Rheological Properties of Compacted Soil-Asphalt Mixtures

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The establishment of a design criterion is an important requirement in connection with the practical use of soil-asphalt mixtures in the field. A study was made of the strength characteristics of these mixtures for certain particular types of stress conditions. The main stress system considered was that of a constant load of unconfined compressive nature applied on a cylindrical specimen with deformation observed as a function of time. Other tests were carried out for constant rates of axial strains with increasing stress. The apparatus used was a modification of a conventional consolidation machine. An automatic recording system consisting of two major components was designed to be used with the machine. One component, a sensitive electric pickup system, was essentially an LVDT unit. The second component, an electric recorder, translated the signal from the LVDT unit through a demodulator to a chart, providing a permanent record. A simple and versatile method of loading was used so that the constant load could be applied quickly and without impact.

Only one soil type, meeting the recommended gradation requirements for soil-asphalt construction, was used. The asphalt was a medium-curing liquid type, meeting ASTM Designation MC-2. Materials were mixed at water contents near the fluffing point and cured in a constant-temperature oven at 110 F, before compaction under a static compressive load in a double-plunger compaction mold. Samples were then extruded and cured until tested at constant temperature and humidity.

Under constant rates of strain and with increasing stress, no appreciable increase in the maximum strength was indicated by increasing the rate of deformation from 0.005 to 0.08 in./min. However, the change in the maximum strength increased rapidly at rates of deformation greater than 1 in./min. The percentage increase in the maximum strength with loading speeds was greater for these mixtures with large percentages of asphalt. For a condition of constant sustained level of stress, the material exhibited the same deformation characteristics as nonlinear viscoelastic materials. Creep deformation and failure did not occur if a certain maximum value of sustained stress level for each mixture was not exceeded. For samples that failed, the strain value at failure was almost the same for the same mixture, irrespective of the applied stress. The relationship between the stress and log time at failure was linear. The stress level and curing time after compaction were the most important factors affecting the rheological properties of the material.

•LOCALLY AVAILABLE road materials are currently being stabilized with various types of binder for economical highway construction in several areas (4, 6). In the future, as coarse mineral aggregates become less plentiful, this method of construction will be used more extensively. One of the most important recent advances is the

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stabilization of soils with asphalt. These asphalt-stabilized materials are generally used for: (a) construction of bases for surface-treated roads with low traffic volume; (b) some main roads having concrete or bituminous surfacing; and (c) waterproofing subgrades to preserve their stability.

A study of the rheological behavior of the soil-asphalt mixtures is needed because there is at present no rational method to calculate the stresses and strains in these mixtures when they are subjected to load. Also, a study of rheological responses could be used to establish a failure criterion, in terms of stresses or strains, for the material. The establishment of this failure criterion is a very important requirement from the point of view of design considerations and practical use of the material in the field.

All available methods used to estimate the stresses in bases or subgrades are based on conditions of ideal elastic materials which generally do not represent the actual behavior of such materials under field conditions. It is generally agreed that the behavior of the bituminous mixtures under field conditions is nonelastic. For instance, after a number of years of use, under the action of wheel loads, the nonrecoverable plastic deformations accumulate. These deformations can be observed in many forms, such as rutting and flow without fracturing. One criterion for a reliable test of this material is that fracture should not be produced during the test.

When a compacted soil-asphalt sample deforms, the solid mineral particles of the filler, sand and clay, do not exhibit any actual flow, but the relative positions and orientations of these particles change. On the other hand, the fluid elements (asphalt, volatiles, and water) exhibit actual flow and possibly rupture during the deformation process of the whole body. Because of this complicated random nature of the elements, the mechanical properties of the whole body of the material must be determined experimentally.

The purposes of this study were as follows:

1. To investigate the rheological behavior of bituminous stabilized soils on a phenomenological level in creep tests by applying a constant load of compressive nature and observing the deformation as a function of time;
2. To determine from the analysis of specific tests if the material exhibited rheological properties of a viscoelastic nature and to determine the linearity or nonlinearity of such a viscoelastic nature;
3. To study the deformation characteristics of bituminous stabilized soils under different levels of constant rate of strain and increasing stress; and
4. To study the effect of some of the controlled and dependent variables of the mixture on its rheological behavior.

EXPERIMENTATION

The objectives of the experimental investigation were to obtain the data required to describe the rheological behavior of the soil-asphalt mixtures and to develop accurate techniques for obtaining the data. As previously stated, the rheological behavior of the bituminous stabilized soils is very complicated. It was necessary to select as simple a state of stress as possible for the investigation. The stress system that would best fit this requirement was that of the steady-load type for which a constant load of unconfined compressive nature is applied on a cylindrical specimen and the deformation of the specimen is observed as a function of time. The creep tests for constant stress levels were carried out in such a manner that failures of specimens took place in intervals of time ranging from minutes to several hours. However, in practice, stresses may be applied either in fractions of seconds, as in the case of stabilized bases beneath a road or runway, or for extremely long periods of time. Thus, it was also essential to study either the effect of the rate of deformation or the rate of load application on the strength of the material. For this reason, other tests have been carried out under constant rates of axial strains with increasing stresses.

Materials Used and Sample Preparations

All tests described in this research were performed on cylindrical specimens 2 in. in diameter and about 4 in. high. The specimens were prepared from several types of mixes of soil and asphalt with differing controlled variables.

Soil.—Although a wide range of soil types could have been used, only one soil, which was locally available, met the recommended gradation requirements for soil-asphalt mixtures (4), and was free of organic materials or roots (also a requirement), was selected for the investigation. Its characteristics are as follows:

Passing No. 40 sieve, 100 percent;
Passing No. 200 sieve, 41.9 percent;
Liquid limit, 18 percent;
Plasticity index, 5 percent; and
Fluff point (avg.), 7 percent.

Asphalt.—The asphalt used was a medium-curing liquid asphalt meeting ASTM Designation MC-2. It was obtained from Texaco, Inc., at Lawrenceville, Ill., and contained 22 percent volatiles by weight.

Sample Preparation

Initially, the air-dry mixture was thoroughly mixed in a Hobart mechanical mixer to secure maximum homogeneity. Moisture was then added to the soil until optimum desirable mixing characteristics were obtained (i.e., the fluff point). After the addition of the water and subsequent mixing, this material was combined with the bitumen and proportioned, by weight, as a percentage of the dry weight of soil. The asphalt was heated to a temperature of 250 F. These materials were agitated in a Hobart mechanical mixer for 2 min. The resulting mixture was then spread about ¼ in. thick in pans and placed in a constant-temperature electric oven at 110 F. The drying period was hr except when it was intended to study the effect of drying time as a variable.

Special molds were constructed so that cylindrical samples, 2 in. in diameter and about 4 in. high, could be prepared.

The mold consisted mainly of a hollow steel cylinder, 2 in. in diameter and 7 in. high, with double plungers at both ends. To have the desirable amount of material in the mold before compaction and to prevent any layering, the material was placed in three layers with each layer given 30 strokes by a sharp-edged steel rod. Compaction was then made by a standard Riehle hydraulic machine. The desirable axial pressure was applied to the specimen being compacted and was maintained constant for 2 min. All samples were prepared under an axial load of 6,000 lb, except when studying the effect of varying the amount of compaction on the creep properties of the material. Finally, the samples were extruded and stored, until tested, in a constant-temperature room at 76 F.

To compare the density of the specimens compacted by this static method to that of a standard compaction test, a mixture of 4 percent asphalt was compacted by both methods and results were compared. The samples compacted under an axial load at 6,000 lb showed a density of about 135 pcf. A similar mixture was compacted according to the modified Proctor method and samples obtained had an average density of about 122 pcf.

Apparatus and Testing Procedure

The nature of both the data required and the material of the samples to be tested made it necessary to design special instrumentation to obtain the desired measurements. The basic apparatus used was a conventional soil-consolidation machine, considerably modified to obtain the desired measurements. Figure 1 shows a general view of the testing arrangement.

An automatic recording system with two major components was used to measure the deformation and rebound of the specimen. One component was a sensitive electrical pickup which was essentially an LVDT (linear variable differential transformer) unit. It consisted of a rod, actuated directly by the compression on the specimen,

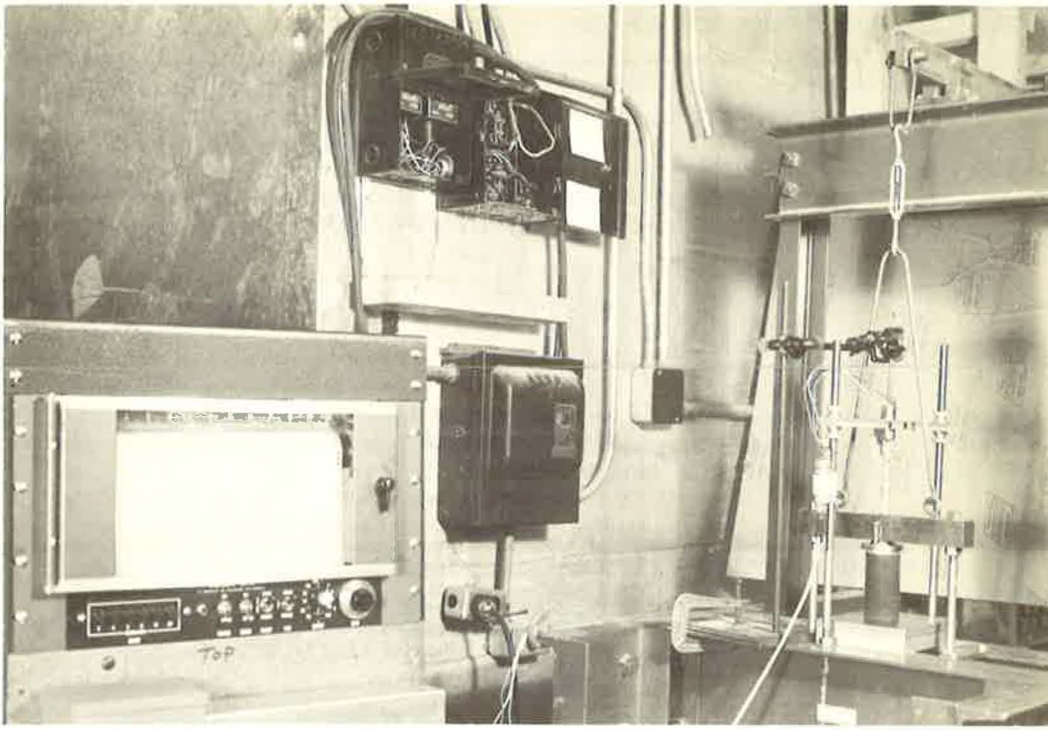

Figure 1. General view of testing arrangement in the steady-load test.

which moves inside a specially wound coil. The coil transmits an electrical signal proportional to the rod motion. The other component of the recording system was an electronic recorder which translated the signal from the LVDT unit, through a demodulator, onto a special type of recorder. The recorder used a 10-in. wide strip of paper which served as a permanent record of the test. This recorder is one of the largest standard commercial units available. The large width of the chart permits an extremely accurate measurement to be obtained for the deformation characteristics of the material, as the width of the paper controls the range of deformation; the other chart dimension is a function of the chart speed and represents the time element. Both recorder range and speed could be readily changed electrically. A dial at the top of the LVDT unit was used to calibrate the recorder at the beginning of each test.

This discussion so far has been concerned with the problem of automatic recording of the data after the load was applied. Since it was necessary to apply a constant load to the specimens in as short a time as possible and without impact, a special method of loading was essential. The problem of designing an automatic system of loading for a lever arm consolidation machine is generally complex and could not be justified on a cost basis for this research (7). However, the problem was solved by using a simple but versatile method. An hydraulic jack was used to support the lever arm of the machine and was lowered gradually until the loading head made contact with the specimen. After the desirable load was placed on the arm and the recorder adjusted, the pressure of the jack was suddenly released, transferring the load very quickly to the sample. The same arrangement was used to raise the lever arm instantaneously, so that the recovery of the sample could be recorded.

To record the recovery, a special arrangement was designed in the pickup system over the sample. A disc-shaped plate was placed beneath the sample and the spherical head of the loading frame. This disc was connected by a ball hinge to a vertical rod which went first through a circular hole in the loading head and then through the LVDT. This arrangement had the advantage that both deformation and rebound were obtained

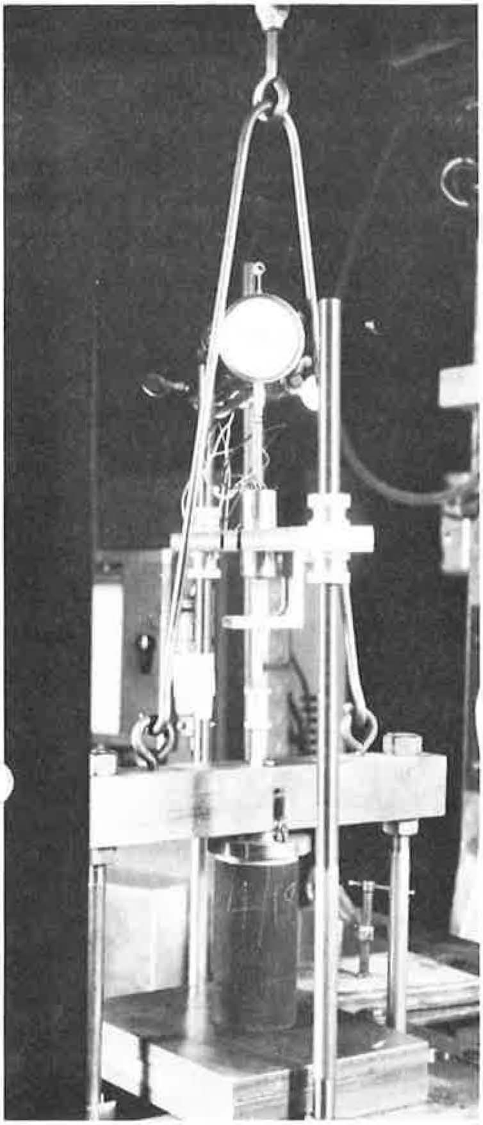

Figure 2. Detailed view of pickup system over specimen.

by direct measurements over the sample and, thus, deflections of the loading frame did not affect the deformation measurements. Figure 2 shows a detailed view of the pickup system over the sample.

Figure 3 shows a reduced-scale reproduction of a typical graph made by the recorder. The actual dimensions of this chart are a width of 10 in. and a length of 36 in. It can be seen that there is essentially no time element involved in placing or removing the load. The absence of any impact was indicated on the graph by the initial movement of the pen.

In the constant-rates-of-strain tests, a standard Riehle hydraulic machine was used. However, the same recording system was used because the dial indicating the rate of deformation on the hydraulic machine was very difficult to adjust accurately to the desirable rate. By use of the automatic system, a permanent record was obtained for the pressure-deformation-time relationship which was used to determine accurately the actual rate of deformation during the test. Another reason for the use of the automatic recording system was that at the higher rates of deformation, it was very difficult to get accurate readings for the deformations with a manually operated Ames dial.

The LVDT setup was successfully used to obtain accurate records for the stress-deformation-time characteristics of the material for small and moderately constant rates of deformations. Even though it was difficult to obtain an accurate load-deformation record at the very large rates of deformations, the maximum strength of the samples was determined accurately and without difficulty.

INTERPRETATION OF RESULTS

Stress-Strain Characteristics Under Constant Rate of Loading and Increasing Stress

Typical stress-strain curves for two mixtures, one with 4 percent asphalt and the other with 7 percent asphalt, are shown in Figures 4 and 5, respectively. Both mixtures originally had 7 percent moisture content and were cured for 3 days after compaction. Except for the variation in the asphalt content, the other parameters were the same.

It was surprising to find that in this type of compacted material, an excellent linear relationship between stress and strain existed for all conditions tested, except for the ɔw stresses. The slope of this curve could be a measure of Young's modulus. It is

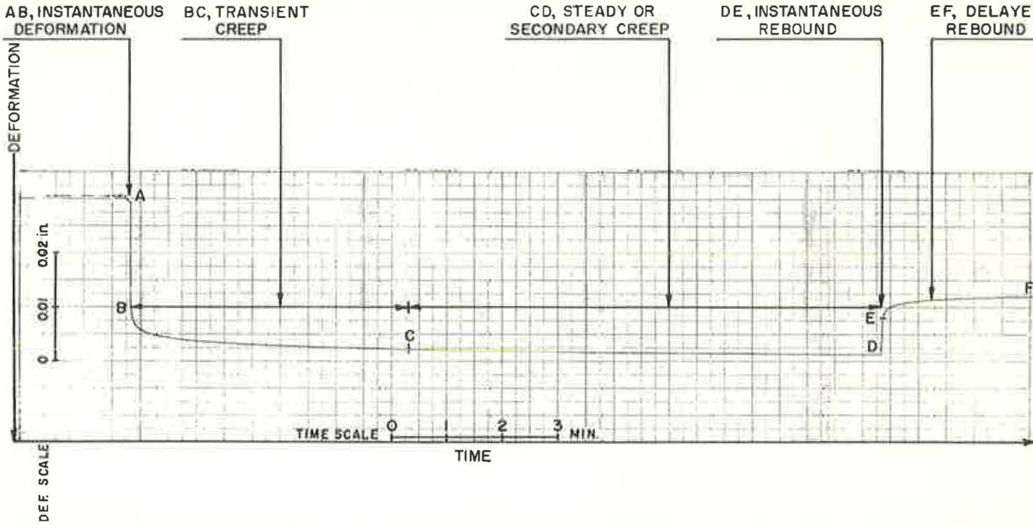

Figure 3. Reproduction of typical graph made by recorder in creep test under constant stress.

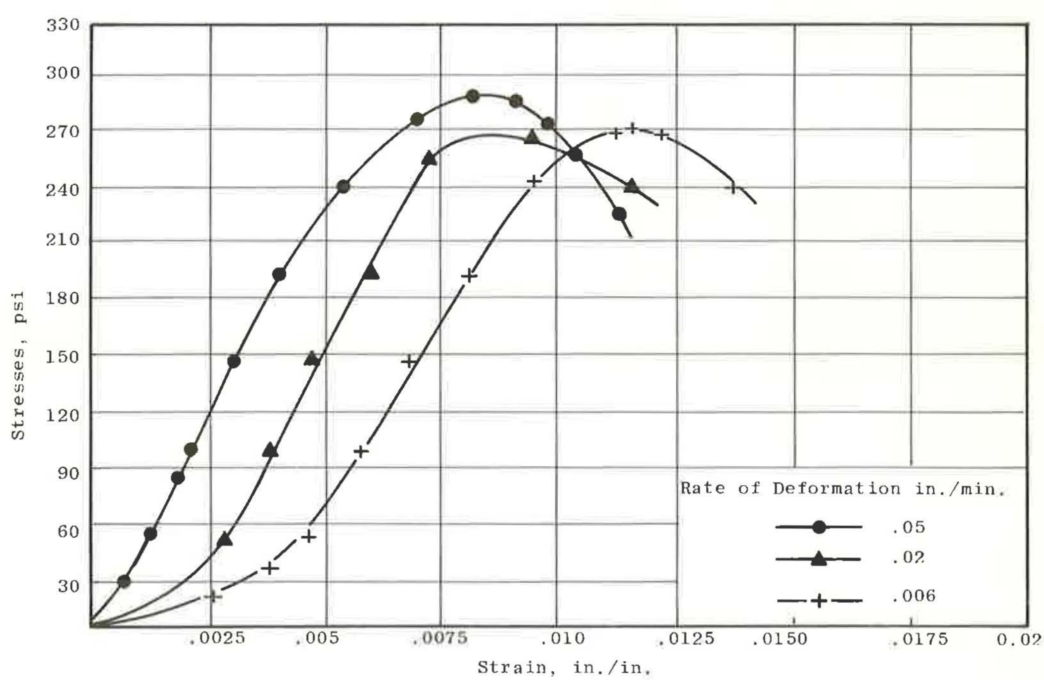

Figure 4. Stress-strain relationship at different constant rates of deformation, 4 percent asphalt.

usually believed that these high initial strains, associated with the curved portion of the graph, are due either to imperfect seating of the specimens or to a mechanism property of the hydraulic testing machine. However, these assumptions seem incorrect for the following reasons:

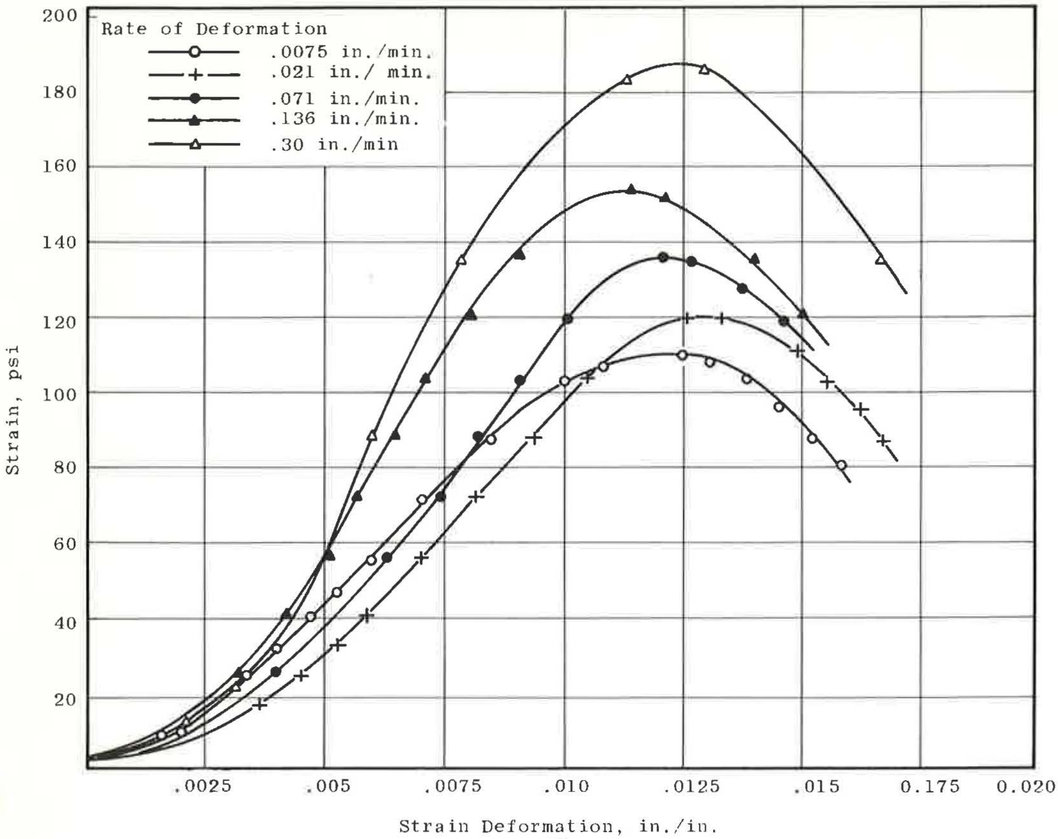

Figure 5. Stress-strain relationship at different constant rates of deformation, 7 percent asphalt.

1. The samples tested were compacted and extruded so that the surfaces were perfectly leveled;

2. The testing machine was equipped with a spherical loading head to assure a perfect contact between the surfaces of the loading head and of the sample at the beginning of the test; and

3. The initial curvature was observed even when a seating load of 8 psi was applied in the beginning of the test, and it was much more pronounced in the mixtures with 7 percent than those with 4 percent asphalt.

This point is emphasized because many materials indicated a behavior similar to these soil-asphalt mixtures. However, in most cases, the initial relation of stress with strain was corrected and the intercept of the linear portion of the curve on the strain axis was considered to be the zero origin.

The initial high strain could be reasonably explained by internal flaws and cracks inside the compacted samples. Examination, visually and with a microscope, of compacted samples with 7 percent asphalt indicated microscopic and macroscopic horizontal cracks perpendicular to the direction of the applied load. It is believed that there is a connection between this crack structure, more pronounced in samples containing a higher percentage of asphalt, and the static method of compaction used to prepare the samples.

During the compaction process, the axial load was increased to a selected level, usually 6,000 lb, and maintained constant for 2 min after which the load was removed very quickly. The amount of compression of the material inside the cylindrical mold was measured during the period when the load was kept constant. With a higher percentage of asphalt, a very small amount of additional compression was achieved by maintaining the load on the specimen. This is probably because the mixture contained a considerable amount of bitumen, water, and volatile materials, and under this high axial static compaction load the liquid phase would flow and fill most of the voids of the mixtures.

The mixture, during the compaction, was completely confined in the steel cylindrical mold with the plungers at the top and the bottom. Thus, with these mixtures containing a high percentage of bitumen, the external compaction load was not carried entirely by the soil grains but also to a great extent by the liquid phase (bituminous material and water). Consequently, when the compaction pressure was released, an elastic rebound took place. The elastic rebound was restricted to the direction of the applied pressure since the sample was still confined in the lateral direction inside the cylindrical mold when the load was released. The rebound in the vertical direction might have been accompanied by an increase in volume, and this, together with the elastic rebound action of the liquid-and-solid phase, may have caused a tension force in the vertical direction. This action could possibly produce these horizontal cracks (perpendicular to the direction of the applied pressure). These cracks and pores may have not been entirely closed even though a linear stress-strain curve was obtained after the initial curved portion at the time of test. A partially closed crack may well behave in an elastic manner similar in operation to a proving ring; nevertheless, the associated modulus will be smaller than for solid material.

After the initial curved portion, the stress-strain curve was linear and then curved until the pressure reached a maximum when it started to decrease slowly; failure occurred sometime later. The maximum compressive strength of the material under a certain constant rate of loading was considered to be that which was recorded when the pressure reached a maximum value. Figure 6 and Table 1 indicate the relationship be-

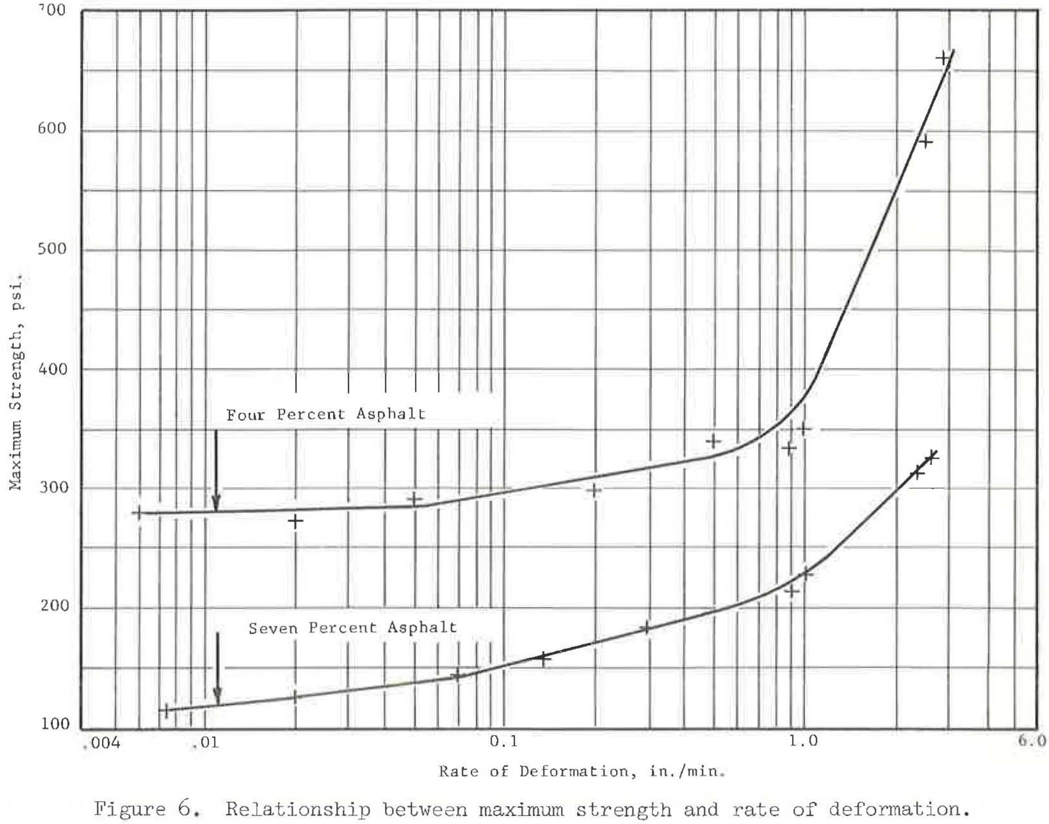

Figure 6. Relationship between maximum strength and rate of deformation.

TABLE 1

EFFECT OF VARIATION OF CONSTANT RATE OF DEFORMATION AND INCREASING STRESS ON MAXIMUM STRENGTH

Asphalt Content (%)	Rate of Deformation (in./min)	Maximum Strength (psi)
4	0.006	280
	0.020	270
	0.050	290
	0.200	300
	0.500	340
	0.900	335
	1.000	350
	2.500	592
	3.000	660
7	0.008	115
	0.021	127
	0.071	144
	0.136	155
	0.300	182
	0.900	235
	1.000	255
	2.400	366
	2.700	380

tween this maximum strength and rate of strain for mixtures with 4 and 7 percent asphalt. The curves in Figure 6 for both mixes indicated no appreciable increase in the maximum strength when the rate of loading was increased from 0.005 to 0.08 in./min; moreover, there is a reasonably clear indication that further reduction in rate of deformation would produce little, if any, further decrease in strength. This conclusion may or may not be due to a real property of the material, since it may have been somewhat influenced by the testing machine (2).

The curve in Figure 6 indicated, however, that the change in the maximum strength increased rapidly at rates of deformation larger than 1 in./min, which is considered similar to a dynamic test condition. It also seems that the percentage increase in strength with increase of loading speeds was higher for the 7 percent than for the 4 percent asphalt mixture.

These observations could be explained by the fact that with the increase in the percentage of asphalt in the mixture, the behavior of the mixture will increasingly reflect the behavior of the asphalt. Bitumen will flow slowly (creep) under the load, but it cannot quickly be plastically deformed. If an attempt is made to produce the deformation quickly by increasing the rate of loading, the bitumen may break in a brittle manner under a much greater stress (15). This phenomenon may also be used to explain the behavior of the compacted mixture when the strength increased very rapidly at greater rates of loading.

Creep Tests Under Constant Stress

Bituminous stabilized soil is formed by an aggregation of loose grains (sand and clay) held together by the interparticle surface forces and by a highly viscous liquid, the bituminous material. Thus, the application of the load caused an initial instantaneous deformation, part of which was inelastic, that resulted in a permanent set. This part of deformation is represented by AB in Figure 3. The continued application of the load caused the material to creep at variable and then constant rates. The variable rate of deformation, referred to in this investigation as the transient creep, is represented on the experimental graph by BC. The part CD approximately represents a constant rate of deformation; however, it can be observed that the total creep increased at a decreasing rate, nonlinear with time. When the test was carried out until fracture was attained, it was found that the rate of deformation increased again before failure took place; this result is represented as a tertiary creep.

On removal of the load at any time before failure, an instantaneous recovery was produced, denoted as DE on Figure 3. This recovery was less than the initial deformation and represents the recoverable part of the instantaneous deformation. Following the instantaneous recovery was the delayed elastic recovery (creep recovery) denoted by EF on the same figure.

The observed behavior of the material under a constant-stress level can be separated into two components. The first is initial instantaneous deformation, which may be composed of two parts:

1. A perfectly elastic deformation which is due to the response of the statistically isotropic rigid skelton formed by the sand, clay, and hardened asphalt film around the particles and is completely recoverable when the load is removed; and

2. An inelastic deformation which is due to the local destruction of cohesion between the particles themselves and between the soil particles and the asphalt film and is irrecoverable.

The second component is creep, which may be composed of four parts:

1. Viscous flow of the bitumen which is irrecoverable;
2. Consolidation, due to seepage or flow of the water from the interior of the sample to the outside surface as a result of applied pressure and evaporation from the surface of the sample, which may be recoverable, irrecoverable, or partially recoverable, depending on the humidity conditions of the environment;
3. Delayed elasticity, due to the asphalt and the interparticle-surface forces between the soil particles acting as a restraint on the elastic deformation of the rigid soil skeleton, which is recoverable; and
4. Permanent deformation caused by localized fractures which is irrecoverable.

The total amount of creep was observed to increase with decreasing rate, depending on the stress level. This phenomenon was observed in all cases except when the load was high enough to cause a rapid failure immediately after loading; in this case the creep rate increased until fracture of the sample took place. The normal phenomenon of the increase of the amount of creep at a decreasing rate might be attributed to the following reasons:

1. The increase in the viscosity of the asphalt film with time;
2. Completion of delayed elastic and inelastic deformation;
3. The partial termination of the effect of local movement of absorbed water; and
4. The readjustment of soil particles under stress.

The original and continued application of the constant load results in the development of stresses on the soil grains which cause the viscous flow of the liquid phase and the movement of the soil grains with time. In doing so, some soil grains push aside the adjacent particles to gain room for turning and displacement. In this new state, the particles may be more stable and, thus, additional energy is required to produce additional particle movement. With time, the readjustment will be slower, resulting in a decreasing rate of creep.

When the sample was allowed to recover and then reloaded repeatedly, the percentage of recovery increased with the second loading and with each further number of cycles of loading. (The percentage recovery, as mentioned here, refers to the ratio of the amount of instantaneous recovery in the unloading cycle to the recovery of the

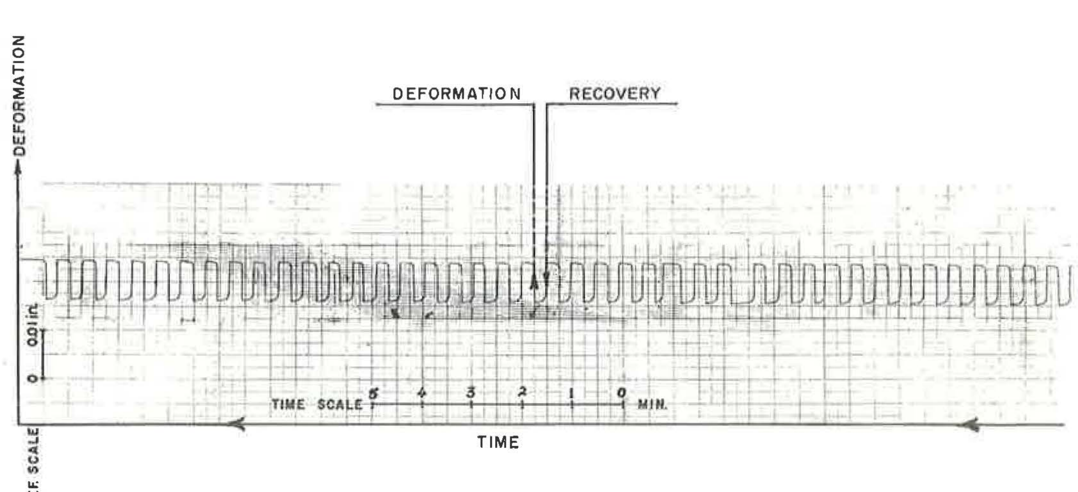

Figure 7. Reproduction of typical experimental chart for recorded deformation-time relationship under a repeated application of stress level of 115 psi.

instantaneous deformation in the loading cycle.) However, the second and further loadings again produced permanent sets, which were smaller than the permanent set produced by the first loading on a fresh sample. Even though the amount of set was less with each load, the accumulation after a number of repeated loads may lead to the rupture of the whole body. Figure 7 represents a typical experimental recorder chart for a deformation-time relationship under a stress level of 115 psi when the application of the stress was repeated several times.

Effect of Variation in the Constant Stress Level on Rheological Behavior.—The character of the rheological phenomenon of the material, as it is influenced by the stress level applied to the specimen, is reflected by the experimental curves, as shown in Figure 8. This figure represents the experimental results of strain-time relationship of the 4 percent asphalt mixture under different stress levels. Concerning this group of curves, the following interpretations could be made.

1. The process of creep characterized by these curves differs, depending on the magnitude of the load. For the stress levels between 153 and 206 psi, samples continued to creep but did not show any sign of failure within the plotted experimental time scale of 1 hr (Fig. 8). However, these creep tests were carried out under these stress levels for longer periods of time until either the sample failed or the creep practically ceased. More discussion will be devoted to this process when the creep rupture tests are described.

These experimental results indicate that there is a definite stress level below which failure did not occur, regardless of the length of time the sample was loaded. This limiting stress level will be denoted here as σ_∞ and will refer to the ultimate continuous strength of the material below which the sample would never fail and in which the total creep continued to increase at a decreasing rate until it practically ceased. The rate of creep deformation became zero, though, after a period of time that depended on the stress level. That is, at lower stress levels the creep ceased faster than at the higher stress levels. On the other hand, if the stress is higher than the limiting stress σ_∞, he creep deformation will not cease and the sample will continue to flow until it fails.

From those creep strength tests in which failure did not occur and in which all creep practically ceased, it is believed that the limit of compressive strength σ_∞ for the mix with 4 percent asphalt is on the order of 0.5 to 0.6 of σ_u, and for 7 percent asphalt the limit of the strength is on the order of 0.7 to 0.75 of σ_u, in which σ_u is the maximum compressive strength of the specimen in a normal unconfined compressive test at a rate of loading of 0.05 in./min.

2. Figure 8 also indicates that when failure took place, every strain value at failure was almost the same, irrespective of the applied stress. This is indicated by the increase in the rate of creep until it reached an almost vertical line indicating failure at strain values between 0.009 and 0.010 in./in. (for a 4 percent asphalt mixture).

3. Figure 9 shows the relationship between the stress level and rate of creep for a mixture with 4 percent asphalt. The rate of creep for each particular stress level was obtained from Figure 8 as the slope of the secondary creep line for the corresponding stress. Numerical values for these interpreted data are presented in Table 2. These experimental results indicated that, in the general case, the rate of creep (within the experimental time scale) was nonlinear with the stress level.

4. Values of both instantaneous and recovery strains for different stress levels are recorded in Table 3. These values could be read as well from Figure 8. They revealed that both instantaneous deformation under the application of the load and the instantaneous recovery were nonlinear with the stress level. This means that although the instantaneous recovery is of an elastic nature, it has a non-Hookian property with the stress level.

5. Figure 10 shows the relationship between the stress and strain after various time intervals from the start of the test. Values used to make the plot were interpreted from Figure 8 and tabulated in Table 4. From these figures it was concluded that the relationship between the stress and deformation in the creep tests is nonlinear and the superposition principle does not hold for such a relationship.

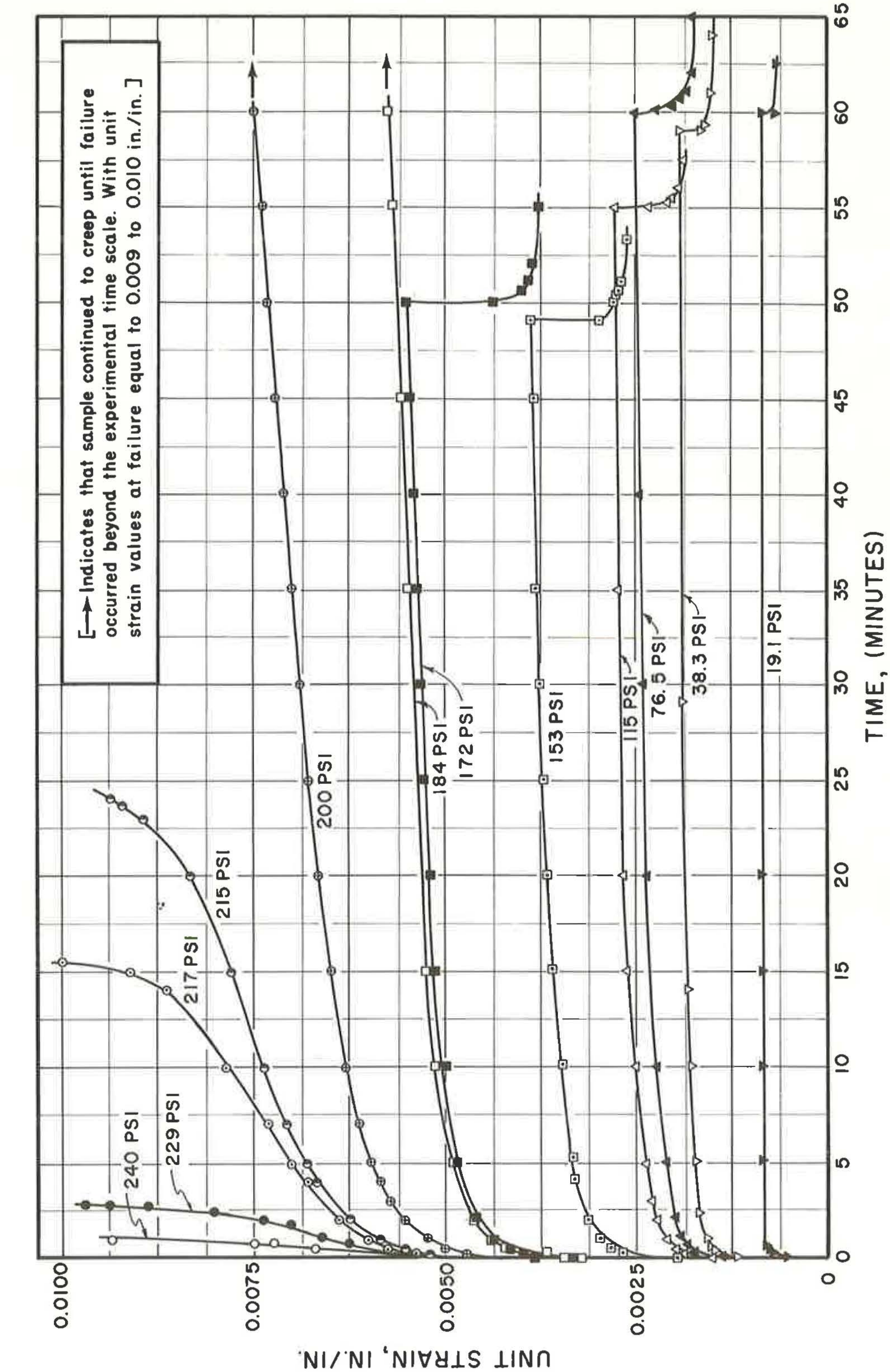

Figure 8. Influence of stress level on strain-time characteristics.

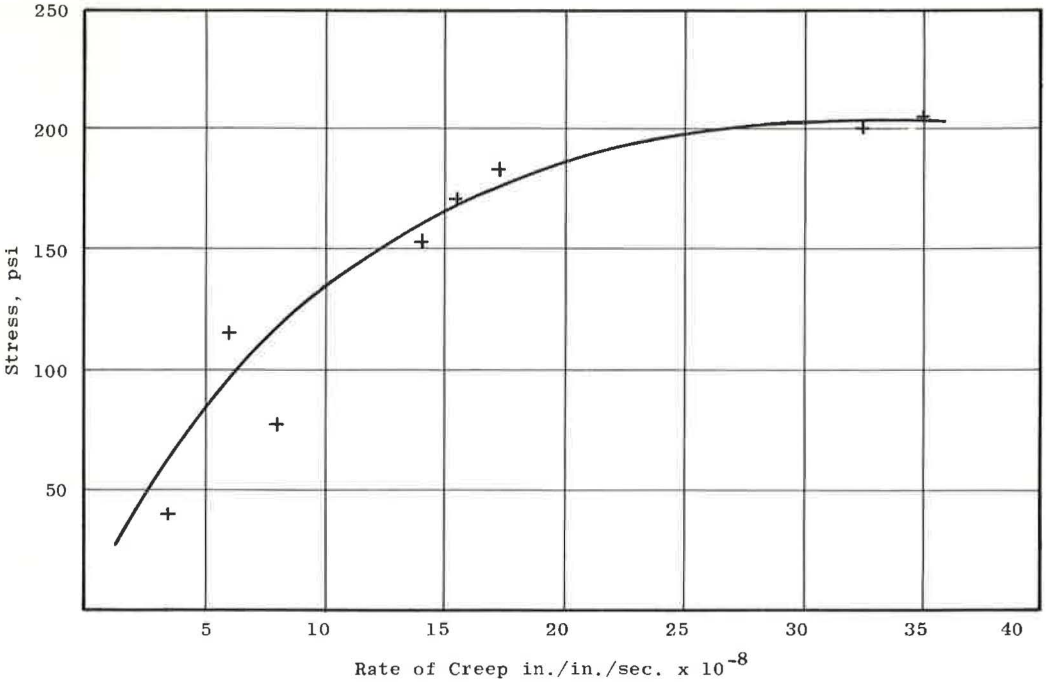

Figure 9. Influence of stress level on rate of creep, 4 percent asphalt mixture.

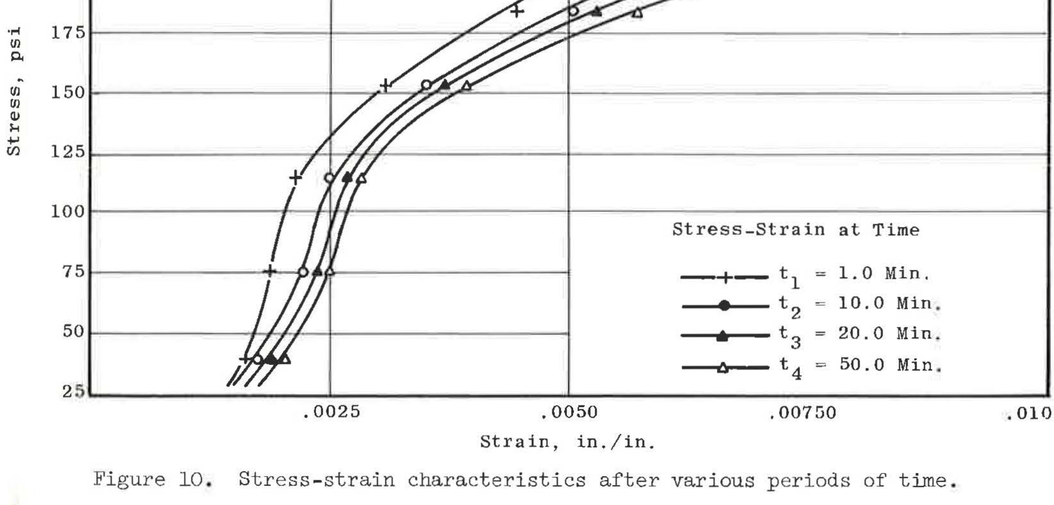

Figure 10. Stress-strain characteristics after various periods of time.

TABLE 2

EFFECT OF STRESS LEVEL IN SUSTAINED CONSTANT LOAD TEST ON RATE OF CREEP FOR A 4 PERCENT ASPHALT MIXTURE[a]

Stress Level (psi)	Rate of Creep (in./in./sec $\times 10^{-8}$)
19.10	0.0
38.30	3.5
76.50	8.0
115.00	6.0
153.00	14.0
172.00	15.5
184.00	17.2
200.00	32.5
206.00	35.0
215.00	-[b]

[a]Rate of creep considered as average slope of strain-time curves between time t = 20 min and t = 60 min; sustained constant load test; 4 percent asphalt mixed.
[b]Sample failed before 50 min.

The nonlinearities in all these relationships indicate that any accurate mathematical treatment for the rheological behavior will be a very difficult problem.

Creep Rupture Tests.—Most creep tests are carried out with such small loads that the specimens never break. However, if the loads approach the breaking strength of the material, the creep test will be terminated after a time by breaking of the specimen. For example, in Figures 8 and 11, any constant stress exceeding 172 psi caused the sample to flow until failure. The process of diminishing strength was reflected by the curves shown in Figure 11 for mixtures with 4 and 7 percent asphalt. The curves show the magnitude of failure strength relative to the time for progressive flow (failure) to set in. The curves indicate generally straight-line relationship between the failure strength and the time to failure on a semilog plot. However, it appears that the curve may have an upward curvature at very short times; also, with long time intervals, it may tend to approach a horizontal asymptote.

It could also be observed from Figure 11 that increasing the asphalt content produced a line with flatter slope. This indicates that by increasing the asphalt content, the process of diminishing strength was less pronounced.

Similar theories used in applied physics, plastics, textiles and even soils (1, 3, 13, 22, 27) suggest that the stress on the specimen and the log time to break should have a linear relationship. Experimental results indicated that a relationship of that nature exists for the material under investigation. This relationship could be represented by an equation of the form

TABLE 3

EFFECT OF STRESS LEVEL ON INSTANTANEOUS DEFORMATION AND RECOVERY[a]

Stress Level (psi)	Instantaneous Deformation Strain (in./in. $\times 10^{-4}$)	Instantaneous Recovery Strain (in./in. $\times 10^{-4}$)
19.1	5.2	1.75
38.3	12.0	2.50
76.5	13.7	3.10
115.0	15.0	5.00
153.0	20.0	9.00
172.0	32.5	-
184.0	33.6	-
200.0	39.0	-
206.0	42.5	13.50

[a]For 4 percent asphalt mixture.

TABLE 4

EFFECT OF STRESS LEVEL ON TOTAL STRAIN VALUES AFTER VARIOUS PERIODS OF TIME[a]

Stress Level (psi)	Time (min)	Strain Value (in./in.)
19.1	1	0.00081
	10	0.00088
	20	0.00088
	50	0.00088
38.3	1	0.00162
	10	0.00178
	20	0.00183
	50	0.00188
76.5	1	0.00194
	10	0.00225
	20	0.00234
	50	0.00248
115	1	0.00212
	10	0.00250
	20	0.00267
	50	0.00278
158	1	0.00300
	10	0.00350
	20	0.00365
	50	0.00390
172	1	0.00435
	10	0.00505
	20	0.00522
	50	0.00550
184	1	0.00443
	10	0.00515
	20	0.00532
	50	0.00563
200	1	0.00500
	10	0.00600
	20	0.00632
	50	0.00690
206	1	0.00523
	10	0.00632
	20	0.00668
	50	0.00731
215	1	0.00600
	10	0.00738
	20	0.00830

[a] Sustained constant load test, 4 percent asphalt mixture.

$$\log t_b = \log A - B\sigma \qquad (1)$$

in which t_b is time to failure for the specimen, σ is the long-term strength, and A and B are constants which may depend on environmental conditions. Several of the studies referred to in the foregoing references dealt with the problem of creep rupture through the mathematical approach of the absolute-rate theory and from a statistical point of view. Equations produced contain values for the amount of activation energy of the material, as a measure of the difficulty for the process to bring about the fracture. Also, the number of bonds between particles per unit cross-sectional area of the material perpendicular to the applied stress is introduced as a factor in some of these theories. However, all these equations could be simplified to the basic form as shown in Eq. 1.

It is emphasized, however, that even though the relationship shown is best represented by a straight line, straight line extrapolation for duration of sustained loads for a long time was not justified. This line may tend to curve and to approach a horizontal asymptote. The values which represent the asymptote of the curve are those of the ultimate continuous strength of the material. If such a breaking strength log-time curve could be extrapolated to an initial ordinate for a very short time (e.g., 0.001 sec), the ordinate in this case may determine the conditional-instantaneous strength of the material; also, the ordinate of any point in the curve determines the continuous strength at any time.

The significance of these phenomena indicates that engineering calculations for such a material must be carried out with respect both to continuous strength and to creep. The strength calculations should consist of the determination of the ultimate (breaking) load for which the stresses at a given instant do not exceed the continuous strength of the material at this instant of time. The deformation or creep calculations involve the determination of the load for which the deformations of creep or their rates at any given time do not exceed permissible specified values.

A group of curves such as that shown in Figure 11 is of great value if this stabilized material is to be used in a pavement structure. In this case, two conditions are possible.

1. Only deformations that cease with time are permissible. In this case, the stress should be less than the ultimate continuous stress (σ_∞) of the material.
2. Continuous deformations (of restricted magnitude) are permissible. In this case, the stress can be greater than the ultimate continuous strength.

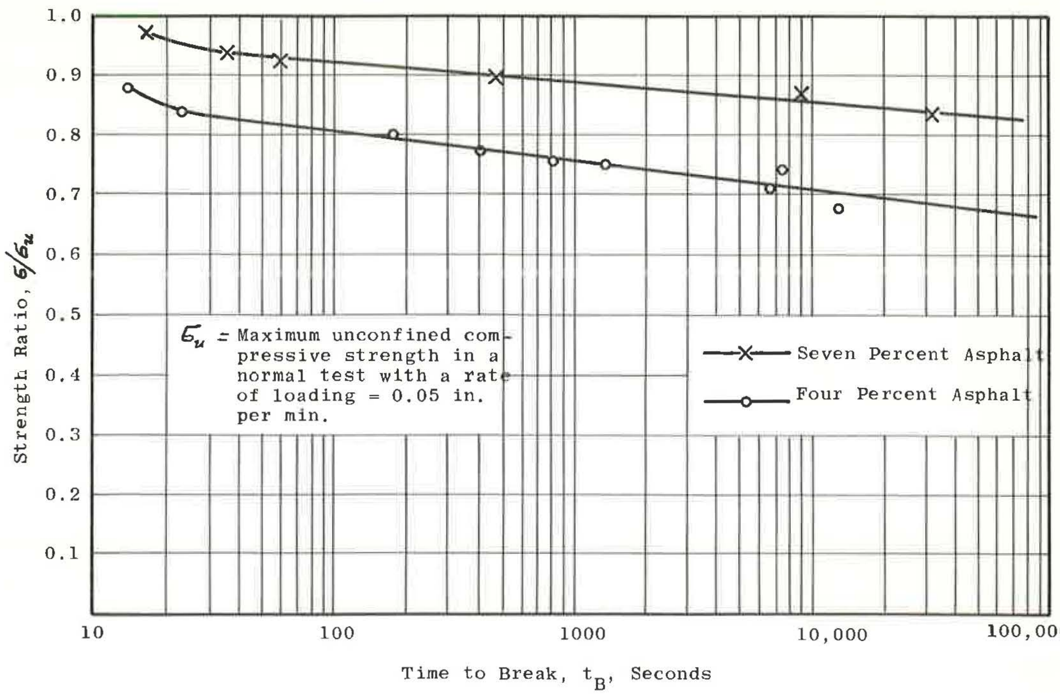

Figure 11. Creep rupture tests showing relationship between time elapsed until failure occurs and strength ratio.

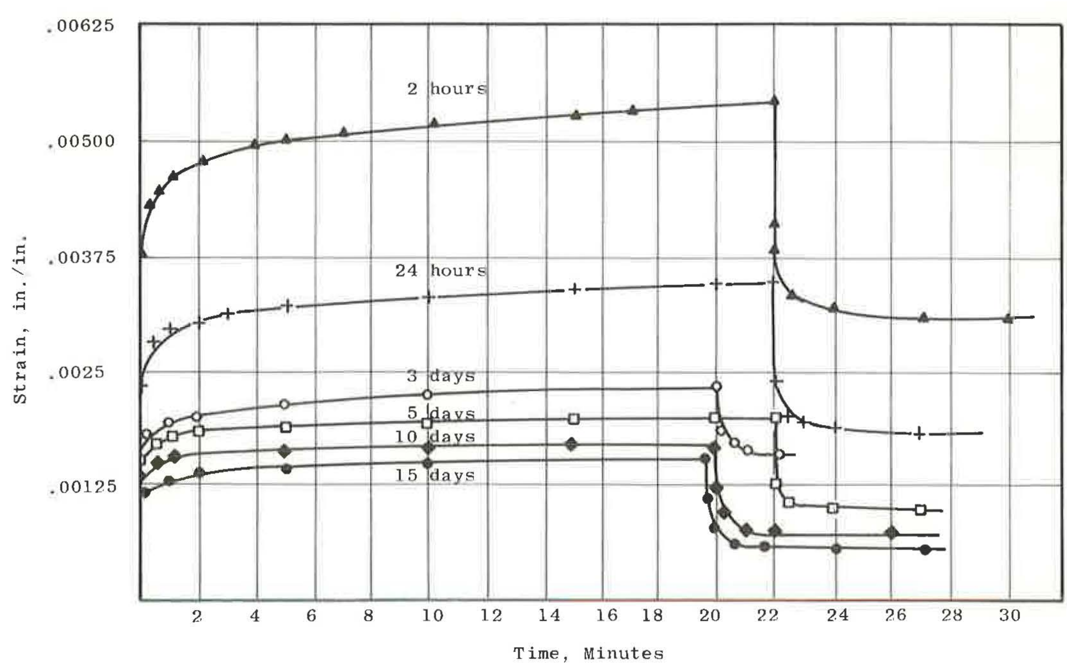

Figure 12. Effect of curing time after compaction on strain-time characteristics of a 4 percent asphalt mixture.

Influence of Curing Time after Compaction. —After compaction, samples were cured in a constant-temperature room (76 F) until tested at the same temperature. The samples were tested under a constant stress of 76.5 psi with all other test conditions similar except the curing time of the samples. Curing time greatly influenced the rheological behavior of the material, and its effect was more pronounced than any one of the other variables studied, except the stress level.

Figures 12 to 15 show the experimental results of the influence of curing time on the instantaneous deformation and rate of creep under the same constant stress level. Figure 12 represents the typical strain-time curves for different curing times. These curves indicate that the recovery proceeded more rapidly with increasing curing time and that the secondary creep component started earlier for samples cured for a longer time.

The percentage recovery, on removal of the load, increased with increased curing time. This is indicated by dividing the values of instantaneous recovery by those of instantaneous deformation for different curing times. Figure 12 shows, for example, that the sample cured for 2 hr exhibited an instantaneous deformation strain and recovery strain of magnitudes of 0.00375 and 0.00125 in./in., respectively; thus, the recovery is 33 percent. However, with a sample cured for 15 days, the magnitude of instantaneous deformation strain and recovery strain were 0.00110 and 0.0005 in./in., respectively, giving a percentage recovery of 45. Also, by increasing the curing time after compaction from 2 hr to 15 days, the modulus of recovery increased from 3.2×10^4 to 6.9×10^4 psi/in./in., which is about 100 percent increase.

Figure 13 shows the relationship between the curing time and the rate of creep. Each sample was kept under a sustained load for 20 to 25 min. Because of this time limitation, the values of rate of creep used in the plotting of this figure were calculated on the basis of a short-time scale (from t = 5 to t = 20 min). Figure 14 shows the relationship between the curing time and the instantaneous deformation. These values of the rate of creep and instantaneous deformation as plotted in Figures 13 and 14 were obtained from Figure 12 and are also given in Table 5. It was also found that the curing time has a significant influence on the maximum strength of the material. Figure 15 represents the relationship between the curing time and maximum unconfined compressive strength of mixtures with 4 and 7 percent asphalt.

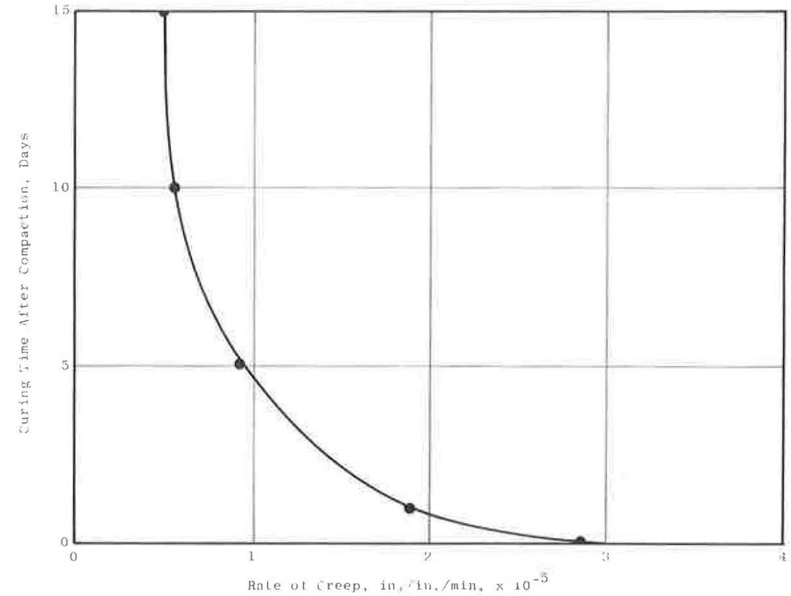

Figure 13. Influence of curing time on rate of creep (based on amount of deformation in 15-min interval of time from t = 5 to t = 20 min).

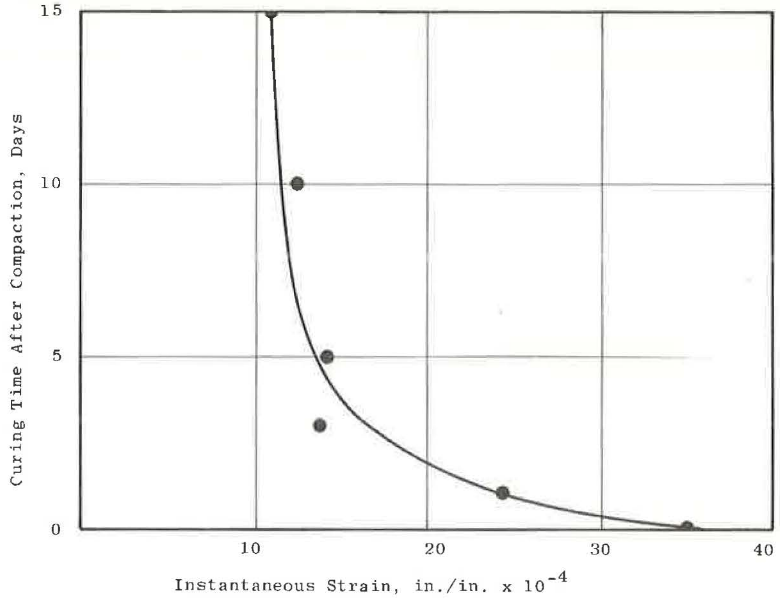

Figure 14. Influence of curing time after compaction on instantaneous strain.

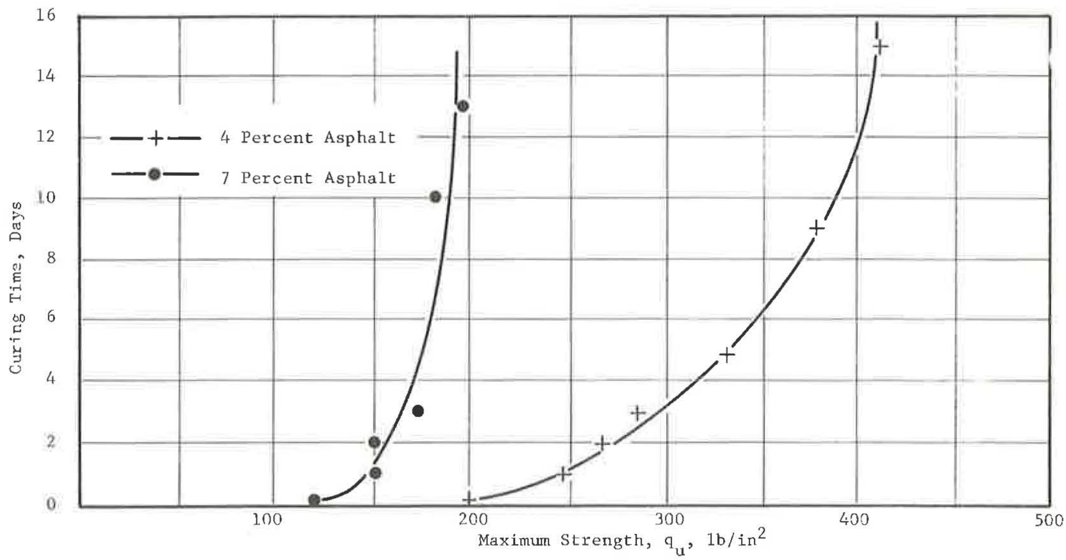

Figure 15. Influence of curing time after compaction on maximum unconfined compressive strength.

From this group of curves it appears that the curing time has a significant influence on the rheological parameters of the material. That is, increasing the curing time for a 4 percent asphalt mixture up to 15 days leads to a 100 percent increase in the maximum strength of the material. Also, the instantaneous deformation and rate of creep for the 4 percent asphalt mixture decreased considerably by increasing the curing time from 2 hr to 15 days. Any curing after 15 days had practically no influence

TABLE 5

INFLUENCE OF CURING TIME ON RATE OF CREEP AND INSTANTANEOUS DEFORMATION[a]

Curing Time	Rate of Creep (in./in./min × 10^{-5})	Instantaneous Strain (in./in. × 10^{-4})	Modulus of Recovery (psi/in./in. x 10^{4})
2 hr	2.85	35.0	2.19
1 day	1.90	24.2	3.17
3 days	1.40	13.7	5.60
5 days	0.93	14.2	5.39
10 days	0.55	12.5	6.11
15 days	0.50	11.0	6.94

[a]For 4 percent asphalt mixture and 76.5 psi stress level; rate of creep considered as average slope of strain-time relationship between t = 5 min and t = 20 min.

on any of the rheological parameters and the curves became asymptotic to the curing time as ordinate.

An increase in curing time from 2 hr to 15 days brought about an 82 percent reduction in the rate of creep. This decrease with greater curing time as shown in Figure 13 may be due to one of the following factors.

1. The evaporation of volatile materials from the bitumen phase will increase the binder's viscosity and, thus, a better bonding action with soil particles will be achieved. This will increase the resistance of the soil particles to movements under sustained loads.

2. The evaporation of part of the moisture that was added to the soil during the mixing process will gradually transfer more stress to the soil grains. The increase in the amount of transient creep with samples tested very shortly after compaction may be attributed to the presence of this excess moisture. Under pressure of sustained

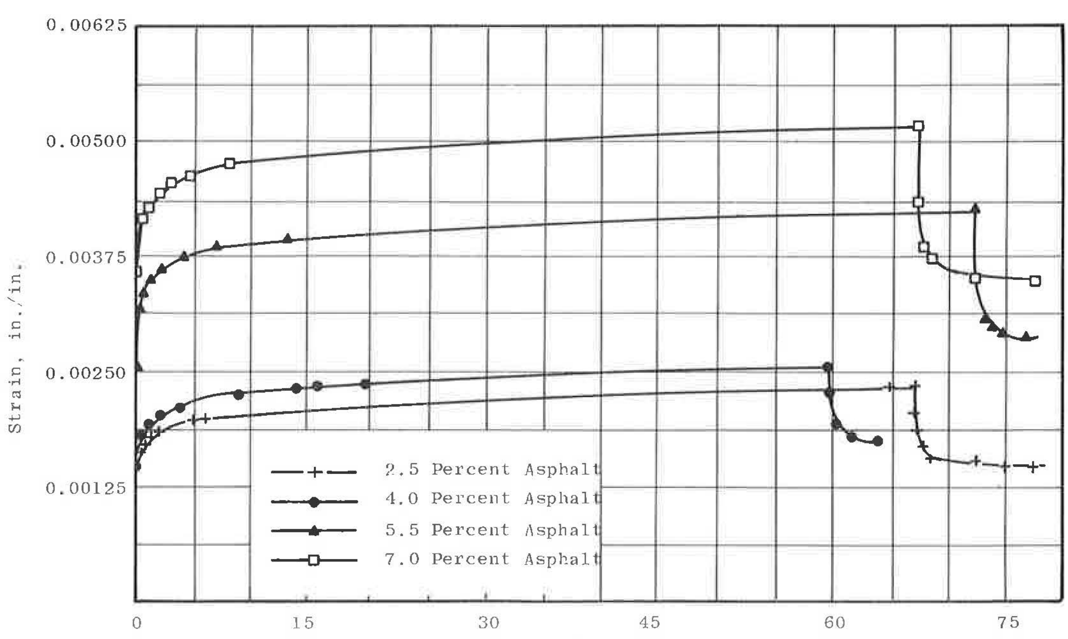

Figure 16. Influence of asphalt content on strain-time characteristics.

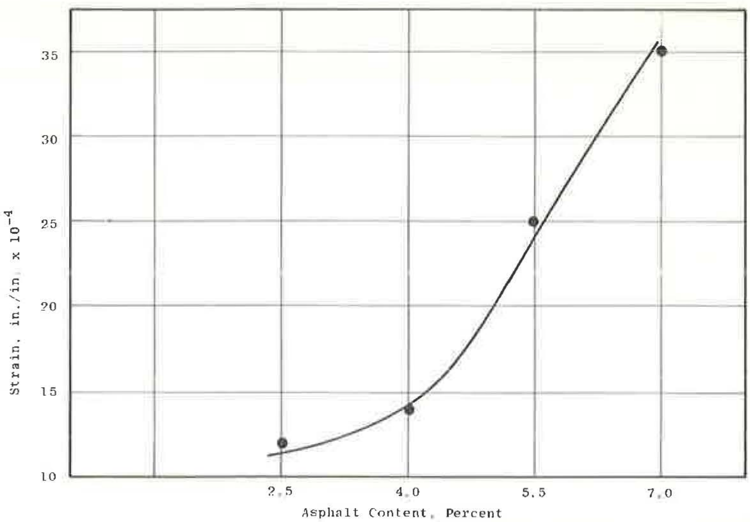

Figure 17. Influence of asphalt content on instantaneous strain.

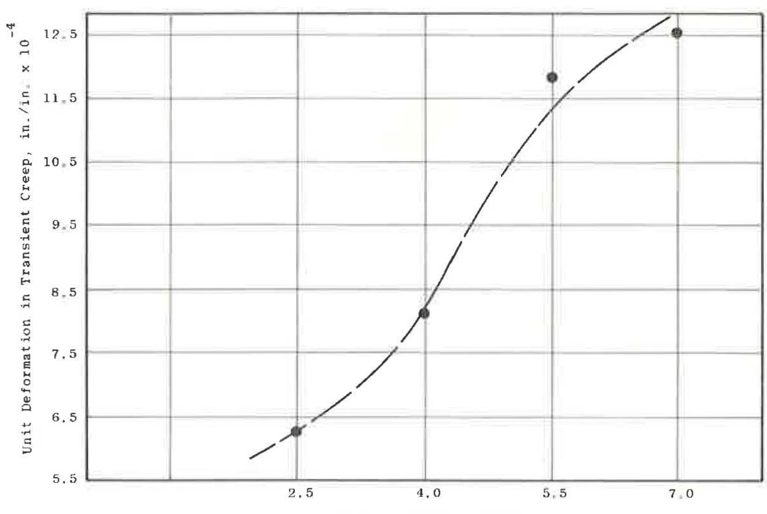

Figure 18. Influence of asphalt content on the magnitude of transient creep.

TABLE 6

EFFECT OF ASPHALT CONTENT ON INSTANTANEOUS STRAIN, AMOUNT OF TRANSIENT CREEP, RATE OF CREEP AND MODULUS OF RECOVERY[a]

Asphalt Content (%)	Instantaneous Strain (in./in. $\times 10^{-4}$)	Rate of Creep (in./in./min $\times 10^{-5}$)	Amount of Transient Creep (in./in. $\times 10^{-4}$)	Modulus of Recovery (psi/in./in. $\times 10^{4}$)
2.5	12.0	0.460	6.2	6.4
4.0	13.7	0.470	8.5	5.6
5.5	25.0	0.475	11.7	3.0
7.0	35.0	0.545	12.5	2.2

[a]From t = 20 min to t = 60 min at stress level of 76.5 psi.

stress, this absorbed water flows into the capillary spaces from which it may flow out and evaporate. According to this concept, creep recovery will not be complete as a result of water that has been driven out of the specimen. This could be an explanation of the observed phenomenon of the reduced amount of percentage recovery with samples of higher moisture content. However, verification for such a theoretical explanation was not carried out as part of this investigation. Tests would need to be conducted very carefully and accurately to determine if there is any appreciable difference in the weight of a loaded and an unloaded specimen. If the theoretical concept is true, specimens under sustained load would show a greater moisture loss than corresponding unloaded specimens.

3. Since a sizeable portion of the soil used is clay, the increased moisture content may have an effect on interparticle surface forces. These forces (of molecular nature) may greatly affect the creep process, especially in the early stage of creep when most of the readjustments of soil particles take place under the applied pressure.

Influence of Binder Content.—Figure 16 shows strain-time curves obtained under a sustained stress of 76.5 psi on compacted specimens made with binder contents ranging from 2.5 to 7 percent asphalt. Figures 17 and 18 show the relationship between the binder content and the amounts of instantaneous strain and transient creep, respectively. Data for the plotting of these curves were obtained from Figure 16 and are given in Table 6.

These results indicate that the effect of the binder content is reflected to a considerable degree in the change of the instantaneous deformation and the magnitude of transient creep. Increasing the asphalt content from 2.5 to 7 percent leads to an increase of the instantaneous deformation of about 200 percent; also, the unit deformation in transient creep increased by 100 percent. The rate of creep was not greatly affected by changing the binder content from 2.5 to 7 percent. (The rate of creep was determined as the slope of the straight-line part of the strain-time curves in Fig. 16.) Numerical values of these creep rates vs the binder content are also shown in Table 6.

One might expect the rate of creep to increase with the increase in the amount of binder. However, experimental evidence, for the particular stress level used, did not support this well-established idea. It may be that the contradiction is only apparent and if the stress had been increased, there would have been more difference in the rates of creep with the increase in the binder content. In such a case, the increase in the amount of binder content from 4 to 7 percent may result in an appreciable increase in the rate of deformation. Generally, it was found that too much binder lubricated the soil particles to such an extent that the mixture lacked stability under stresses. This was reflected experimentally by: (a) the reduced values of maximum uncompressive strength in a constant rate of deformation test; (b) the appreciably increased amounts of instantaneous and delayed deformations in sustained constant-stress tests even under low stress levels; and (c) the probable increase in the rates of deformations (in a constant stress test) when the stress levels are large enough to produce an appreciable difference.

SUMMARY AND CONCLUSIONS

The objective of this research was to make a study of the strength characteristics of the soil-asphalt mixtures for certain particular types of stress conditions. The main stress system considered was that of a steady-load type for which a constant load of unconfined compressive nature was applied on a cylindrical specimen and the deformation of the specimen was observed as a function of time. Other tests were carried out at constant rates of axial strains with increasing stress.

Only one soil type and one type of asphalt were used in this investigation. All conclusions drawn are applicable only to the particular type of mix used and under the same environmental conditions which have been described. The major conclusions resulting from this investigation are as follows:

1. Under constant rates of strain and with increasing stress, no appreciable increase in the maximum strength was indicated by increasing the rate of loading from

0.005 to 0.08 in./min. However, the change in the maximum strength increased rapidly at rates of deformation greater than 1 in./min. It also seemed that the percentage increase in the strength with increase of loading speeds was greater for the 7 percent than for the 4 percent asphalt mixtures.

2. Under constant sustained level of stress, the material exhibited a deformation characteristic of a viscoelastic nature. The application of the load caused an instantaneous deformation (part of which was elastic and part plastic). Continued application of the load caused the material to creep. On removal of the load an instantaneous recovery was produced, which was less than the initial instantaneous deformation, followed by the delayed elastic recovery.

3. Neither instantaneous deformation nor recovery were linear with the stress level. The rate of creep was also nonlinear with both time and stress.

4. There was an actual value of sustained stress level of about 0.5 to 0.6 of σ_u (in which σ_u refers to the maximum unconfined compressive strength) with 4 percent asphalt mixture and of about 0.7 to 0.75 of σ_u with 7 percent asphalt mixture, below which the creep deformations ceased and failure did not occur. If the sustained stress was greater than these levels, the creep continued until the sample failed.

5. For the samples when failure took place, every value of the strain at failure was almost the same, irrespective of the applied stress.

6. Experimental results indicated that for those samples for which failure took place by creep and diminishing strength, the stress and the log time to break have a linear relationship.

7. The curing time up to 3 days after compaction had a very significant influence on the rheological properties of the material. Increasing the curing time of a 4 percent asphalt mixture to 15 days led to a 100 percent increase in the maximum strength of the material and the instantaneous deformation and rate of creep decreased more than 60 percent.

8. The effect of the binder content was reflected most in the magnitudes of the instantaneous deformation and transient creep. As a result of increasing the aphalt con tent from 2.5 to 7.0 percent, the amount of instantaneous strain increased 200 percent.

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