147.3	8.2	43						
	159.2	4.5	38						
•	167.2	2.2	26					•	
15A	127.4	28 9	5030	9.485	3.582	0.881	16.752	6.759	0.976
	127.4	81	4977						
	147.3	25	518	1.534	0.925		1.121	0.676	
	159.2	12	260						
	183.1	15	78						
	191.0	8.2	31						
	207.0	6.3	30						
20A	151.2	23	808	6.449	2.092	0.817	12.551	3.671	0.924
	191.0	13	424						
	207.0	29	145	1.726	0.852		1.780	0.878	
	222.9	11	118				•		
	230.8	2.6	31						

Table 16. Stress-applications at 2% and 5% strain, Series A.

The intercept, calculated by extrapolating Eq. (42) to zero deviator stress, has no physical significance since it represents the calculated number of zero deviator stress applications necessary to produce the stipulated strain.

The values of β calculated for total strains of 2% and 5% exhibit some variation in some test groups. From derivation of Eq. (42), the difference between the 2% and 5% strain curves should be constant and independent of deviator stress level. However, this derivation was

				. <u></u>	Regression 2%	analysi	в, 1n N _G ver	sus D .5%	
Group	D, psi	N, 2%	N, 5%	Intercept, ^s e	$\beta/2 \times 10^2$,	r	Intercept, ^{'⁸e}	β/2 × 10 ² , ³ e	r
25B1	127.4 143.3	174 41	7921 498	10.538	4 . 459	0.983	16,015	6.351	Ó.922
	163.2 191.0 207.0	25 6.0 4.8	138 30 41	0.803	0.475		2.599	1.538	
20 B 1	111.4 127.4	190 46	4744 1000	8.975	3.372	0.979	13.089	4.743	0.965
	143.3 179.1 191.0 207.0	31 9.5 7.9 3.4	2 50 8 5 59 37	0.630	0 . 385	ı	1.050	0.642	
60B1	127.4 127.4	28 41	1343 1221	7.407	2.833	0.922	13.687	5.199	0.966
	143.3 163.2 207.0	43 24 3.6	703 82 25	1.070	0.684		1.246	0.796	

Table 17. Stress-applications at 2% and 5% strain, Series Bl.

Table 18. Stress-applications at 2% and 5% strain, Series B2.

			N, 5%	2%			5%		
Group	D, psi	N, 2%		Intercept, ⁸ e	β/2 x 10 ² , ⁸ e	r	Intercept, ^S e	β/2 x 10 ² , s _e	r
25B2	183.1 199.0	42 39	836 466	5.433	0.901	0.974	13.613	3.776	0.997
	199.0 238.8	40 26	405 100	0.305	0.148		0.389	0.189	
40B2	199.0 238.8	46 32	1536 226	5.645 _	0.885		16.920	4 . 805 _	`
60B2	183.1 199.0	44 41	1247 989	5.094	0.706	0.994	13,567	3.443	0.986
	238.8	30	198	0.156	0.075		1.195	0.574	

based on the assumption that the effect of ϵ_0 could be neglected if it is small compared to ϵ . Validity of this assumption has been shown in the previous section, but in some groups, especially in Series B2, the value of ϵ_0 apparently has considerable effect on the calculated value of β at 2% strain.

							s, ln N _s versus D 5%		
Group	D, psi	NT 29	N, 5%	Intercept,	$\beta/2 \times 10^2$	r	Intercept,	β/2 x 10 ²	r
		Ng 216		⁸ e	5e		8e	8e	<u>`</u>
25C	115.4 139.3	11289 4380	 14150	13.305	5.495	0.963	14.890	5.878	0.919
	151.2 191.0	4380 738 200	1902 462	1.648	1.036		4.076	. 2. 514	
40C	99.5 111.4	193 105	912 441	8.029	2.741	0.721	9.990	3.221	0.849
	119.4 135.3	205 61	695 248	2.180	1.860		1.658	1.415	
60 C	79.6 91.5	231 .93	1516 471	12.961	9.327	0.996	17.102	12.179	0.996
	99.5 111.4	42 12	129 34	0.516	0.536		0.736	0.765	

Table 19. Stress-applications at 2% and 5% strain, Series C.

Strain Rate-Stress Relationships

A necessary condition for valid application of Eq. (41) to the deformation of materials is that the value of strain rate $\dot{\epsilon}$ must be determined at the point where strain acceleration $\ddot{\epsilon}$ is zero. A method of determining strain rate at the point where $\ddot{\epsilon} = 0$ has been reported by Noble (1968). Calculated values of strain rate were plotted versus strain corresponding to the calculated strain rate. From these plots, points of minimum strain rate could be determined, representing the point $\ddot{\epsilon} = 0$. The point actually determined by this graphical method is d $\dot{\epsilon}/d\epsilon = 0$, but it can easily be shown that d $\dot{\epsilon}/dt = 0$ at the same point.

The above method of determining meaningful strain rates was used in this investigation. Strain rate was calculated for each point on the strain-stress application curve. Calculations were made with a computer program by taking differential strain between two points and dividing by number of stress applications between points. The value of strain rate thus determined was reported for the leading point of the two considered. This method is not exact since slope of the strain-stress application curve was computed for an increment of the curve and reported as strain rate at a point. However, by choosing points at close enough intervals of stress application, precision can be adequate. This method is believed to be as precise as, and less prone to error than, any graphical method of determining strain rate at a point.

Values of the strain rate thus determined were plotted versus the respective value of strain at which they occurred. Because of the wide range in the value of strain rate for each stress level, the curves were plotted with strain rate on a logarithmic scale. Figures 12 and 13 show these plots for Groups 10A and 25C. As can be seen in Fig. 12, not all curves exhibit a definite minimum value of strain rate. Some, especially at lower stress levels, have a minimum value after which the strain rate increases and then decreases. To determine a strain rate value corresponding to $\ddot{e} = 0$ for all stress levels, a line was drawn connecting the minimum points of those curves which did not exhibit minima; strain rate at the point where this line intersected curves with no definite minimum was used as the strain rate for that respective stress level.

The phenomenon of some curves having a minimum point followed by an increase and then further decrease in strain rate is attributed to confinement of the specimen in the triaxial test. Increasing strain rate likely represents incipient rupture of the material, but rupture is prevented since the specimen is confined in the triaxial cell.

Tables 20 through 23 show the values of strain rate thus determined for each stress level in all test groups. Also included in these tables

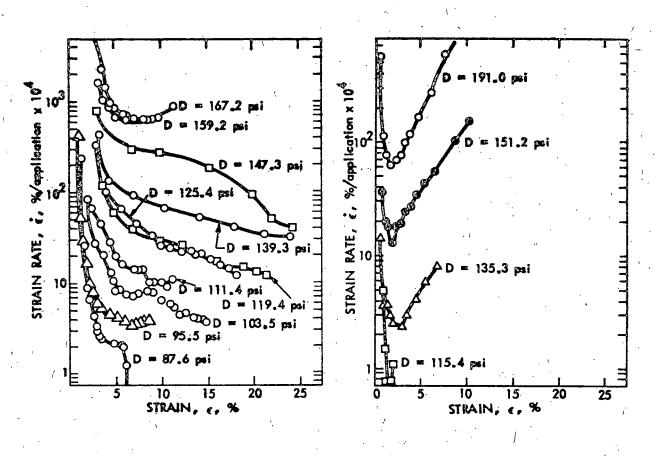


Fig. 12.

Strain rate versus strain, Group 10A. Fig. 13. Strain rate versus strain, Group 25C.

is moisture content (or asphalt content) as determined at the time each specimen was molded. Regression results shown were obtained from regression of logarithm strain rate versus deviator stress in each test group. Consolidation and shear temperatures as well as confining pressure were held constant within each test group. Moisture content or asphalt content was not included as a variable in this analysis. Any effect due to variation in moisture content or asphalt content is included in the standard error of the slope and intercept. Column headings are as previously defined except that "d.f.," residual degrees of freedom of the regression, has been added.

· 1

		<i>L</i>	Moisture	Regr	ession analy ln é versus		
Group	D, psi	ė x 10 ⁴ , %/appl	content, %	Intercept, s _e			r
5A	63.7	7.6	7.35	- 10.625	5.715	3	0.987
	75.6 99.5 119.4	23.0 68.0 300.0	7.77 7.44 7.73	0.529	0.527		
10A	127.4 87.6 95.5	270.0 2.0 3.5	7.21 7.29 6.93	- 15.081	7.611	8	0.993
	103.5 111.4 119.4	7.4 14.0 37.0	8.69 7.42 7.69	0.422	0.327		
ų	125.4 139.3 147.3 159.2 167.2	45.0 86.0 300.0 590.0 660.0	7.08 8.22 8.07 6.11 7.35				
15A	127.4 127.4	2.5	6.93 7.10	- 14.472	5.200	4	0.977
	147.3 159.2 183.1 191.0 207.0	14.0 33.0 78.0 82.0 220.0	7.31 7.17 8.08 6.97 7.08	0.979	0.578		
20Å	151.2 191.0 207.0 222.9	3.0 15.5 88.0 98.0	8.07 6.92 7.35 7.28	- 17.103 1.681	5.815 0.829	3	0.971
	230.8	400.0	7.17				

Table 20. Deviator stress-strain rate, Series A.

Representative plots of logarithm strain rate versus deviator stress are shown in Figs. 14 and 15. The results shown and tabulated in Tables 20 through 23 were obtained by holding T_s , T_c and P constant, so the combined effects of these factors are included in the calculated intercept.

			Moisture	Regr	ession anal ln é versus		
Group	D, psi	έ × 10 ⁴ , %/app1	content, %	Intercept, ^s e	β/2 x 102, s _e	d.f.	r
25B1	127.4	1.8	6.71	- 17.487	7.294	3	0.972
	143.3 163.2 191.0	14.0 32.0 600.0	7.23 7.88 7.47	1.714	1.014		<i>.</i> .
	207.0	500.0	7.18	9	× .		
40B1	111.4 127.4	2.5 18.0	6.98 7.00	- 13.885	5.490	4	0.984
	143.3 179.1	27.0 150.0	6.84 6.80	0.803	0.491		
	191.0 207.0	400.0 680.0	7.42 7.06	, · · .			
60B1	127.4	10.0	7.58	- 14.171	5.787	3	0.998
•	127.4 143.3	12.0 26.0	7.00 7.49 7.00	0.320	0.204		
	163.2 207 . 0	105.0 1050.0	7.22		•		

Table 21. Deviator stress-strain rate, Series B1.

Table 22. Deviator stress-strain rate, Series B2.

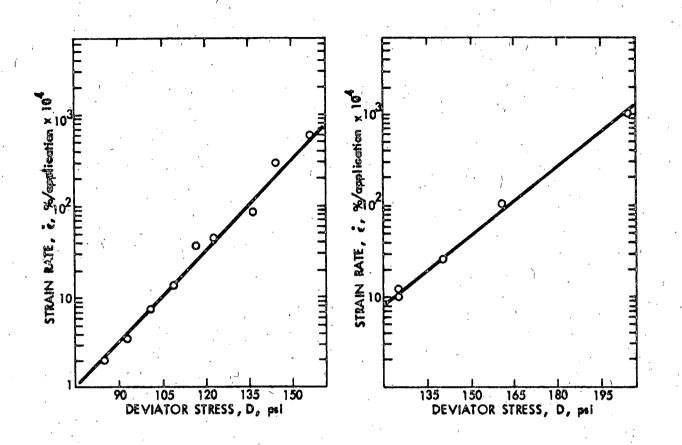
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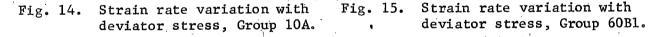
		4	Moisture		ession analy ln <u>e versus</u>		
Group	D, psi	έ χ 10 ⁴ , %/app1	content, %	Intercept, s _e	β/2 x 10 ² , s _e	d.f.	r
25B2	183.1 199.0	10.0 18.0	7.19 7.04	- 15.343	4.650	2	0.976
	199.0 238.8	32.0 140.0	7.48 8.20	1.497	0.727		
40 B2	199.0 238.8	11.0 62.0	7.34 7.61	- 9.678	1.440 —	0	· _ ·
60B2	183.1 199.0	10.0 14.0	8.06 6.83	- 12.710	3.131	1	0.995
· .	238.8	55.0	7.69	0.614	0.295		

		,	Asphalt	Regr	ession analy 1n é versus			
Group	D, psi	έ x 10 ⁴ , %/appl		Intercept, se			r	
25C	115.4 135.3	0.75 2.4	3.98 3.98	- 16.474	6.155	2	0.985	
	151.2 191.0	13.0 74.0	3.49 3.49	1.151	0.763			
40C	99.5 111.4	2.0 82.0	3.91 3.94	- 18.555	11.171	2	0.838	
	119.4 135.3	88.0 160.0	4.03 4.03	6.020	5.138			
60C	79.6 91.5	12.0 63.0	3.94 3.91	- 19.018	15.397	2	0.998	
•	99.5 111.4	2 90. 0 1500.0	4.04 4.05	0.641	0.633			

Table 23. Deviator stress-strain rate, Series C.

 $a_{i} = b_{i}$





Effects of Other Variable Quantities

Effects of all linear terms in Eqs. (41) and (42) can be evaluated by multiple linear regression techniques. The multiple linear regression model assumes the effect of one variable quantity is unchanged by the level of any other variable quantity. If this assumption is valid for the data obtained, values of β determined within each test group would be the same regardless of the level of any other variable. Since the computed value of β is different for each test group, a statistical test is necessary (Snedecor and Cochran, 1967, pp. 432 ff) to determine

if the values of calculated β are significantly different or if the differences can be attributed to experimental errors.

Table 24 shows the calculated test statistic for β values calculated from Eq. (41), the tabulated value of the distribution function for the appropriate degrees of freedom at the 0.01 significance level, and the resulting conclusion for each combination of groups and/or series. The conclusions are based on relative magnitude of the calculated and tabulated values. If the calculated value of the test statistic is less than the tabulated value, the values of β calculated at different levels of other variables do not significantly differ from one another. Conversely, if the calculated value of the test statistic is greater than the tabulated value, one or more of the β 's are significantly different than some other β values, i.e. not all β 's are from the same population.

Group/series combination	Calculated F	Tabulated ^F 0.01	Conclusion
All groups, Series A	4.99	5.01	May be combined
All groups, Series Bl	2.26	7.56	May be combined
All groups, Series B2	1.61	30.82	May be combined
Series A and Bl	3.07	3.53	May be combined
Series A and B2	5.59	3.81	Cannot be combined
Series A, Bl and B2	3.70	3.06	Cannot be combined
Series B1 and B2	2.92	4.86	May be combined
All groups, Series C	3.09	10.92	May be combined

Table 24. Test for combination of groups and series.

As shown in Table 24, if the statistical test indicates that all are from the same population (variations are attributed to experimental error), the assumption that the effect due to deviator stress is the same regardless of the level of other variables is valid and those combinations of groups and/or series may be combined in a multiple linear regression analysis.

If the statistical test indicates that values are not from the same population, those combinations cannot be analyzed by multiple linear regression techniques. Significant differences in values may be caused by variable effects of deviator stress at different levels of other variables, or such differences may be caused by another variation in the material system that was not considered in the analysis.

Conclusions based on test statistics calculated for β values determined from Eq. (42) are the same as those in Table 24. No attempt was made to `combine the results of Series C with the results from any other series, since the asphalt stabilization of Series C made a different material system than that of the other series in the investigation.

Multiple Regression Analysis

The results of multiple linear regression analyses for those combinations of groups and/or series of tests that may be combined are shown in Tables 25,through 27. In Table 25, strain rate is considered as the dependent variable and all other quantities, <u>viz</u>. D, p, T_s and T_c as independent variables. In Tables 26, and 27, the number of stress applications at which 2% of 5% strain was reached is the dependent variable while independent variables are the same as in Table 25.

Serie s	p, psi	т _с , ос	τ _s , oC	Residual, d.f.	Intercept, ⁸ e	$\Delta H^*/k \times 10^{-3},$	$\beta/2 \times 10^2$, se	µ́, 8 е	α, s _e	R ²
A	5 10	25	25	23	- 8.775	· · ·	6.233	0.470	_ .	0.928
<i></i>	15 20	•			0.326		0.362	0.032	2	
B1	10	60	25 40 60	13	7.482	2.337	6.056		_ ,	0.947
			25		2.859	0.906	• 0.396	•		
B2	20	60	40 60	6	- 18.422 2.679	- 1.426 0.748	3.772 0.521	-	· -	0.901
A and B1	5 10 15	25 60	25 40	37	0.748	2.367	6.141	0.464	0.060	0.937
	20		60 60		3.051	0.875	0.263	0.027	0.007	
B1 and B2	10 20	60	25 40 60	21	- 8.552 2.642	0.637 0.827	5.466 0.416	0.340 0.032	÷	0.896
		•	25					<u>,</u>	s _e	
С	10	60	40 60	9	48.253 9.329	19.825 3.369	7.618 1.688	-	• .	0.794
С	10	60	25 40 60	8	31.644 13.045	19.781 3.072	9.306 1.839	3.7 2.2		0.848

Table 25. Multiple regression analysis, Eq. (41).

Results in Table 25 were obtained from regression of the logarithm of strain rate on deviator stress as shown in Tables 20 through 23 and the respective levels of other variables shown in Table 25. Results in Tables 26 and 27 were obtained from regression of the logarithm of N $_{\rm c}$ versus respective levels of deviator stress shown in Tables 16 through 19 and other variables as shown in Tables 26 and 27.

Two regression analyses are shown in Table 25 for the combinations of all groups in Series C, one in which the variables are as indicated above and the other (last line in Table 25) in which asphalt content of the specimen was included as an independent variable, assuming a

Series	p, psi	T _c , oC	Τ <mark>s</mark> , οC	Re sidual, d.f.	Intercept, ^s e	∆H*/k × 10 ⁻³ , ^s e	β/2 x 10 ² ^s e	μ, s _e	α, s e	r ²
A	5 10 15 20	25	25 ·	24	7.308 0.493		5.005 0.534	0.261 0.047	-	0.802
	20		25							
B1	10	60	40 60	13	4.194 2.222	1.490 0.704	3.678 0.307		v 	0.917
			25			· .				
B2	20	60	40 60	6	5.802 0.666	- 0.190 0.186	0.756 0.129	-	-	0.852
A and Bl	5	25								
	10 15 20	60	25 40 60	38	0.181 0.419	1.753 1.202	4.410 0.354	0.219 0.036	0.036 0.009	0.816
B1 and B2	10 20	<u>,</u> 60	25 40	21	0.574 2.826	1.612	2.574 0.419	0.147 0.030	-	0.668
		,			·,			ω,	^s e	
			25		· ,					
С	1.0	60	40 60	7	- 28.194 7.089	11.205 1.697	5.047 0.996	0.8 1.1	34 85 ;	0.859

Table 26. Multiple regression analysis, Eq. (42), 2% strain.

linear relationship between logarithm of strain rate and asphalt content. The coefficient of asphalt content is designated ω . As can be seen from comparison of these two analyses for Series C, the inclusion of asphalt content improved regression results; i.e. the value of R^2 increased when asphalt content was included. Regression analyses of results from Series C reported in Tables 26 and 27 include asphalt content as an independent variable. Multiple regression analyses of the other combinations of groups and series were also made in which moisture content of each specimen was included as an independent variable. However, the largest change in the value of R^2 was 0.003, regardless of the inclusion of moisture content as a variable.

Series	p, psi	т _с , °С	Ts, °C	Residual, d.f.	Intercept, ⁸ e	∆H*/k x 10 ⁻³ , ^s e	β/2 x 10 ² , s _e	∕ ⊭, s	α, s _e	R ²
A	5 10 15 20	25	25	24	8.125 0.773		6.069 0.837	0.455 0.074		0.688
B1	10	-60	25 40 60	13	10.269 3.830	1.180	5.302 0.530	—	-	0.885
B2	20	60	25 40 60	6	19. 453 3.323	- 1.795 0.925	\3.719 0.692		-	0.842
A and Bl	5 10 20	25	25 60	38	1.522 6.390	1.332 1.832	5.725 0.539	0.430 0.055	0.077 0.014	0.755
Bl and B2	10 20	60	25 40 60	21	11.116 2.862	- 0.132 0.895	4 .922 0.457	0.272 0.033	<u>.</u>	0.854
		2						ω,	s _e	
C	10	60	25 40 60	8	- 26.125 - 10.886	11.624 2.797	6.072 1.419	0.6 1.1		Q.773

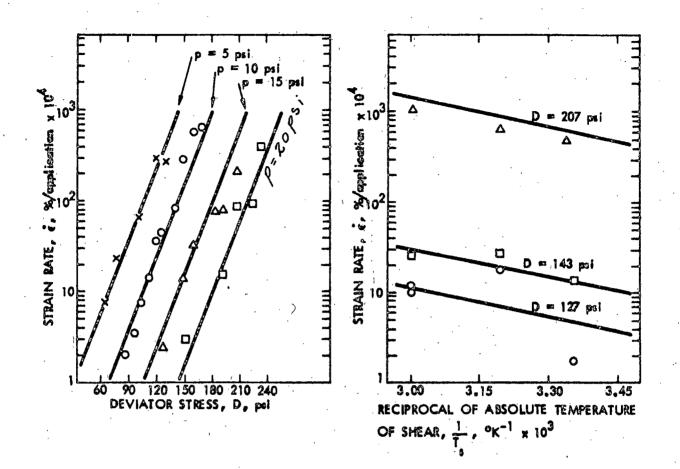
Table 27. Multiple regression analysis, Eq. (42), 5% strain.

The minor change in regression results due to the moisture content variable may be attributed to several factors, one of which is that for the granular materials investigated, the effect of moisture content may be relatively small. With the narrow range of moisture content used, any such effect has been masked by other experimental variations. Another probable cause is that the moisture content used in the regression analysis was that determined for each specimen during the molding process, which was not necessarily the moisture content of the specimen when it was sheared. Unlike the asphalt content of specimens in Series C, moisture content of specimens in Series A, B1, and B2 was changed after molding by consolidation and especially by the cooling process. It is probable that both factors discussed above are partial causes for moisture content having no apparent effect on strain rate. Determination of the effect of moisture content on deformation rate would require that a larger range of moisture content be used in the investigation and that moisture content of the specimen at shearing be determined and used as the value of moisture content in regression analysis.

Values of the intercept, as shown in Tables 25 through 27, were calculated values obtained by extrapolating Eq. (41) or (42) to zero values of all independent variables. In many cases, no physical significance could be attached to the value of the intercept. This was especially true in those regression analyses in which shear temperature T_s was included as a variable. Since T_s appears in the equations as the reciprocal of absolute temperature, the intercept was obtained by extrapolating the reciprocal of absolute temperature, as well as the other independent variables, to zero. As can be seen from Tables 25 through 27, the value of the intercept calculated in this manner was greatly dependent on the value of $\Delta H^*/k$.

Figure 16 shows the effect of deviator stress on strain rate for different levels of confining pressure for all groups in Series A. The lines have been obtained from the calculated regression coefficients in Table 25; the plotted points are observed data.

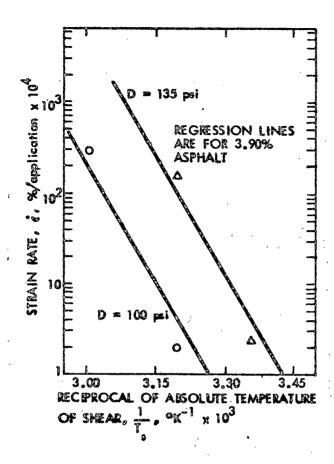
Figures 17 and 18 are plots of the logarithm of strain rate versus reciprocal of absolute temperature for different levels of deviator stress for Series Bl and C, respectively. As before, the lines have been calculated from the regression coefficients in Table 25 and the points are observed data.





deviator stress, Series A.

Fig. 16. Strain rate variation with Fig. 17. Strain rate variation with shear temperature, Series Bl.



Volume Change Relationship

Equation (41) was derived by combining the effects of consolidation pressure and normal stress, setting their coefficients ($\beta \Delta V/V$ and γ) equal to an experimentally determined coefficient, μ . The results of multiple linear regression analyses indicate Eq. (41) is an adequate representation of material behavior and replacement of $\beta \Delta V/V + \gamma$ by μ is a reasonable approximation.

In the development of the failure

Fig. 18. Strain rate variation with shear temperature, Series C. criterion ($\ddot{\epsilon} = 0$), it was found that $\ddot{\epsilon} = \dot{\epsilon}(-\beta P_n \frac{d \Delta V/V}{dN} - \frac{2}{\epsilon} \frac{d\epsilon}{dN})$ as in Eq. (25b). This implies that when $\ddot{\epsilon}$ is greater than zero (strain acceleration positive), $-\beta P_n \frac{d \Delta V/V}{dN}$ must be greater than $\frac{2}{\epsilon}$ $\dot{\epsilon}$.

Figure 19 shows strain and volume change data versus number of deviator stress applications for a test in Group 40B2, D = 199.0 psi. The values of $\beta P_n \frac{d \ \Delta V/V}{dN}$ and $\frac{2}{c}$ è at different points on the curve (calculations are shown in the Appendix) also demonstrate the relationship between rate of volume change and rate of deformation. At 6000 applications of deviator stress, the values of $\beta P_n \frac{d \ \Delta V/V}{dN}$ and $\frac{2}{c}$ è are 1.4 $\times 10^{-3}$ and 24.2 $\times 10^{-3}$, respectively, indicating that at this point, è is

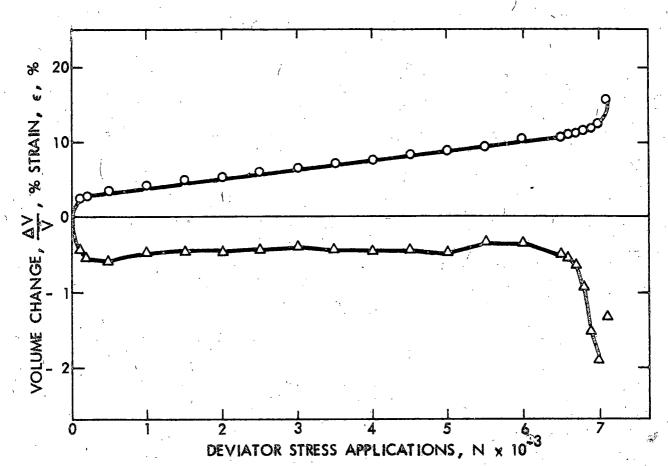


Fig. 19. Axial strain and volume change versus deviator stress applications, Group 40B2, 199 psi.

decreasing. At 6800 applications the values are 25.7 \times 10⁻³ and 24.6 \times 10⁻³, respectively, indicating an increasing deformation rate.

Data from this particular test specimen demonstrates the implications of the relationship expressed by Eq. (25b), i.e. as the rate of volume change becomes negative, the rate of strain increases sharply. Not all the other test data exhibit the relationship of increasing strain rate and decreasing rate of volume change to such a marked degree, as shown in Fig. 19. Further confirmation of the relationships between rate of strain and rate of volume change will require greater precision and sensitivity of volume change and deformation measurements than were used in this investigation.

DISCUSSION AND CONCLUSIONS

Discussion

Results of this investigation show that the initial transient creep portion of the number of applications versus deformation curve is described by Eq. (18). The total strain that can be represented by this equation varies from 2.74 to 8.97% for untreated specimens and from 0.88 to 5.63% for asphalt-treated specimens.

In the tests on untreated material, there is no apparent trend indicating total strain over which Eq. (18) describes material behavior is related to deviator stress, confining pressure, consolidation temperature or shear temperature. In asphalt-treated specimens of Series C, the total strain described by Eq. (18) is apparently related to shear temperature as seen in Table 13, while there is no apparent trend with deviator stress. Consolidation pressure and temperature and confining pressure were constant in Series C.

As noted in development of the model equations for analysis of the results, Eq. (18) is entirely empirical. No generally accepted interpretation of the theoretical significance of this relationship is known. It is possible that, at least in particulate systems such as were studied in this investigation, the number of bonds at the interparticle contacts increase in proportion to the reciprocal of deformation squared. While such a hypothesis is conjectural, such a mechanism would not be contrary to the energy barrier concept of resistance to deformation.

The relationship between shear temperature and range of strain over which Eq. (18) is applicable, as observed in Series C, may also occur in untreated material. But the higher activation enthalpy of asphalttreated material makes the effect more apparent.

In developing the model equations, β was assumed to be a constant equal to β'/kT_s . If β is a constant, β' must vary inversely as T_s varies. As shown in Table 24, the experimental values of β cannot be assumed to be equal for all the untreated material. However, in those combinations of test groups or series where T_s was the only variable (Series B1, B2 and C), β can be considered constant. This implies that variation in β is due to something other than changes in shear temperature.

Three values of β have been calculated for each test group, one each from Eq. (42) at 2% and 5% strain (Tables 16 through 19) and one from Eq. (41) (Tables 20 through 23). Values of β for each test group generally agreed quite well, the most notable exceptions being Series B2 and Group 40C. Since development of Eq. (42) involved an approximation that the effect of ϵ_0 be negligible, it might be anticipated that those determinations of β from Eq. (42) would be subject to greater error than those calculated from Eq. (41). The correlation coefficient of a regression analysis is a measure of how well the observed data fits the model equation. Therefore, correlation coefficients should indicate if one model equation describes observed data better than another.

Considering only deviator stress as an independent variable, the mean correlation coefficients from Eq. (42) at 2% and 5% strain are 0.934 and 0.957, respectively. Considering the same independent variable, the mean correlation coefficient from Eq. (41) is 0.973. A test to determine if these differences are statistically significant indicates they are not. Based on results of this investigation, Eq. (41) does not provide a significantly better estimate of the value of β than does Eq. (42) at constant levels of p, T_c and T_s.

When p, T_c and T_s are included as variables, mean values of the multiple R^2 for Eq. (42) at 2% and 5% strain are 0.819 and 0.800, respectively; for Eq. (41) the mean R^2 is 0.910. These differences are statistically significant when either of the values from Eq. (42) are compared to that from Eq. (41). The difference between R^2 values calculated from Eq. (42) is not significant.

When all variables are considered, Eq. (41) describes observed behavior better than Eq. (42), and values of material parameters calculated from Eq. (41) are subject to less error than those from Eq. (42). This is probably due to the fact that Eq. (42) does not adequately describe the effect of structure when p, T_c and T_s are varied. Since Eq. (41) provides the best estimates of material parameters, those values shown in Table 25 have been used to compare results reported by other investigators.

The value of α has been determined using only two levels of consolidation temperature, thus leaving it poorly defined.

Values of μ determined with four levels of confining pressure in Series A and combination of Series A and Bl is consistent. In the combination of Series Bl and B2, the value is somewhat less than other determinations, but Series Bl and B2 have only two levels of confining pressure. Because this coefficient contains the effects of both consolidation pressure and normal stress, it is difficult to compare this value with results of other investigators who used direct shear tests. The value of μ is 10 times the value of the coefficient for normal stress determined by Noble (1968) from direct shear tests on silt. Part of this difference is a result of the combination of effects of P_n and P_c in this investigation, but much of the difference is probably a result of the greater volume change necessary for deformation of the granular materials used in this investigation.

Values of β are quite consistent for all combinations of groups or series with the notable exception of Series B2. The value of $\Delta H^*/k$ for Series B2 is of opposite sign than other determinations. A negative value of $\Delta H^*/k$ would mean a decrease in shear temperature would increase deformation rate. This is not possible unless the decrease in shear temperature also induces other changes in the material. As temperature of the specimen was lowered, the moisture content increased. During the experimental phase of the investigation, based on preliminary results from Series B1, it was thought any changes in moisture content during cooling would have a negligible effect on deformation rate. However, in Series B2 this effect is not negligible.

The correlation coefficients in Tables 21 and 22 indicated less variation in those test groups in which shear temperature equaled consolidation temperature than in those in which shear temperature was less than consolidation temperature. Results of statistical tests shown in Table 24 indicate results of Series B2 cannot be combined with any other series except B1. Thus, when Series B1 and B2 are considered, the differences are not significant; when Series B2 is considered in any other combination, results of Series B2 are significantly different than results of other series.

From comparison of results obtained from various combinations of test groups and series, it appears results from Series B2 are unreliable and that this can be attributed to changes in moisture content during cooling.

Since results of Series Bl are apparently not affected, it is probable that the change in moisture content due to cooling is related to confining pressure. Results from Series B2, because of their apparent unreliability, have not been used to compare with results reported by others.

Values of β' (volume of a flow unit) for treated and untreated material are shown in Table 28 with the results of other investigators. Calculations of β' from β are shown in the Appendix.

Material	Reference	Clay content < 2µ, %	$\beta' \times 10^{-4}$	3√β' A
Clay	Noble, 1968	80.4	67.1	87.6
Silt	Noble, 1968	26.0	14.2	52.1
Granular material	This study	1.7	7.4	42.0
Asphalt cement	Moavenzadeh and Stander, 1966	. <u> </u>	37.0	71.9
Asphalt cement	Herrin and Jones, 1963	_	39.9	73.5
Asphalt treated granular material	This study	.1.7	11.2	48.2

Table 28. Volume of a flow unit at 300°K.

Experimentally determined values of β' are probably average flow unit volumes. Table 28 indicates the average flow unit volume in untreated material decreases as clay content decreases. Consideration of the types of bonds in particulate systems, i.e. bonds between water layers on clay mineral surfaces and at points of contact between larger solid particles, provides a basis for interpreting the relationship between clay content and average flow unit volume. When the percentage of clay is high, the flow unit approaches the size of clay mineral platelets about 10 Å thick. As clay content decreases, bonds associated with clay mineral surfaces have less effect on the average size of an experimentally determined flow unit and flow unit size approaches that of distances between asperities on solid particle surfaces. As shown in Table 28, the flow unit size for material with very low clay content is still considerably larger than interatomic dimensions.

Experimental values of β' for asphalt-treated material are roughly one-third the values reported by Moavenzadeh and Stander (1966) and Herrin and Jones (1963) for 60 to 70 penetration grade asphalt cements. The flow unit size of asphalt-treated material is probably dependent on the asphalt film thickness on the granular particles. If so, flow unit volume should vary with asphalt content, approaching that of asphalt cement at higher asphalt contents. The coefficient of asphalt content, ω , would then represent the change in β' due to change in film thickness, or asphalt content. Where asphalt content was included as a variable, the deformation rate increased with increased asphalt content, which would coincide with an increase in β .

Confirmation of this interpretation of the effect of asphalt content on deformation rate will require investigation of material with greater ranges of asphalt content than were used in this study. Also, any interrelationships between flow unit size, asphalt content and gradation of material would need to be determined.

Activation enthalpy, ΔH^* , can be determined from the coefficient of $1/T_c$ in Eq. (41). Values of activation enthalpy for the materials in

this investigation, with results reported for several other materials, are shown in Table 29.

Material	Reference	∆H*, kcal/mole
Metals	Finnie and Heller, 1959	50
Concrete	Polivka and Best, 1960	54
Asphalt cement (penetration 72)	Herrin and Jones, 1963	44.6
Asphalt cement (penetration 63)	Moavenzadeh and Stander, 1966	21.0
Asphalt cement (penetration 30)	Moavenzadeh and Stander, 1966	32.0
Asphalt treated granular material	This study	39.4
Snow	Landauer, 1955	14
Ice	Barnes and Tabor, 1966	29.7
Ice	Glen, 1953; 1955	.31.4
Ice	Gold, 1967	15
Water	Glasstone <u>et al</u> ., 1941	4-5
Soils	Mitchell <u>et al</u> ., 1968	25-45
Soil (clay)	Noble, 1968	12-29
Soil (silt)	Noble, 1968	4-7
Granular material	This study	4.7

Table 29. Activation enthalpy.

The value of ΔH^* for asphalt cement from Herrin and Jones (1963) is the average of five values determined from strain rates and shear temperatures at each of five shear stress levels. These values of ΔH^* were determined from regression of the logarithm of strain rate on the reciprocal

of absolute temperature at constant shear stress; the determinations thus made ranged from 43.4 to 46.8 kcal/mole. The analysis reported by Herrin and Jones assumed a hyperbolic sine relationship between strain rate and shear stress. They determined material parameters at each temperature by choosing values of the parameters which best fit their data; values thus determined were used to evaluate ΔH^* . The value of ΔH^* (62 kcal/mole) reported by Herrin and Jones differs considerably from the value of 44.6 calculated from their data. However, calculation of ΔH^* from strain rate and shear temperature at constant shear stress does not involve intermediate steps or empirically determined material parameters.

Values of activation enthalpy of asphalt cement and asphalt-treated granular materials are of the same order of magnitude. The activation enthalpy of asphalt-treated granular material is probably greatly influenced by activation enthalpy of the asphalt cement used. Comparison of activation enthalpy of various asphalt cements in Table 29 indicates penetration grade and activation enthalpy are not closely related.

Activation enthalpy of untreated granular material determined in this study agrees closely with that reported by Noble (1968) for silt and approximates the activation enthalpy of water. The hydrogen bond energy in water is about 5 or 6 kcal/mole (Rodebush and Buswell, 1958; Fyfe, 1964, p. 92). This agreement between hydrogen bond energy and activation enthalpy of untreated material indicates bonds in untreated material may consist of hydrogen bonds between adsorbed water molecules on the mineral surface.

Suggestions for Further Research

Based on results of this investigation, the effects of several variable quantities studied need further clarification. Extension of these findings to more general material systems will require determination of the effects of several quantities not studied here. The following are suggested items for further investigation:

- Behavior of granular materials with a wider range of asphalt and water contents.
- Separate determination of the effects of consolidation pressure and normal stress.
- Effects of clay content or other variations in gradation on flow unit size.
- Relationships of asphalt cement properties and activation enthalpy of asphalt-treated materials.
- 5) Determination of the functional relationship of structure to deformation and volume change at various levels of shear and normal stress.
- 6) Relationships between the range of transient creep and conditions of shear temperature and shear and normal stress.
- Effect of consolidation temperature on deformation rate be extended to asphalt-treated materials.
- 8) Effects of frequency and duration of stress application on deformation rate. This is especially important if the findings of this investigation are to be extended for use in pavement design where not only the magnitude of imposed stresses but also the frequency of application (traffic density) and

duration of stresses (traffic speed) may be of great importance.

- Relationships between asphalt content, material gradation and flow unit size.
- 10) Effects of combinations of pore fluids (e.g. water and asphalt cement) in varying proportions on activation enthalpy and flow unit size.

<u>Conclusions</u>

A model for behavior of granular material subjected to repeated loads is proposed. This model is based on bonds formed at interparticle contacts, resistance to rearrangement of particles, and internal structure of the material. Stresses applied to the material are transferred through the bonds, and deformation of the material occurs by breaking of bonds and rearrangement of particles. The total resistance to deformation constitutes an energy barrier to deformation of the material mass, termed the activation energy. This energy barrier may be surmounted by bonds having sufficient thermal and mechanical energy.

Based on this model of resistance to deformation, an equation was developed beginning with the Arrhenius equation of chemical kinetics. Separation of the contributions of various factors to the activation energy enabled determination of their individual effects. Equation (41) was shown to describe the observed behavior of both untreated and asphalt-treated granular materials over the range of variables considered.

Using the equation developed from the energy barrier concept and an empirically determined relationship between total strain and number of

applications of stress, an integrated equation was developed to relate number of applications of stress with other variables at fixed levels of deformation. Equation (42) describes material behavior over the ranges of deviator stress considered, when other variables were held constant. However, Eq. (42) does not describe observed material behavior over the range of variables considered as well as Eq. (41) which was based only on energy barrier concepts.

Experimental tests, consisting of 64 repeated load triaxial compression tests on an untreated and asphalt-treated granular material provided the following observations:

1) Repeated load triaxial compression tests yield a linear relationship between the logarithm of strain rate and deviator stress. The proportionality coefficient may be used to evaluate volume of a flow unit. This volume was considerably smaller than that reported by others for finer grained materials.

2) Activation enthalpies obtained from coefficients of the relationship between logarithm of strain rate and reciprocal of absolute temperature of shear were about the same as the activation enthalpy of the pore fluid.

3) Repeated load tests yielded a linear relationship between the logarithm of stress applications at constant strain and deviator stress. The proportionality coefficient in the model equation was the same as the coefficient for deviator stress-logarithm of strain rate relationship. Experimentally determined values from each of the two methods are, in most cases, in close agreement.

4) Activation enthalpies determined from Eq. (41), based on strain rate, differ by about 50% from those determined from Eq. (42) based on

total strain. Because the multiple linear regression correlation coefficients for Eq. (41) are higher than those of Eq. (42), activation enthalpies determined from Eq. (41) are considered better estimates.

5) Increased temperature of consolidation decreased the deformation rate, but the relationship is poorly defined since only two levels of consolidation temperature were used.

6) Increased confining pressure in the triaxial cell decreased the rate of deformation. This effect is interpreted as a decrease in the size of flow units as the confining pressure is increased. Test methods used in this investigation did not permit determination of separate effects of normal stress and consolidation pressure.

This study of behavior of granular materials subjected to repeated loads has yielded equations which reasonably describe deformation behavior of the materials. However, modification of Eq. (42) will probably be required if it is to describe material behavior as well as Eq. (41). Interdependency of some measured quantities (e.g. volume change, pore pressure and confining pressure) may dictate other modifications of the equations as their effects become more completely understood. Further investigation based on the equations proposed herein seem justified in order to confirm, and extend to a wider range of materials and other variables, the findings of this investigation. The model equation describes material behavior under stress conditions very similar to those imposed on pavement structures in terms of fundamental parameters which might be used as a rational basis for analysis of pavement deformations.

EPILOGUE - PAVEMENT PERFORMANCE

Equation (42) relates the number of applications of stress to produce a given deformation to those factors which affect the rate of deformation, viz., activation enthalpy, temperature, imposed stress, confining stress and flow unit size.

Application of this equation to design or analysis of prototype pavements will require empirical correlations between laboratory behavior and field performance. Because confining stress in a prototype pavement is variable depending on depth, vertical stress, and material properties, conditions of confining stress in prototype pavements are difficult to simulate in laboratory tests, introducing the need for correlations between laboratory test and pavement performance.

Activation enthalpy can be determined in the laboratory and can be considered constant for the duration of the testing procedure. However, in the case of asphaltic concrete or asphalt-treated material, the chemical changes occurring in asphalt cement due to several years exposure to climatic elements may have considerable effect on activation enthalpy of the material. This effect should be determined or accounted for from experience to make the equations applicable to prototype pavements.

The dwell time of the imposed stress was held constant in this investigation. Since experience has shown that the greatest distress or deformation of flexible pavements occurs where traffic stress is static or slow moving, it is probable the time that stress remains on the pavement affects the rate and amount of deformation caused by a given number of applications. The effect on deformation due to variable dwell time

could be determined by laboratory experimentation and probably field correlation. Other variables also should be considered, for example . effects due to mixed traffic, such as wheel or axle load equivalency. These variables have been mentioned to illustrate some of the work necessary to extend findings from laboratory research described here to applications in prototype installations.

This discussion has assumed that a criterion of pavement performance can be based on limiting or specified deformations. This is tantamount to saying that a pavement "fails" when it reaches some amount of deformation, as opposed to rupture of the pavement mass. This deformational criterion of pavement performance is essentially that used in the analysis of results from the AASHO Road Test (Highway Research Board Special Report 61E).

In that analysis, a pavement was considered to have "failed" when the present serviceability index (PSI) reached a given level. The equation for PSI indicates it is a function of measured pavement deformations represented by slope variance and rut depth, and localized rupture represented by cracking and patching. The major factor in serviceability loss was slope variance.

Since the equation used to analyze results of the AASHO road test and Eq. (42) are both based on deformation criteria, it may be instructive to compare Eq. (42) and the AASHO equation which was developed by using curve fitting techniques.

The AASHO equation is

$$\frac{(C_{o} - p)}{(C_{o} - C_{1})} = \left(\frac{W}{p}\right)^{B}$$

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(43)

where

- p is the present serviceability index,
- C is the initial serviceability index,
- C₁ is the "failure" serviceability index,
- W is the weighted number of axle applications when the service-

ability index is p,

- ρ is the weighted number of axle applications when p = C_1 or the number of axle applications to cause "failure," and
- B is an exponential multiplier which accounts for imposed stress, axial configuration (single or tandem) and pavement structure.

Taking logs of both sides of Eq. (43) gives

$$\log \left(\frac{C_{o} - p}{C_{o} - C_{1}}\right) = B(\log W - \log \rho).$$
(44)

For comparison, if the temperature is constant, Eq. (38) may be written

$$e^{3} = Z't \exp \frac{\beta L}{2A} \exp - \mu p$$
 (45)

where Z includes effects of activation enthalpy and consolidation temperature. Making the same substitutions as in Eq. (42) to obtain an expression in terms of number of applications,

$$\epsilon^3 = Z'N \exp \frac{\beta L}{2A} \exp - \mu p.$$
 (46)

Taking logs of both sides gives

$$3 \ln \epsilon = \ln Z' + \ln N + \frac{\beta L}{2A} - \mu p. \qquad (47)$$

Comparison of Eqs. (44) and (47) indicates that on the left side of both equations is a logarithmic measure of deformation — serviceability loss in the case of Eq. (44) and percent strain in the case of Eq. (47). Both have a logarithmic intercept, ρ in Eq. (44) and Z' in Eq. (47). Both utilize a logarithmic measure of the number of load applications, W in Eq. (44) and N-in Eq. (47).

The nature of the effect of stress intensity is different in the equations since this is included in the multiplier B in Eq. (44) and as a separate additive term in Eq. (47). Equation (47) also includes a term to account for confining pressure. It may appear that no such term is included in Eq. (44), but since confining pressure in a prototype pavement is a function of depth, vertical stress intensity, and material properties, an effect of lateral pressure is probably included in Eq. (44). This is because the multiplier B includes effects of load intensity in addition to depth and relative strength coefficients for each layer of the pavement structure.

The relationships between AASHO equations and those developed in this study cannot be determined without a more complete knowledge of material behavior under repetitive loading conditions determined by further laboratory studies and correlation with performance of prototype pavements. However, it is significant that the quantities that control deformation based on theoretical considerations and experimentally verified in this study, are remarkably similar to those quantities which provided the best fit in the empirical curve fitting techniques used in analyzing AASHO test road results.

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APPENDIX

Calculation of $\beta P_n \frac{d \Delta V/V}{dN}$ and $\frac{2}{c} \dot{\epsilon}$: Group 40B2; D = 199.0 psi $Pn = D/2 + p = \frac{199.0}{2} + 20.0 = 119.5 psi$ $\beta = 3.772 \times 10^{-2}$ (from Table 25, Series B2) 6000 applications $\frac{d \Delta V/V}{dN} = -0.03 \times 10^{-2}$ % per stress application $\dot{\epsilon} = 12.6 \times 10^{-4}$ % per stress application $\epsilon = 10.4\%$ $\beta P_{\rm p} = \frac{d \Delta V/V}{dN} = (3.772 \times 10^{-2})(119.5)(-0.03 \times 10^{-2}) = -1.4 \times 10^{-3}$ $\frac{2\dot{\epsilon}}{c} = \frac{2}{0.104}$ (12.6 × 10⁻⁴) = 24.2 × 10⁻³ 6800 applications $\frac{d \Delta V/V}{dN} = -0.57 \times 10^{-2}$ % per application $\dot{\epsilon}$ = 14.0 \times 10⁻⁴ % per application $\epsilon = 11.4\%$ $\beta P_n \frac{d \Delta V/V}{dN} = (3.772 \times 10^{-2})(119.5)(-0.57 \times 10^{-2}) = -25.7 \times 10^{-3}$ $\frac{2\dot{\epsilon}}{\epsilon} = \frac{2}{0.114}$ (14.0 × 10⁻⁴) = 24.6 × 10⁻³ Calculation of flow unit volumes: Example calculation for Series A and Bl combined $\beta/2$ from Table 25 = 6.141 x 10⁻² $\frac{\text{in.}^2}{1\text{b}}$

$$k = 1.380 \times 10^{-16} \frac{\text{dyne-cm}}{^{0}\text{K}}; T = 300^{\circ}\text{K}$$

$$\beta' = 1.380 \times 10^{-16} \times 300 \times 2 \times 6.141 \times 10^{-2} \times 14.503 \times 10^{-6}$$

$$= 7.37 \times 10^{-20} \text{ cm}^{3}$$

$$= 7.37 \times 10^{4} \text{ A}^{4}.$$

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