Effect of Degree of Aging on Creep and Relaxation Behavior of Sand-Asphalt Mixtures

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Previous work on the study of aging is reviewed. The creep parameters of mixture viscosity and modulus of recovery developed by Wood and Goetz were selected for use in comparing the creep characteristics of the aged and unaged mixes.

A 60-70 penetration asphalt was used. Ottawa sand of maximum size No. 16 was used as aggregate. The gradation was within the limits of ASTM Designation: D1663-59T. Three different mixes were made with 9, 12, and 15 percent asphalt content by weight of aggregate. Three degrees of aging were used: 77 F (unaged), 140 F, and 225 F for 1 wk. Specimens, 3.5 cm in diameter and 7 cm high, were made and tested in creep and relaxation. Maximum creep strain was limited to 1.2 percent and the relaxation strain was 1.4 percent.

The rate of creep generally decreased with increase in the degree of aging. With the higher asphalt content mixes, the difference in the creep rates was less marked. The maximum relaxation load increased with aging.

For the particular results obtained, a semilog relation was developed showing the variation of mixture viscosity with the degree of aging. A similar expression was developed relating the maximum relaxation load to the degree of aging.

•WORK ON the aging of bituminous materials with time has continued since the first paper on the subject was presented by Hubbard (7) in 1913. Hubbard showed that the hardening of asphaltic materials on exposure was due to both volatilization and oxidation. Reeve (20) next showed that polymerization and intermolecular reactions induced by heat, in addition to volatilization, were responsible for hardening. Sabbrow (22), after undertaking research on the aging of road tar in France, concluded that the effect of evaporation was far greater than that of oxidation.

Most recent researchers have agreed that the main causes of age hardening of bituminous materials are oxidation, photooxidation, volatilization, polymerization, thixotropy, syneresis and separation (27). The main effect of these processes, in varying degrees, is to cause asphalt to become less ductile, lose its penetration, and gradually develop a structure, thereby causing brittleness and failure of pavements. The most important causes of hardening are oxidation, volatilization and polymerization.

To study these effects, asphalts are usually artificially aged in the laboratory by the technique of accelerated weathering. Ovens are to reproduce various conditions representing long periods of aging in actual practice. High-temperature weathering is used in the study of volatilization and oxidation. Artificial light is used to study the effects of photooxidation, and infrared and ultraviolet weathering are used to study the effects of the sun's radiant energy. Selection of an aging method depends on the effect being studied.

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Because the problem of aging is an important factor in the life of a bituminou pavement, investigators have directed their research to its effects on particular properties of bituminous materials and mixtures. Aging is not a physical property which can be measured in numerical terms. There is, therefore, as yet no scale for it. The main problem has been to find some way of measuring the rate of change due to aging of any particular property of bituminous materials with time and thereby to deduce a method of measuring the durability of an asphaltic pavement.

Of historical interest is the work of Sabbrow and Renausie (23) who put forward a method of measuring the aging effects of road binders by means of an aging coefficient. He used the following equation to measure the likelihood of a binder softening during the summer months:

$$C_{v/t} = \frac{V_v - V_p}{A_p} \tag{1}$$

where

$C_{v/t}$ = aging coefficient at temperature t;

V_v = viscosity after artificial aging at temperature t;

V_p = viscosity of original binder; and

A_p = loss in weight during aging.

This, therefore, used change in viscosity as a measure of aging. They in fact carried out field studies to correlate the aging coefficient with the development of cracks in pavements.

Some investigators measured changes in the penetration of the asphalt, for they felt that this was a very important property. Hubbard (8) indicated that a penetration of 30 or less for asphalts subjected to freezing may result in cracking. Powers (19), as a result of his own studies, concluded that pavements containing asphalts with a penetration of less than 10 would be subject to cracking.

McKesson (15), on the other hand, felt ductility was a better measure of hardening than penetration. Vokar (31) used the softening point of asphalt together with changes in ductility and penetration to measure the hardening of asphalts.

The U. S. Bureau of Public Roads (11) developed the thin-film oven test which is used in its work. The Bureau has published data showing the relation between loss of penetration and changes in softening point of various film thicknesses of asphalt after aging under high-temperature weathering for as long as 10 hr.

California (25) developed a test in which Ottawa sand is coated with various films of asphalt, weathered for specified periods in a weathering machine, and then subjected to the abrasive action of 100 gm of steel shot falling 1 m. Loss of weight is used as a measure of the durability of the asphalt.

With the development of the microviscometer by Shell (5), much work on aging has been based on measuring the change in viscosity after aging using the aging index, defined as the ratio of the viscosity of the weathered to the unweathered material as measured by the microviscometer. The results presented by Shell Development Co. show that as the duration of high-temperature weathering is increased, the aging index rises sharply. The microviscometer method of determining the change in the viscosity of the asphalt due to aging is being widely used in research. The value of the aging index can be used as a measure of the durability of the pavement by correlating it with the behavior of the pavement.

Traxler (29) investigated the effect of prolonged heating of asphalt films of 15 μ at 325 F in air. His results also reveal a rapid increase in the viscosity of an asphalt with the duration of aging by direct heat. This information is very helpful in determining the choice of aging temperatures and the duration of aging.

In undertaking any aging experiments, therefore, the choice of the method, duration and temperature of aging is very important. Most often the method of aging is determined by the property being studied and its correlation with the actual conditions in a pavement. Vallerga et al. (30) studied the relative effects of different types of laboratory aging techniques and found that the effect on either penetration or softening point varied depending on whether the method used was direct heating in no light, aging in ultraviolet light, or aging in infrared light. The most important thing, therefore, is the correlation of results with field conditions. Hveem, Zube, and Skog (9), using the California infrared machine, showed that exposing asphalt for 1,000 hr in such a device was equivalent to 5 yr of pavement life. It has been estimated that most of the aging takes place within this period of time. Clark (2), on the other hand, carried out a set of correlation studies which compared the weathering of asphalt in an oven for weeks at 150 F with the aging of pavement. He concluded that 1 wk of aging at 150 F was equivalent to 1 yr of natural weathering of a pavement. Comparison of laboratory aging with life of bituminous materials in the field is of great importance in using the laboratory data for design.

Most investigators have felt that, because asphalt is the main cause of loss of durability, it should be isolated and studied independently; therefore, most work on the aging of bituminous concrete has been confined to analyzing the change in the properties of pure asphalt.

Recently, investigators have begun to study the aging of the bituminous concrete mass. Although the study of asphalt film is easier, it cannot be a proper substitute for the study of the mix. Analyzing this approach, Mack (14) states that the mechanical strength of mineral aggregate is greater than that of the asphalt. The adhesion energy between asphalt and aggregate is greater than the cohesive energy of the asphalt. Failure in a pavement, therefore, occurs when the external forces exceed the cohesive forces in the asphalt film. Mack further states that there is sufficient evidence to indicate that even simple liquids in thin films have properties different from those in the mass. Principal effects are considerably increased viscosity and greater elastic strength of the liquid near the surface of the solid. In bituminous pavements, asphalt films behave like solids. He concludes that, in view of these factors, the consistency of asphalts in mass cannot be extrapolated to thin films and any evaluation of the hardening effect in relation to their suitability as binders is best carried out on bituminous mixtures.

Mack measured the bearing strength of asphalt-sand mixtures for aged and unaged specimens and arrived at the following significant conclusions:

1. The bearing strength of unaged asphalt-sand mixtures decreases generally with deviation from Newtonian flow of the asphalt used; and
2. Aging increases the bearing strength markedly at 77 F in all cases, but only in two cases at 60 F.

In view of the increased consistency of the asphalts, the latter result is interesting in that bearing strength bears no relationship to the consistency of the asphalt. Mack indicated that strains in the asphalt-sand mixtures are not independent of the degree of compaction. To eliminate compactive effort, measurements must be carried out on mixtures of the same dimensions for a given weight. Aging does not affect the total strain.

There are also other factors which make the investigation of the asphalt aggregate mixture a closer approximation to what actually happens in the field. There is a substantial amount of hardening through loss of penetration during mixing (1). Because the duration of mixing also greatly affects hardening, a maximum length of time is required in most specifications for mixing. Other variables are the degree of compaction, void content, and permeability of the mix (14). In investigating aggregate asphalt mixtures, therefore, most of these effects will be present.

To evaluate the hardening effects on the mass by mechanical tests as recommended by Mack, the properties to be studied and the parameters involved must be carefully selected if any useful results are to be obtained. Fink (3), in his recommendations, indicated that measurement of an appropriate physical property of an asphalt before and after aging was the key factor in hardening studies. He thought it would be ideal to obtain a complete picture of rheological behavior as a function of loading time and temperature.

The results of recent research have confirmed that the stress characteristics of flexible pavements are time dependent. Mack (13) showed that deformation of a bituminous mixture consists of an elastic (recoverable) part and a nonrecoverable part. The type of behavior in deformation shown by asphaltic mixtures is termed viscoelastic behavior, the analysis of which belongs to the study of rheology of materials. To evolve theoretical equations representing the stress and strain characteristics of linear viscoelastic materials, model representation is used. The models consist essentially of various arrangements of springs and dashpots which represent the elastic and viscous behavior of the materials.

The stress-strain characteristics of asphaltic mixtures as obtained from creep tests consist of three essential parts (13): (a) an instantaneous elastic strain independent of time; (b) a retarded elastic strain which is a function of time; and (c) viscous strain whose rate decreases with time. Various attempts have been made to develop the simplest model that will duplicate all these features in its stress-strain curve. Burger's model (12, 15, 16, 29) seems adequate as it exhibits all the foregoing features in its stress-strain curves. This model consists of four elements which combine the Maxwell and Kelvin models.

The equation of deformation of the model is represented by:

$$\frac{d\gamma}{dt} = \frac{\tau}{\eta_1} + \frac{d\tau}{dt}\frac{1}{G_1} + \frac{d}{dt}\left[\frac{1}{\eta_2} e^{-\frac{G_2 t}{\gamma_2}} \int \tau e^{-\frac{G_2 t}{\gamma_2}} dt\right] \qquad (2)$$

where

G_1, G_2 = spring constants (spring modulus),
η_1, η_2 = dashpot constants (viscosity),
τ = applied stress, and
γ = deformation.

In creep tests where the creep load is static and constant $d\tau/dt = 0$. Solving Eq. 2 for a static creep load gives:

$$\gamma = \frac{\tau}{G_1} + \frac{\tau}{G_2}\left(1 - e^{-\frac{G_2 t}{\eta_2}}\right) + \frac{\tau}{\eta_1} t \qquad (3)$$

where

τ/G_1 = instantaneous elastic deformation,
$\tau/\eta_1 t$ = permanent deformation after time t, and
$\frac{\tau}{G_2}\left[1 - \exp(-G_2/\eta_2 t)\right]$ = retarded elastic strain.

It has been argued that this model configuration does not truly represent the behavior of the asphalt mixture in practice. Pister and Monismith (18) show that in Burger's model the instantaneous elastic strain is equal to the elastic rebound regardless of the duration of loading, whereas in practice this is not the case. The amounts of elastic recovery vary with the duration of loading. Hence, they felt that a model similar to Burger's but incorporating this variability of elastic recovery with time would be more appropriate. For the scope of the present work, however, Burger's model is assumed because of its relative simplicity.

Mathematical analysis of Burger's model and its various modifications become complex except in very simple cases. Using the model as a basis for evaluation, an empirical study of the actual curves obtained from creep tests are used in the present work. The study of the effects of hardening on the viscoelastic characteristics of the mixtures is essentially concerned with comparison and not with actual solutions of the equations which represent the behavior of the material as obtained from model analysis. Therefore, the derivation of parameters which can be affected by various hardening effects is bound to be the best approach.

In this connection, the work of Wood and Goetz (32) seems the most significant. They studied the rheological characteristics of sand-asphalt mixtures by undertaking unconfined compression creep tests on various specimens and thereby obtaining the deformation time curves for the mixtures.

Using Burger's model, they analyzed the curves from two main properties, elastic instantaneous strain and viscous deformation. The second term in Eq. 3 shows retarded elasticity of the Kelvin element. The effect of this element is usually pronounced in the first section of the creep curve, giving it the parabolic shape. As the test continues, this effect quickly dies out and, as Wood and Goetz pointed out, the remainder of the curve is for all practical purposes straight with a fairly constant slope.

If, therefore, the parabolic section of the curve is ignored, the slope of the straight portion could be measured and used as a parameter. This section of the curve can be said to be represented by the last term in Eq. 3. The reciprocal of the slope of the curve at this section represents the viscosity of the mixture. Wood and Goetz defined the product of the applied stress and the reciprocal of this slope as the mixture viscosity (V) in pound-seconds per square inch.

To measure the elastic component, they divided the applied stress by the rebound strain to obtain a second parameter which they termed the modulus of recovery (R). They showed that within the limits of experimental error the modulus of recovery and the mixture viscosity are independent of the applied stress. This property, if exact, makes these two parameters useful tools in the study of aging. The effects of aging on the values of these two parameters provide a useful basis for comparing the degrees of age hardening. The two parameters depend on properties affected by aging, namely, the viscous behavior of the mixture and its elastic or rigid behavior. Their use should, therefore, prove fruitful.

In discussing the foregoing results, Mack (32) pointed out that if the strain is plotted against the log of time, the parabolic section of the creep curve comes out as a straight line. This becomes obvious on examining the exponential nature of this part of the curve. If a straight line is obtained, its slope could also serve as a parameter, since it depends on the viscosity, which could then also be investigated as a possible third parameter for use in aging.

For a complete study of the rheological properties, an examination of the stress relaxation behavior of the mixture would provide a useful comparison. The best model representation of relaxation behavior has been shown to be the generalized Maxwell model with a series of elements (18).

Stress at any time is represented by the following equation:

$$\sigma = \epsilon \int_0^\infty G\,(T_{rel})\; e^{-\frac{t}{T_{rel}}}\; d\,(T_{rel}) \tag{4}$$

where T_{rel} is relaxation time and ϵ is strain. The ratio of stress to strain is known as the relaxation modulus, $E_r\,(t)$. This gives another parameter which can be used to compare the properties of the mixture. The modulus of relaxation is widely used in work on polymers (30). Since the relaxation behavior depends on the viscous properties of the mix, hardening should have a marked effect on the modulus of relaxation and could also be used as a basis of comparing the degree of aging.

MATERIALS AND TEST PROCEDURE

Aggregate

To study properly the effects of aging, it was considered necessary to eliminate any unknown factors caused by the properties of the aggregate. To eliminate disintegration and aggregate reactivity with asphalt in the mix, the aggregate had to be inert, sound, and durable. Aging effects, thereby, would be confined to changes in the asphalt properties. Ottawa sand was chosen as meeting these requirements, and silica sand powder was used as mineral filler.

It was desirable that the gradation of the sand be within the specification limits of ASTM Designation: D 1663-59T for sheet asphalt. By plotting the specification limits on a log plot, a straight line lying within the specified range was obtained. This straight line represented a gradation shown mathematically as:

$$P_i = P_o\left(\frac{d_i}{D_o}\right)^n \quad (5a)$$

or

$$\log P_i = \log P_o + n \log \left(\frac{d_i}{D_o}\right) \quad (5b)$$

where

P_i = percent passing sieve size being considered,
P_o = percent passing maximum sieve size,
d_i = diameter of required size,
D_o = diameter of maximum size aggregate.

The exponent, n, is the slope of such a line and when its value is approximately 0.5, the equation will be the same as Fuller's for maximum density. Table 1 gives the gradation analysis of dry sand used in this study.

The specific gravity of the aggregate was determined using the hydrometer method of ASTM Designation: C 188-44. This method was considered suitable because of the high percentage of fines in the aggregate.

Asphalt

A 60-70 penetration asphalt available in the laboratory was used. The properties of this asphalt have been determined in other tests (33). Three different asphalt contents were chosen, of which two, and 12 percent, were within ASTM specification limits and one, 15 percent, was higher than specified.

Preparation of Mix

The method adopted was similar to the California test method (No. Calif. 350-A) (9). The sand was divided into three equal batches and preheated to a temperature of 325 F in an oven. The asphalt was also heated to a uniform temperature of 325 F and the required amount was poured on the preheated sand and mixed thoroughly in a large bowl for 2 min, insuring that all the sand was evenly coated. To reduce the amount of aging, no further heating was done during this process. After mixing, the sample was portioned into three equal parts and spread out in open containers in preparation for aging.

TABLE 1

SIEVE ANALYSIS OF OTTAWA SAND[a]

Sieve Size	% Passing	% Retained	Wt of Materials (gm)
No. 16	100	0	—
No. 30	75	25	1,750
No. 50	45	55	2,100
No. 100	26	74	1,330
No. 200[b]	15	85	770
			1,050
Total			7,000

[a]Hydrometer analysis: avg. sp. gr., 2.645; value used, 2.65.
[b]Silica sand used for sizes ≤ 200.

Method of Aging

It was decided to age the mixtures at three different temperatures which had been previously employed in other work on aging: 77, 140, 225 F. The standard temperature of 77 F was selected as a basis for comparison; 140 F is used for the Shell aging index (5), and 225 F is widely used in aging work (9, 29).

The aging was undertaken in electric ovens in the presence of air. It was decided to use an aging period of 1 wk, based on the work of Clark (2) and Traxler (29). Clark indicated that 1 wk of aging in a

TABLE 2

DENSITIES OF SPECIMENS

Specimen	A/C Content (%)	Avg. Weight (gm)	Height (cm)	Density (gm/cu cm)	Theoretical Max. Density	Voids (%)
A-9	9	140	7.0	2.09	2.35	11
B-9		140	7.0	2.09	2.35	11
C-9		140	7.0	2.09	2.35	11
A-12	12	135	7.0	2.00	2.25	11.1
B-12		135	7.0	2.00	2.25	11.1
C-12		135	7.0	2.00	2.25	11.1
A-15	15	130	7.0	1.91	2.15	11.1
B-15		130	7.0	1.91	2.15	11.1
C-15		130	7.0	1.91	2.15	11.1

laboratory oven at 150 F was equivalent to 1 yr of aging in the field. By using the same duration, it was hoped to eliminate the time element from the number of variables. The three samples were spread out so that most of the material was exposed to the effects of heating. The principal agents in this type of aging would be volatilization and oxidation. After aging, the mixtures were stored in an inert atmosphere of carbon dioxide until ready for use.

Preparation of Specimens

The specimens were prepared in molds of 1 ⅜-in. diameter with 2 ⅞-in. internal dimensions. The molds were preheated in an oven to a temperature of 270 F. The aged sand-asphalt mixture was divided into four portions weighing 140 gm each. It was estimated that about 0.3 lb, or 134 gm, would be necessary for each specimen.

Each portion was then reheated in an oven to a temperature of 270 F for a period of 15 min. It was removed and the mold filled in four equal lifts. Compaction was done with the help of a Harvard miniature compactor, using 20 blows of 45 lb for each lift. The sample was extruded from the mold with a special extractor and allowed to cool before weighing.

In the case of samples with asphalt contents of 12 and 15 percent, the extraction from the mold could not be done immediately after compaction because the specimens tended to lose shape and collapse when hot. After compaction, the molds and the specimens were placed in a refrigerator and allowed to cool down completely. They were then removed and the outside of the molds were heated until heating effects just showed on the inside edges of the samples, but the middle cores were not affected. The molds were then placed in the extractor and the samples were forced out, numbered, and stored in a refrigerator in the presence of CO_2 until ready for testing.

Creep Tests

The creep test apparatus consisted of a triaxial cell, and loading was done by consolidation weights applied to the loading frame. Water at a constant 25 C was circulated around the test cell to insure testing at a constant temperature.

Deformation was recorded by means of an LVDT transducer connected to a Varian recorder (Model G-14). The recorder had two chart speeds of 1ft/min and 1 in./min, either of which was used depending on the speed of deformation of specimen and sensitivity required.

The amount of deformation allowed on the sample was limited to 1 or 2 percent, avoiding stressing the material to failure. In practice, deformation was limited to 0.03 in. The average height of a specimen was 2 ¾ in. This, therefore, represented a strain of 1.1 percent. After the set deformation was attained, the load was removed.

The recorder was allowed to run until the deformation became constant. At least two tests were run for each specimen for the same load. Three sets of loadings were used for each set of specimens.

Relaxation Tests

Six specimens were selected from the 9 and 12 percent asphalt content specimens and for the three degrees of aging. The relaxation tests were carried out on an Instron testing machine which measures and records both stresses and strains automatically and can record either variable load at constant strain or variable deformation at constant stress. To test the specimens, a deformation of 1 mm was applied to the specimen within a period of 0.1 min and maintained. The maximum load induced and subsequent stress relaxation were automatically recorded on a chart.

As mentioned previously, the strains obtained in the creep test are not independent of the degree of compaction. To limit any variation in the results due to variation in the density of the specimen, great control was exercised in the compaction. The densities obtained for each asphalt content were in agreement to within 1 percent. Table 2 gives the average bulk densities and percent voids of various mixtures used in this study.

The main difficulty in conducting creep tests was in the application of the creep load. The range of strain measured was only 1.2 percent maximum (i.e., about 0.035 in.). This measurement could easily be upset by the slightest vibration produced in placing the weights. Any erratic initial developments were usually noted and used as the zero error.

The specimens tested in creep generally showed an instantaneous and a delayed strain. When unloaded, the specimens showed an instantaneous rebound, a delayed rebound, and a permanent strain. When the same specimens were reloaded, the magnitude of instantaneous rebound was closer to instantaneous strain than during the first loading. It was decided, therefore, to load and unload each specimen at least twice. For consistency, only the curves obtained from the first reloading were used in computations.

The creep tests on the 15 percent A/C mix were carried out with as little delay as possible because the specimens tended to slump if left in the cell at the test temperature of 77 F. They were usually not removed from storage until a short time before testing.

To obtain the rebound modulus, the instantaneous rebound strain was measured from the recorder charts. It was difficult to measure this quantity because it was difficult to know precisely how much of the rebound was instantaneous and how much was retarded. The rebound modulus (12) was calculated as follows:

$$R = \frac{T}{E_R} \tag{6}$$

where T is applied stress (kg/sq cm), and E_R is rebound strain.

The slopes S of the stress-strain creep curves at the point where the slope is almost constant were measured as follows:

$$S = \frac{\Delta e}{\Delta t} \tag{7}$$

From this the mixture viscosity (V) can be obtained as follows:

$$V = T/S = \frac{T}{\frac{\Delta e}{\Delta t}} \text{ kg/sq cm-sec} \tag{8}$$

RESULTS AND DISCUSSION

Typical creep curves obtained for various mixes are shown in Figures 1 through 3, and values of mixture viscosity, creep modulus, and modulus of recovery (R) are given in Tables 3 through 6.

No relaxation tests could be undertaken on the 15 percent asphalt content mixtures because by the end of the creep tests (in waiting for the cell to drain out before removal of the specimen) the samples had slumped badly and could not have given useful results. The relaxation curves shown in Figures 4 and 5 are for 9 and 12 percent A/C mixtures. Tables 7 and 8 give the values obtained and the calculated values of the relaxation modulus.

An examination of the deformation time curves in Figures 1 through 3 shows that the general outlines of these curves exhibit the predicted characteristics, i.e., an instantaneous elastic deformation and rebound, a time-dependent deformation, and a permanent deformation.

The results showed that the creep curves obtained for the specimens under the first application of load had a very high initial value of instantaneous deformation, far larger than the elastic rebound. It was felt that this was most likely due to initial compression of the specimens. Despite the dense gradation of the mixtures, Table 2 indicates that the mixes contained relatively high percentages of voids. After the initial loading, the material settled and gave more consistent results.

An examination of the creep curves for the various degrees of aging shows a definite difference in the rate of creep (Figs. 1, 2, and 3). For the 9 and 12 percent asphalt content, mix A shows the highest rate of creep, followed by mix B and mix C. The high degree of aging to which mix C was subjected seems to reduce the viscous component of the mix, producing a low viscous deformation. The closeness of curves A and B in Figures 2 and 3 indicates that the degree of aging to which B was subjected was not high enough to make a marked difference as in C. For the 15 percent asphalt content mix (Fig. 3), the slope of curve C is again much lower, but a close examination of the curves shows that the difference between the curves is less marked. This is probably due to a lower degree of aging taking place in the mix with higher asphalt content. It is clear, therefore, that aging does affect the rate of creep and the elastic deformation. The next problem is how to measure these changes.

Earlier, some parameters were developed for measuring the characteristics of the mix based on Burger's model. This model assumes that the viscoelastic behavior of the material is linear. For this linearity to be satisfied, the instantaneous elastic deformation and the retarded elastic deformation (represented by the parabolic section of curve) should be a mirror image of the rebound strain section. The only curves that seem to satisfy this property are those for the group C specimens. The groups A and B specimens indicate that their viscoelastic behavior is not exactly linear. Linearity, however, can be used as an approximation for these mixtures. Table 9 gives the values of its constants for various mixes used in this study.

Wood and Goetz (32), using Burger's model, evolved the parameters of modulus of recovery (R) and mixture viscosity (V). They further suggested the use of these parameters as measures of the degree of aging of mixtures. As indicated before, the creep curves were affected by the aging process; therefore, R and V were calculated to see if any possible interpretation could be made of possible trends in their values. The values obtained appear in Tables 6 and 10. The modulus of recovery values obtained, apart from a few scattered values which do not obey the trend and are obviously erratic, showed a decrease with the degree of aging. To use such a parameter for design, it is necessary to evolve some relationship linking the value of the modulus of recovery to the degree of aging measured, perhaps in terms of temperature or degree-days.

The main problem in measuring the modulus of recovery is the difficulty of measuring the instantaneous rebound. It is difficult to determine exactly where this rebound ends and the retarded rebound begins. It might be possible to measure this value more accurately if, for example, a higher recorder chart speed is used. Even then, removing the load instantaneously to record the rebound is difficult unless an automatic loading

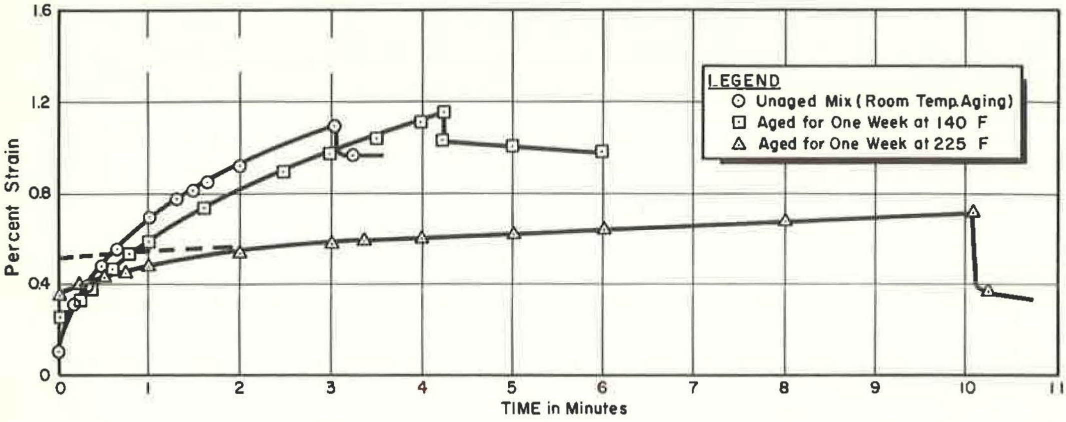

Figure 1. Creep curves, 9 percent A/C, 50 kg (5.2 kg/sq cm) load.

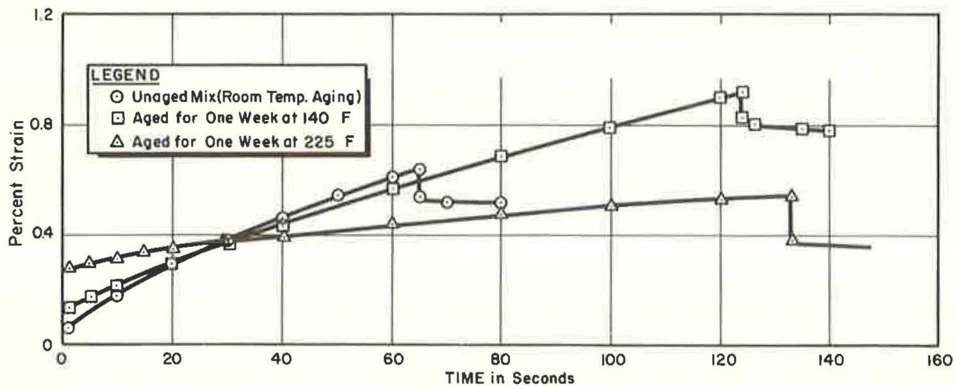

Figure 2. Creep curves, 12 percent A/C, 5 kg (0.52 kg/sq cm) load.

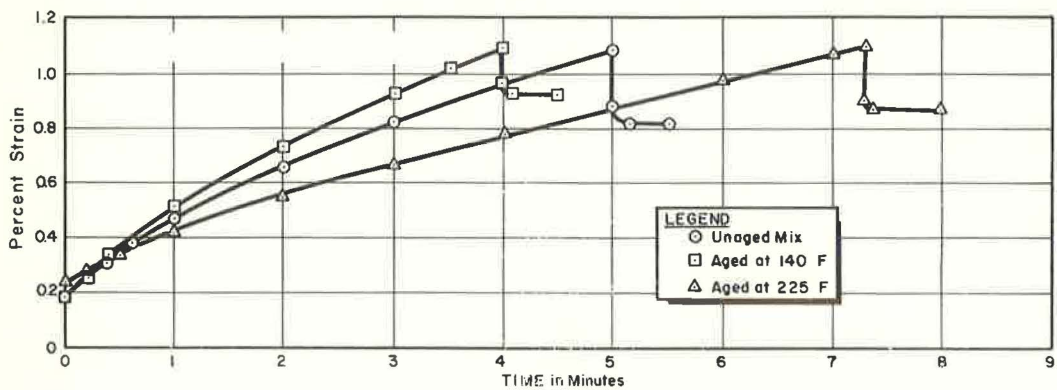

Figure 3. Creep curves, 15 percent A/C, $2\frac{1}{2}$ kg (0.263 kg/sq cm) load.

TABLE 3

CREEP TEST, 9 PERCENT A/C MIXTURES

Specimen A-9[a]				Specimen B-9[a]				Specimen C-9[a]			
t (min)	γ (× 10^{-3} in.)	ε (× 10^{-3})	$E_c(t)$ (kg/sq cm)	t (min)	γ (× 10^{-3} in.)	ε (× 10^{-3})	$E_c(t)$ (kg/sq cm)	t (min)	γ (× 10^{-3} in.)	ε (× 10^{-3})	$E_c(t)$ (kg/sq cm)
0	2.5	0.91	5710	0	3.0	1.1	4700	0	9.5	3.4	1530
0.25	18.8	3.20	1800	0.2	7.0	2.54	2050	0.25	10.8	3.86	1350
0.5	13.0	4.73	1100	0.6	12.5	4.55	1170	0.5	11.8	4.24	1230
0.66	15.0	5.45	953	1.0	14.5	5.82	890	0.75	12.5	4.48	1160
1.0	18.8	6.84	750	1.4	19.0	6.91	752	1.0	13	4.67	1110
1.33	21.0	7.64	680	1.8	21.3	7.72	673	2	14.5	5.22	990
1.66	23.0	8.39	620	2.0	22.3	8.48	613	3	15.8	5.69	915
2.0	25.0	9.10	570	3.0	26.5	9.64	541	4	16.5	5.94	877
2.3	26.5	9.65	540	3.4	28	10.2	510	5	17.0	6.1	854
2.6	28	10.70	486	3.8	29.3	10.65	487	6	17.5	6.3	826
3.0	29.5	10.70	-	4.0	30	10.9	476	8	18.5	6.7	776
3.05	26.5	9.65	-	4.2	31.25	11.45	454	10	19.5	7.00	743
3.5	23.5	8.54	-	4.2	28	10.2	-	10.1	19.5	7.00	743
4.0	23.0	8.36	-	4.4	28	10.2	-	10.1	10.0	3.65	-
10.0	22	8.00	-	6.0	27.5	9.8	-	10.2	9.8	3.56	-
								12	7.5	2.73	-

[a]Load: 50 kg (5.2 kg/sq cm).

TABLE 4

CREEP TEST, 12 PERCENT A/C MIXTURES

Specimen A-12[a]				Specimen B-12[a]				Specimen C-12[a]			
t (sec)	γ (× 10^{-3} in.)	ε (× 10^{-3})	$E_c(t)$ (kg/sq cm)	t (sec)	γ (× 10^{-3} in.)	ε (× 10^{-3})	$E_c(t)$ (kg/sq cm)	t (sec)	γ (× 10^{-3} in.)	ε (× 10^{-3})	$E_c(t)$ (kg/sq cm)
0	1.0	0.36	1440	0	3.2	1.11	470	0	4	1.46	356
2	1.5	0.54	963	2	3.5	1.28	408	1	7.5	2.72	191
5	2.5	0.91	572	5	4.5	1.65	315	5	8.0	2.90	179
10	4.5	1.63	319	10	6.0	2.19	238	10	8.5	3.08	169
20	8.0	2.90	179	20	8.0	2.92	178	15	9.0	3.26	159
30	10.5	3.80	137	30	9.90	3.62	144	20	9.5	3.45	151
40	12.5	4.65	112	40	12.0	4.38	119	30	10.3	3.74	139
50	15.0	5.42	96	60	15.6	5.68	92	40	11.0	3.99	130
60	16.8	6.12	85	80	18.9	6.89	73.6	60	12.0	4.35	119
65	17.5	6.36	82	100	21.8	7.91	65.8	80	13.0	4.72	110
66	14	5.09	-	120	24.7	9.00	57.9	100	14.0	5.09	102
67	14	5.09	-	124	25.6	9.31	56	120	14.5	5.28	98.4
70	14	5.09	-	125	22.6	8.2	-	133	15.0	5.42	96.0
				135	21.6	7.86	-	134	10.5	3.80	-
				140	21.4	7.80	-	135	10.3	3.70	-
								150	10.0	3.64	-

[a]Load: 5 kg (0.52 kg/sq cm).

TABLE 5

CREEP TEST, 15 PERCENT A/C MIXTURES

Specimen A-15[a]				Specimen B-15[a]				Specimen C-15[a]			
t (min)	γ ($\times 10^{-3}$ in.)	ϵ ($\times 10^{-3}$)	Ec(t) (kg/sq cm)	t (min)	γ ($\times 10^{-3}$ in.)	ϵ ($\times 10^{-3}$)	Ec(t) (kg/sq cm)	t (min)	γ ($\times 10^{-3}$ in.)	ϵ ($\times 10^{-3}$)	Ec(t) (kg/sq cm)
0	5	1.8	1.46	0	5	1.8	1.41	0	6.5	2.36	110
0.2	6.9	2.5	105	0.2	68	2.46	1.07	0.1	7.0	2.54	102
0.4	8.8	3.1	84.7	0.4	8.8	3.20	0.823	0.2	7.75	2.71	95.5
0.6	10.3	3.75	70.1	0.6	9.5			0.3	8.25	3.00	86.3
1.0	13.0	4.73	55.7	1	14.0	5.09	0.517	0.5	9.25	3.36	77
2.0	18.3	6.65	39.6	2	20.0	7.25	0.363	1.0	11.25	4.08	63.5
3.0	22.8	8.28	31.8	3	25.8	9.35	0.282	2.0	15.0	5.45	47.5
4.0	26.5	9.63	27.6	3.5	28.3	10.20	0.258	3.0	18.5	6.72	38.5
5.0	30.0	10.9	24.0	4	26	10.90	0.241	4.0	21.5	7.8	33.2
5.1	22.5	8.2	3.20	4.5	26	9.44	-	5.0	24.5	8.9	29.1
5.2	22.5	8.2	3.20	-	-	9.44	-	6.0	27.0	9.8	26.4
5.6	22.5	8.2	3.20	6	26	9.44	-	7.0	29.5	10.7	24.2
6.0	22.5	8.2	3.20	6.5	26			7.3	30	10.9	23.7
								8.0	24	8.7	

[a]Load: 2 ½ kg (0.263 kg/sq cm).

TABLE 6

MODULUS OF RECOVERY

Specimen	Load (kg)	Rebound Strain ($\times 10^{-3}$)	Modulus of Recovery
A-9	50	1.0	5,200
B-9	50	1.25	4,160
C-9	50	3.35	1,550
A-12	5	1.27	410
B-12	5	1.11	470
C-12	5	1.63	320
A-15	2 ½	1.5	173
B-15	2 ½	1.5	173
C-15	2 ½	1.6	162

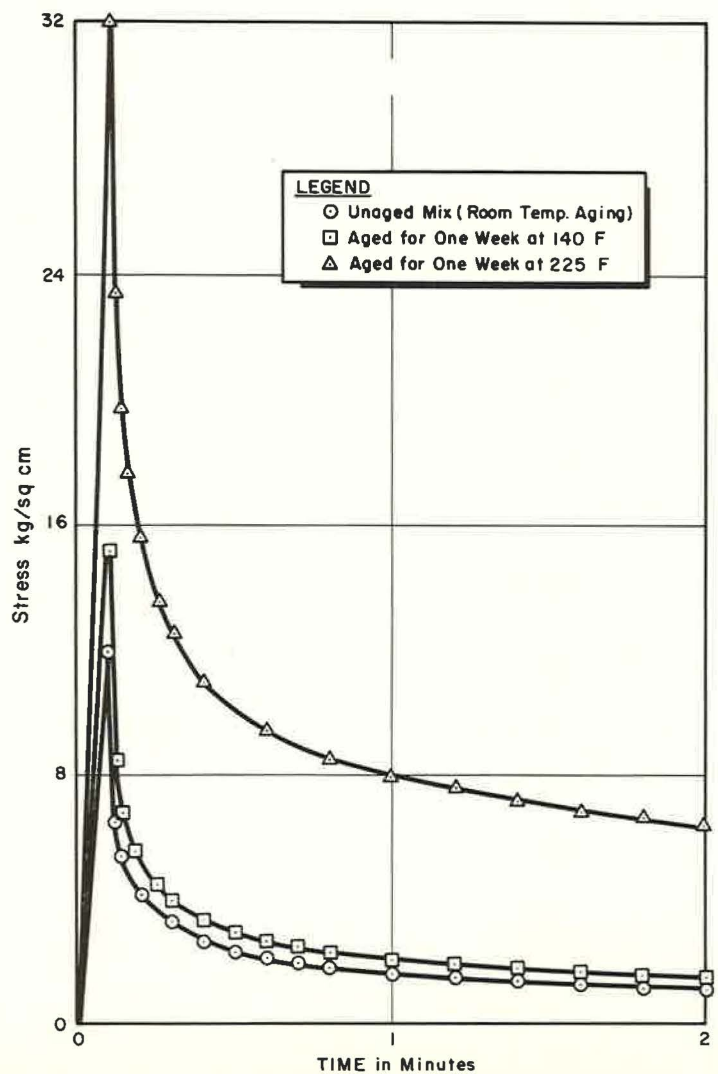

Figure 4. Stress relaxation curves, 9 percent asphalt content.

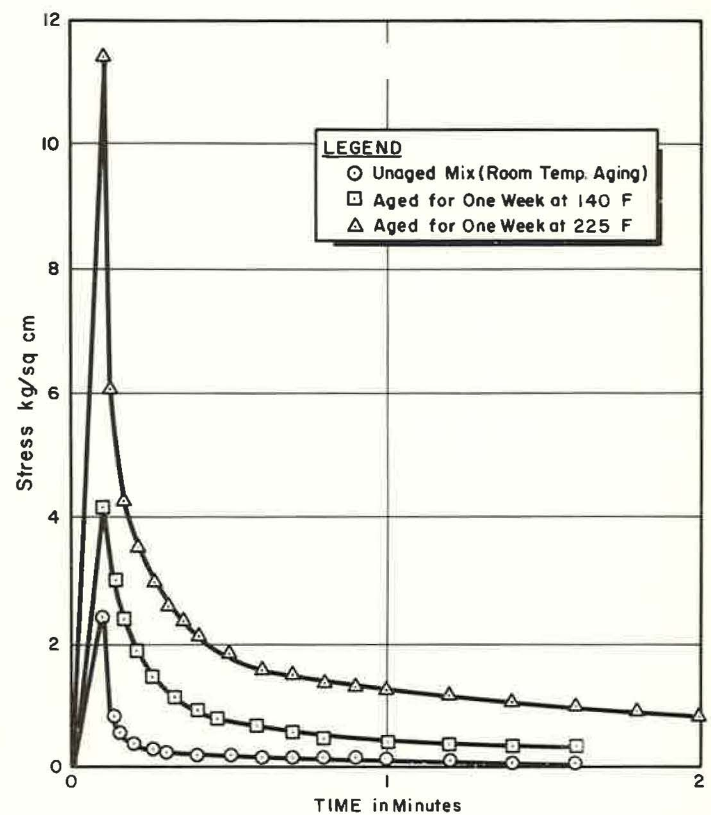

Figure 5. Stress relaxation curves, 12 percent asphalt content.

TABLE 7

RELAXATION TESTS, 9 PERCENT A/C MIXTURES

Specimen A-9-1				Specimen B-9-1				Specimen C-9-1							
Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R}(t)$ (kg/sq cm)	Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R}(t)$ (kg/sq cm)	Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R}(t)$ (kg/sq cm)	Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R}(t)$ (kg/sq cm)
0.1	115	11.95	870	0.1	145	15.1	1100	0	0	0	-	-	-	-	-
0.12	62	6.44	470	0.12	80	8.3	606	0.1	310	32.2	2340	1.2	72	7.5	545
0.13	52	5.4	3.94	0.14	65	6.75	492	0.12	225	23.4	1700	1.4	68	7.09	515
0.16	49	5.1	3.21	0.20	50	5.2	380	0.14	190	19.7	1440	1.6	65	6.75	492
0.18	46	4.8	348	0.25	43	4.46	326	0.16	170	17.7	1290	1.8	63	6.55	476
0.20	40	4.15	303	0.30	38	3.94	288	0.18	155	16.1	1170	2.0	60.2	6.27	456
0.25	35	3.64	265	0.35	35	3.63	266	0.20	150	15.6	1135	2.5	57.8	6.0	438
0.30	31	3.22	235	0.40	32	3.32	242	0.25	130	13.5	985	3.0	53	5.5	400
0.35	28.5	2.95	216	0.45	30.2	3.14	229	0.30	120	12.5	910	3.5	50	5.2	380
0.40	26	2.7	197	0.50	28.5	2.96	218	0.35	112	11.5	850	4.0	48	5.0	364
0.50	23	2.4	174	0.60	26	2.7	197	0.40	106	11.0	803	4.5	46	4.8	350
0.60	21	2.18	159	0.7	24	2.5	182	0.45	102	10.1	774	5.0	44.2	4.57	335
0.70	19	1.97	144	0.8	22.5	2.34	170	0.50	98	10.0	743	5.5	43	4.47	326
0.80	18	1.87	136	1.0	20.4	2.12	154.5	0.60	91	9.45	690	6.0	42	-	318
0.90	16.8	1.74	127	1.2	18.6	1.94	141	0.70	86	8.94	650	6.5	41	-	310
1.0	15.8	1.64	120	1.4	17.4	1.80	132	0.80	82	8.52	620				
1.2	14.4	1.5	109	1.6	16.4	1.7	124	0.90	80	8.31	606				
1.4	13.3	1.38	101	1.8	15.4	1.6	116.5	1.0	76.5	7.95	580				
1.6	12.3	1.28	93	2.0	14.5	1.5	105								
1.8	11.6	1.20	88	2.5	13.2	1.37	95.5								
2.0	11.0	1.14	83.4	3.0	12.1	1.26	89								
2.5	9.8	1.00	74.2	3.5	11.4	1.18	82								
3.0	9.0	0.935	68	4.0	10.7	1.11	78								
4.0	7.8	0.81	59	4.5	10.1	1.05	73								

TABLE 8

RELAXATION TESTS, 12 PERCENT A/C MIXTURES

Specimen A-12-4				Specimen B-12-3				Specimen C-12-3							
Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R(t)}$ (kg/sq cm)	Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R(t)}$ (kg/sq cm)	Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R(t)}$ (kg/sq cm)	Time (min)	Load (kg)	Stress (kg/sq cm)	$E_{R(t)}$ (kg/sq cm)
0	0	0	-	0	0	0	-	0	0	0	-	1.2	10.8	1.12	82
0.1	23	2.39	166.8	0.1	40	4.16	303	0.1	110	11.4	834	1.4	9.9	1.04	75
0.12	8	0.82	58	0.12	35	3.54	267	0.12	58	6.02	438	1.6	9.2	0.95	69.7
0.14	6	0.624	43.4	0.14	29	3.02	220	0.14	47	4.89	356	1.8	8.6	0.89	65
0.16	5	0.52	36.2	0.16	23	2.39	174.2	0.16	41	4.26	310	2.0	8.2	0.85	62
0.18	4.4	0.457	31.9	0.18	20	2.08	151.3	0.18	37	3.85	280	2.5	7.2	0.75	54.5
0.20	3.6	0.374	26.4	0.20	18	1.87	136.2	0.20	33.5	3.5	255	3.0	6.5	0.68	49.2
0.25	2.8	0.29	20.2	0.25	14	1.45	106	0.25	28.3	2.95	214	3.5	6.0	0.624	45.4
0.30	2.3	0.24	17.4	0.30	11.5	1.2	87.1	0.30	25	2.6	189	4.0	5.6	0.58	42.4
0.35	2.0	0.208	15.1	0.35	10	1.04	75.6	0.35	22.5	2.35	170	4.5	5.2	0.54	39.4
0.40	1.8	0.187	13.6	0.40	9	0.93	68.2	0.40	20.5	2.14	155	5.0	4.9	0.50	22
0.45	1.6	0.166	12.6	0.50	7.5	0.78	56.8	0.45	19.2	1.98	145	5.5	4.6	0.47	19.7
0.5	1.4	0.145	10.6	0.60	6.4	0.66	48.4	0.5	18.0	1.87	136	6.0	4.4	0.45	18.1
0.6	1.22	0.127	9.24	0.70	5.5	0.57	41.6	0.6	16.2	1.6	122				
0.7	1.1	0.114	8.34	0.80	5.0	0.52	37.9	0.7	14.8	1.54	112				
0.8	1.0	0.104	7.57	0.90	4.5	0.47	34.1	0.8	13.6	1.40	103				
0.9	0.9	0.094	6.8	1.0	4.3	0.45	32.6	0.9	12.8	1.34	96.8				
1.0	0.82	0.085	6.2	1.2	3.7	0.39	28	1.0	12.0	1.25	91				
1.2	0.7	0.073	5.3	1.4	3.3	0.34	25								
1.4	0.65	0.068	4.92	1.6	3.0	0.31	22.7								
1.6	0.53	0.055	4.01	1.8	2.8	0.29	21.2								
1.8	0.51	0.053	3.96	2.0	2.5	0.26	18.9								
2.0	0.49	0.051	3.7	2.2	2.4	0.25	18.2								

TABLE 9

MODEL CONSTANTS[a]

Specimen	Asphalt	Condition	G_1 (kg/sq cm)	G_2 (kg/sq cm)	η_1 (kg-sec/sq cm)	η_2 (kg-sec/sq cm)
A-9	9	A	4,330	1,040	1.01×10^5	3.4×10^4
B-9	9	B	2,370	1,530	1.43×10^5	8.2×10^4
C-9	9	C	1,530	3,080	1.82×10^6	19.4×10^4
A-12	12	A	1,300	346	6.63×10^3	5.32×10^3
B-12	12	B	472	371	6.73×10^3	7.41×10^3
C-12	12	C	193	520	1.92×10^4	1.80×10^4
A-15	15	A	140	158	9.63×10^3	1.30×10^3
B-15	15	B	140	141	6.86×10^3	0.554×10^3
C-15	15	C	114	169	1.39×10^4	1.06×10^3

[a]For curves shown only.

TABLE 10

MIXTURE VISCOSITY

Specimen	Load (kg)	Slope of Curve ($\times 10^{-6}$)	Mixture Viscosity ($\times 10^6$ kg-sec/sq cm)	Average ($\times 10^6$ kg-sec/sq cm)
A-9-1	20	30	0.67	
A-9-3	50	29	1.7	1.14
B-9-1	20	5.16	3.87	
B-9-2	50	23.2	2.16	3.01
C-9-1	20	1.13	17.8	
C-9-4	50	2.86	16.9	17.4
A-12-1	5	73.6	0.068	
A-12-2	10	930	0.1075	
A-12-3	20	242	0.082	0.085
B-12-1	5	41.6	0.12	
B-12-2	20	18.8	0.106	0.113
C-12-1	5	14	0.357	
C-12-2	10	3.4	2.94	
C-12-3	20	1.47	1.36	2.15
A-15-1	5	1.36	0.037	
A-15-2	10	310	0.032	0.035
B-15-1	2.5	25.4	0.099	
B-15-2	5	46.2	0.082	
B-15-3	10	120	0.108	0.093
C-15-1	2.5	24	0.111	
C-15-2	5	37.5	0.133	
C-15-3	10	95.0	0.103	0.116

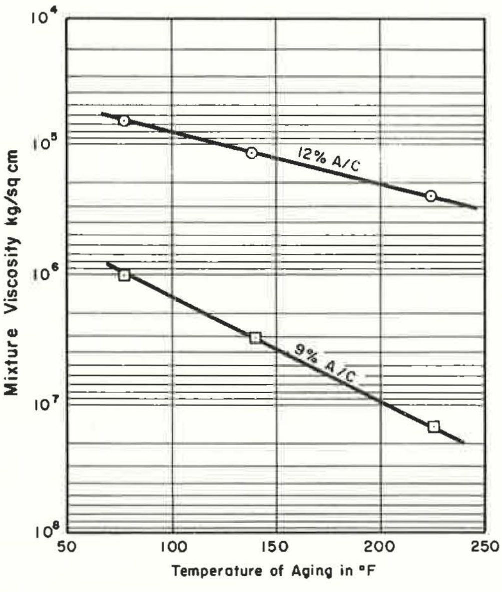

Figure 6. Log mixture viscosity vs temperature of aging.

system is used. On the whole, because of the practical difficulty of finding the correct value of rebound, it does not seem that the modulus of recovery could be used as a practical parameter for aging measurements.

The mixture viscosity values obtained showed a more promising trend. It is clear from the results given in Table 10 that mixture viscosity increases with the degree of aging. This seems a more reliable parameter, easier to measure and to control. With the limited range of values obtained in this experiment, it is not possible to say categorically what sort of relation can be evolved relating the mixture viscosity to the degree of aging. However, the observed data appear to indicate that a semilog relationship exists. The log V vs temperature generated a straight line (Fig. 6) which results in the following relation:

$$V = e^{kT_A} \tag{9}$$

where T_A is aging temperature, and k = a constant which varies with percent asphalt in mix. To confirm the existence of such a relationship, which could be of great use in the study of mixes, more experiments would be necessary.

To obtain a reliable value of V, great care must be exercised in selecting loading cycles to insure consistency. As the sample is loaded and unloaded several times,

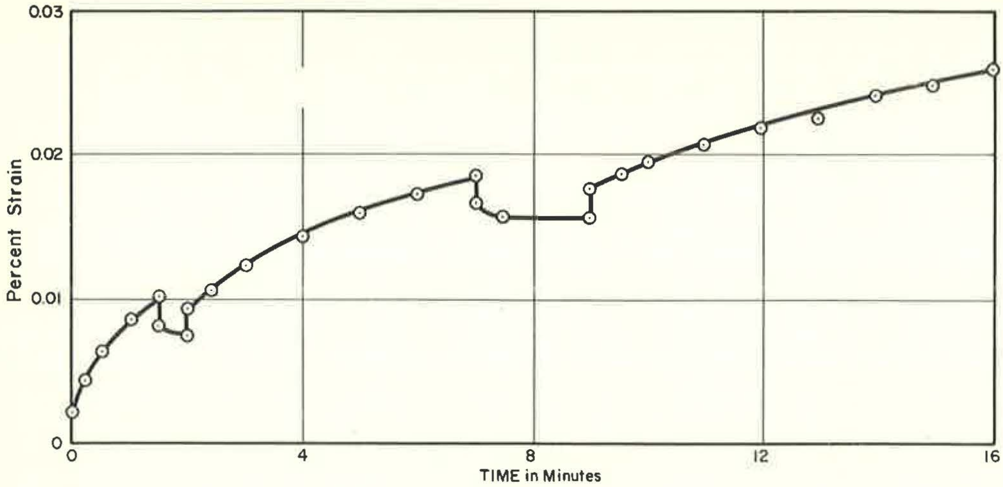

Figure 7. Effect of repeated loading on creep, 15 percent A/C, 2½ kg (0.263 kg/sq cm) load.

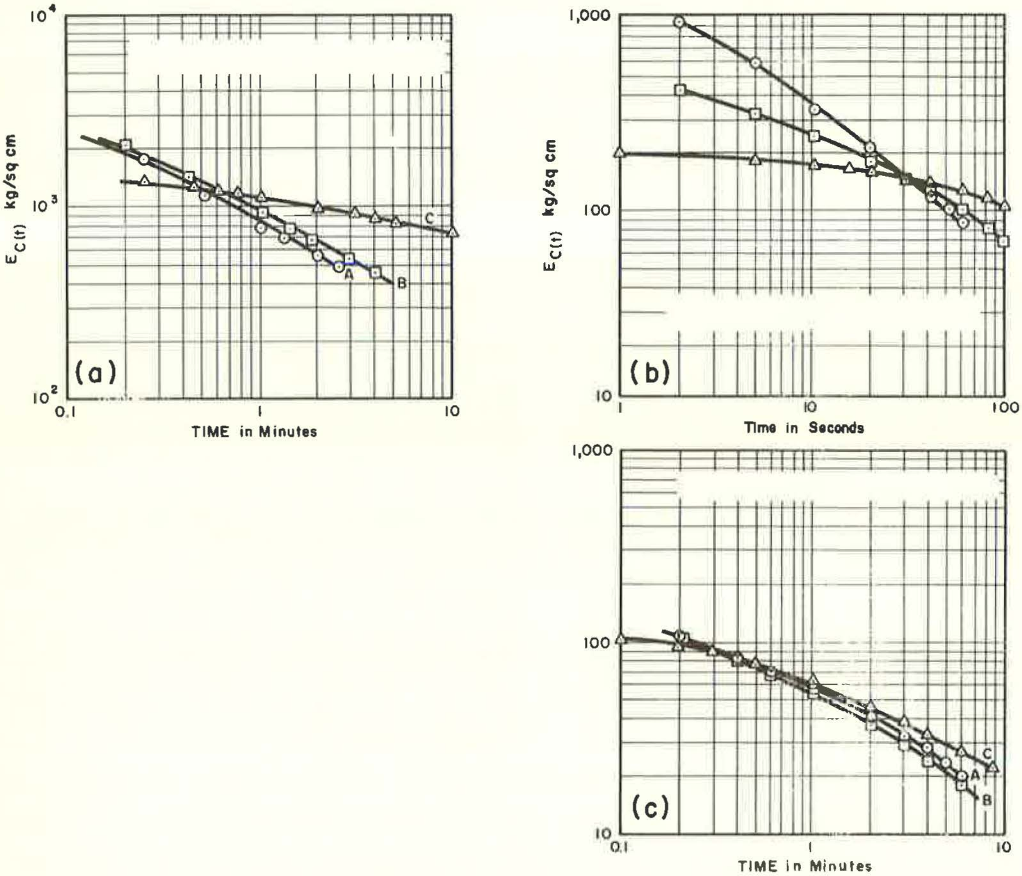

Figure 8. Log-log plots of creep modulus vs time: (a) 9 percent A/C, 50 kg (5.2 kg/sq cm) load; (b) 12 percent A/C, 5 kg (0.52 kg/sq cm) load; and (c) 15 percent A/C, 2½ kg (0.263 kg/sq cm) load.

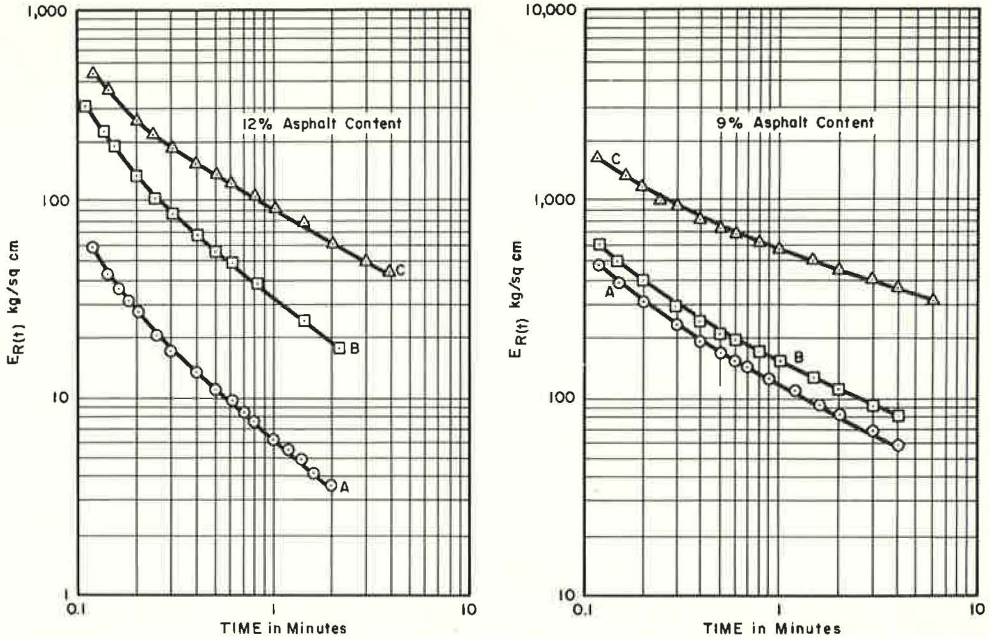

Figure 9. Log-log plot of relaxation modulus vs time.

the slope of the creep curves progressively decreases as shown in Figure 7. It is necessary, therefore, to select the same load cycle for all the specimens before evolving values. The decrease in the slope of the creep curve provides further evidence that the viscoelastic behavior of the asphalt mixture may not be exactly linear. This decrease in the rate of creep with repeated load may be caused by stiffening of the mixes due to densification of specimens.

A plot was made of the log of creep modulus vs the log of time (Fig. 8). Although no obvious trend was noticed in these curves, future results may indicate one.

The relaxation curves in Figures 4 and 5 again show differences due to aging. These curves, like the creep curves, also showed that for the duration of aging employed, the 140 F aging temperature did not alter the viscoelastic characteristic of material significantly, whereas aging at 225 F changed this behavior considerably. A plot of relaxation modulus vs log of time did not produce a straight line, thus indicating that the relaxation behavior of these asphaltic mixtures may be that of a complex model.

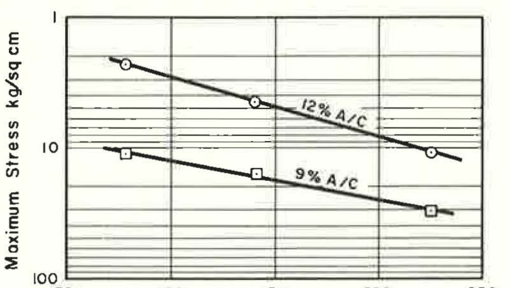

Figure 10. Log maximum relaxation stress vs aging temperature.

A plot of the log of relaxation modulus vs log of time shown in Figure 9 exhibits marked curvature which again indicates that a simple viscoelastic model may not be representative of the mixtures used.

An investigation was made of the possible existence of a relation between the degree of aging and the maximum relaxation stress attained by the material for the 1-mm deformation of 1.42 percent strain. It appears that a semilog relation is possible and that a relationship of the form, $P_R = e^{bT_R}$, might be possible where P_R is maximum relaxation stress, T_R is temperature of aging in degrees Fahrenheit and b is a constant (Fig. 10). This relation, if it exists, could also be useful in studying the effect of aging on mechanical properties of asphaltic mixtures. It is difficult to confirm definitely the existence of this relation with the limited data obtained. The relationship, however, would be much easier to measure than the other parameters mentioned earlier if the right equipment were used.

CONCLUSION

The results of this study appear to justify the following conclusions. It should be realized that these conclusions are applicable only to the particular kinds of mixtures used in this investigation. Within the limitations of the tests performed and the data obtained, it would seem that:

1. Aging does affect the creep and relaxation characteristics of the mixtures studied;
2. Aging reduces the rate of creep of the mix, resulting in a harder mix with a higher elastic response and a lower viscous component;
3. Within the range of the materials studied and the procedures used in this study, there appears to be a certain relationship between mixture viscosity and aging temperature, and a maximum relaxation stress and aging temperature; and
4. The creep modulus did not seem to indicate any significant relation with aging, but the relaxation modulus showed a more significant variation with the degree of aging.

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