Modes of Failure and Strength of Asphalt Films Subjected to Tensile Stresses

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The primary purpose of this investigation was to study the behavior of thin films of asphalts subjected to tensile stresses. A number of theories that might explain the behavior of asphalts or similar materials in thin films are reviewed and the advantages and disadvantages of each theory are discussed. To verify the hypotheses and theories related to tensile properties of asphalts, laboratory experiments were conducted on thin asphalt films under controlled test conditions. The variables studied, selected on the basis of theoretical consideration, were film thickness, rate of extension, temperature, and size of specimen.

The failure of mechanism of asphalt films can be placed in three categories—brittle fracture, tensile rupture, and shear flow—all of which are influenced by the variables studied. Equations are presented for predicting the limiting value of the film thickness corresponding to each type of failure. A hypothesis is also developed that explains this failure mechanism and the behavior of asphalts over a wide range of film thicknesses. It is also shown that two theories—the hydrodynamic theory and the theory of potential energy and cavities—could be used to predict the tensile strength of asphalts in thick and thin films, respectively.

•CRACKING and subsequent failure of bituminous surfaces can often be attributed to excessive tensile stresses induced in pavements by various causes. As a result of the bending of pavements under wheel loads, tensile stresses are developed depending on the relative positions of the load and the point of the pavement under consideration. Tensile stresses may also be developed in certain types of bituminous surfaces, such as surface treatments, as a result of the forward motion of the wheel which tends to dislodge the aggregates from the surface. Also, the nonuniform deformation of underlying surfaces often contributes substantially to these stresses. When these tensile stresses exceed the tensile strength of the asphalt present in thin films between the aggregates, the pavement will fail.

Failure of bituminous mixtures, which depends on the rheological behavior of asphalt, is due not only to simple tension or to simple shear alone, but also depends on the behavior of asphalt subjected to combined stresses. Thus, an understanding of the mechanism of failure and the rheological behavior of the material in simple tension, as well as in simple shear, is required for the final evaluation of any mix design. In turn, the rheological behavior of asphalts under tensile stresses is affected by many factors, including the rate of loading, temperature, and the thickness of the film separating the particles of the aggregate. Because the thickness of asphalt films is influenced by many factors and is expected to be variable in pavements, the strength of the mixture could be better predicted if the behavior of the material were known over a wide range of thicknesses.

Although asphalt is extensively used as a binder for many types of bituminous surfaces, some basic information concerning its behavior and its suitability for each type

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of pavement is not yet available. A thorough investigation of tensile properties of asphalts in thin films should provide a part of the information required for predicting the behavior of binder in pavements. Such a study should lead to a better understanding of the behavior of asphalts in pavements and eventually to the development of a theoretical method of design.

STATE OF PRESENT KNOWLEDGE

Present knowledge of the tensile properties of asphalts in thin films is limited to studies conducted by Mack (18) and Wood (29, 30). These investigators have conducted a limited but worthwhile study of the behavior of thin films of asphalts under tensile stresses. However, the knowledge of similar behavior of other materials in thin films might be of significant value for obtaining more information about the theoretical behavior of asphalts. Extensive literature exists on the subject of adhesives and other materials. Thin films of asphalts subjected to tensile stresses should behave in a similar manner. Accordingly, a number of theories that might be applicable to asphalts have been investigated to determine if they explain the behavior of this material in thin films.

Strength-Thickness Rule

The "strength-thickness" rule which indicates the dependence of the tensile strength of materials on the magnitude of the film thickness, when tested in thin films, is well established. According to this rule, the tensile strength of thin films of a material, when tested in tension, increases as the thickness of the film decreases. Extensive experimental evidence is available to support the existence of such a rule in liquids, as well as in solids. In liquids, the theoretical and experimental works of Stefan (27) and Reynolds (24) with Newtonian liquid support the existence of such a relationship between strength and film thickness. Their research was later used for the study of non-Newtonian liquids. In solids, the tensile tests carried out by Crow (10) on soldered butt joints between copper rods indicate that the tensile strength increases very rapidly as the film thickness decreases. The existence of such a strength-thickness rule has also been confirmed for many different kinds of adhesives by McBain and Lee (19), Dietz (11), and Meissner and Bauldauf (21), Koehn (15) and other investigators.

Thus, according to the strength-thickness rule, the tensile strength of asphalt in thin films might be expected to vary with the film thickness. The result of investigations by Mack (18) indicates that the tensile strength of asphalts, when plotted on logarithmic scales, increases linearly to a maximum and then decreases as the film thickness continually decreases. On an arithmetic scale this relationship would be in the form of a curve that increases, levels off, and then decreases as the film thickness increases. The experiments on thin films of asphalts conducted by Wood (29, 30) indicate that tensile strength decreases rapidly as the film thickness increases and then eventually levels off with little change in the tensile strength at a film thickness of 200 μ.

A controversial point in the tensile strength-film thickness relationship is the existence of an optimum film thickness. The theoretical and experimental works of Mack (18) indicate the existence of a definite optimum film thickness in the very thin film range. This optimum film thickness varies with the type of asphalt, the viscosity and the temperature. According to this investigator, the theoretical explanation for the optimum film thickness is based on the energy requirement for breaking the bonds between the asphalt molecules. This optimum film thickness is reported to vary from 25 to 50 μ for different types of asphalts. Koehn (15) has reasoned differently as a result of his observations concerning the decrease of tensile strength in the region of very thin films. According to his explanation, the decrease of tensile strength of adhesives at a thickness of almost 10 μ is merely dependent on the lack of uniformity of the films. The presence of gaps or voids in the film or the metal-to-metal contact at the high points of the surface results in reduction of contact area. This could also cause stress concentration in the film. However, the result of an investigation by Wood (29, 30), who has tested asphalt films as thin as 10 μ, does not show that there is any optimum point in the film thickness.

Theories Explaining Strength-Thickness Rule

Many different thoughts and theories have been suggested to explain the strength-thickness relationship of asphalts and other materials in thin films which behave similarly under tensile stresses. These theories, ranging from a purely mathematical expression to simply an expression of thoughts, have failed to explain the behavior of these materials in the entire range of film thicknesses. Most of these theories have not yet been widely accepted and the usefulness of such theories has remained controversial. The most common of these theories are discussed subsequently.

Hydrodynamic Theory.—The strength-thickness relationship of materials tested in tension can be explained to some extent by the hydrodynamic theory, one of the first theories developed to explain the behavior of materials in thin films (21, 22, 24, 27). According to this theory, the flow behavior of thin layers of viscous materials, placed between two parallel plates and subjected to a pull, varies with the thickness of the layer. As the film thickness decreases, a larger stress is required to deform the material to a certain value. Furthermore, when a layer of Newtonian or non-Newtonian liquid is subjected to tension, in addition to deforming in the direction of the applied stress, it flows horizontally between the two parallel plates. In other words, horizontal shear forces are present (22). Because the inward movement of the material in contact with the two plates is prevented, the theory assumes that the flow perpendicular to the direction of the applied stress at any other plane is a parabolic function of the distance between the two plates. Therefore, the inward velocity of the flow, which is a parabolic function of the film thickness, is considerably smaller in the thinner films.

Because the reduction of deformation and flow is the basis of this theory, the hydrodynamic theory could be also named after the mechanism on which it is based. The theories of "restraint of deformation" or "reduction of plastic flow," which are encountered in the literature, are principally the same as the hydrodynamic theory (8, 14, 21, 26).

The hydrodynamic theory is credited to the experimental and theoretical works of Stefan (27) who measured the force necessary to separate, at a given rate, two circular glass disks immersed in a liquid. The mathematical derivation of this theory, which is rather difficult in Stefan's paper, has been simplified by Bikerman (4). For two parallel plates with radius of R, which are completely immersed in a Newtonian liquid with the viscosity equal to η, the relationship between the applied force, F, and the film thickness, H, can be written as follows:

$$F = \frac{dh}{dt} \frac{3\eta\pi R^4}{2H^3} \quad (1)$$

If the two parallel plates are not immersed in the liquid, and the volume of material does not exceed the volume between the two plates, Eq. 1 can be written as follows:

$$F = \frac{dh}{dt} \frac{3V^2\eta}{2\pi} \frac{1}{H^5} \quad (2)$$

in which V is the volume of material confined between two parallel plates.

Because Eq. 2 does not properly indicate the flow properties of non-Newtonian liquids, Scott (25) has developed a general formula for this class of materials. The flow of a non-Newtonian liquid that follows de Waele-Ostwald's law can be expressed by

$$\dot{\gamma} = \tau^n / K$$

in which n is a constant of the material and $\dot{\gamma}$ and τ are rate of shear and shear stress, respectively. The term K is related to the viscosity of the material. When n = 1, the material is Newtonian liquid and K is equal to viscosity, η. Eq. 3 is Scott's formula derived for these materials. In this equation, the sign of the applied load has been reversed in order to be applicable to tensile forces rather than compressive forces.

$$F^n = \frac{dh}{dt} \frac{(2n)^n K \quad (n+2)V^{\frac{3n+1}{2}}}{(3n+1)^n \quad \pi^{\frac{n+1}{2}}} \frac{1}{H^{\frac{(5n+5)}{2}}} \tag{3}$$

The basic equations thus obtained are adaptable to tests performed with different forms of loading. Strasburger (28) has used such a basic formula for the tests run by the constant velocity of separation. In this case, the term dh/dt in Eqs. 2 or 3 is a constant and is equal to the rate of extension set for the testing machine. In the same equations, it is deduced that

$$H = H_o + t\dot{\delta}$$

in which

H_o = initial thickness of material;

$t\dot{\delta}$ = Δh, the amount of deformation in t seconds of testing;

$\dot{\delta}$ = rate of extension; and

t = time of testing (sec).

Therefore, in a test run with a constant rate of extension, the only unknowns in Eqs. 2 or 3 would be t and F. Given the time of testing, t, the tensile force acting on the material is easily obtained.

The maximum tensile force that can be applied before the film fails is also easily obtained from these equations. So that this might be done, the amount of deformation of the film at the moment of failure ($t\dot{\delta} = \Delta h$) should be inserted in the equations. Moreover, in Eqs. 2 and 3 it is observed that the tensile strength is inversely related to the film thickness. When the film thickness decreases, a higher tensile force is required for the failure of the film. Furthermore, it is indicated that the type of material, viscosity, and rate of loading significantly influence the tensile strength of the film.

Limitations of Theory.—As stated previously, the hydrodynamic theory was founded on the assumption that a material flows slowly between two parallel plates when they are pulled apart. Flow may be considered to be a failure in shear. It is known that horizontal flow occurs as a result of a pressure difference built up in the material by application of external load. However, if the pressure difference is relieved by presence of cavities or air channels, the theory is no longer valid (6). Moreover, if, during the separation of the plates, the material forms into filaments or a number of threads and cavitation results, this theory would be invalid for the remainder of the experiment (2, 12).

Another limitation placed on the theory is Stefan's assumption concerning the rate of loading. For slow rates of loading, according to fundamental assumptions, materials flow laminarly and give way in shear. However, for rapid rates of loading the films rupture without any appreciable flow. The occurrence of a rupture in the film indicates that the failure is governed by tensile rather than shear flow alone. Because the viscous resistance increases with an increase in the rate of load application (23), the flow and deformation of the material between the parallel plates is considerably reduced in a fast rate of loading. Thus, for rapid rates of loading, the work required to cause the flow of liquid by overcoming the viscous resistance is much greater than the work required to form two new surfaces (work of cohesion) (1). In this case, the failure occurs in tension and the theory is no longer valid.

The viscosity of material pulled between the parallel plates also limits the application of this theory. The influence of viscosity on flow properties of the material is the same as the effect of the rate of loading; i.e., the higher the viscosity of the material, the greater would be the restraint of deformation and flow. Bikerman (6) observed that material with intermediate range viscosities does not flow toward the axis of the whole system, as is predicted by the theory. Rather, it flows toward many centers spread all over the film. At further separation of the plates, filaments or threads start from these points. Bikerman's observation simply proves that the failure of the material is due more to tensile stresses than to shear stresses. As previously stated, this would happen when the flow is restrained by extremely viscous resistance of the material.

The applicability of hydrodynamic theory depends not only on the viscosity of the material or the rate of the loading, but also on the thickness of the material. Because according to this theory, the velocity of flow in the horizontal direction is a parabolic function of the film thickness, the flow in thin films is considerably less than in thick ones. In thin films, where the material is more restrained from the flow, tensile stresses are developed and failure occurs in tension (22). The experiments conducted by Bikerman (5) on an asphalt film of 1 μ thickness indicate that failure occurred by rupture at a much smaller load than predicted by the theory. Of course, his experimental result is also influenced by the viscosity of the asphalt.

It should be stated that the foregoing discussion on the applicability of the hydrodynamic theory in thin films holds true only for the case of testing in tension.

Theory of Potential Energy and Cavities.—According to this theory, when a material fails in pure tension, the strength is partly a function of secondary valence forces between adjacent molecules (18). Because with an increase in distance between molecules the repulsive forces diminish more rapidly than attractive forces, the attractive forces would primarily govern the strength of the material. The energy associated with attractive forces is inversely proportional to the sixth power of the distance between the adjacent molecules (17). Tensile rupture, however, occurs in the material when the applied force equals the maximum force due to the potential of the secondary bonds. This theoretical strength, which is a constant of the material, depends on the degree of the packing of molecules in that material (18). Materials with closely packed molecules are characterized by molecules of low potential energy and have higher theoretical tensile strength than materials with loosely packed molecules.

To explain the strength-thickness rule of materials with this theory, the influence of cavities and orientation of molecules on theoretical strength should be considered. Mack (18) has stated that because of these cavities, the rupture stress is lower than the theoretical value and varies with the number of cavities. Because cavities are associated with an increase in volume and are dependent on the tensile strain, it can be concluded that film thickness influences the observed rupture stresses. Furthermore, the change in the orientation of molecules at different film thicknesses influences the strength-thickness relationship.

The relationship obtained between tensile strength and film thickness, according to this theory, can be expressed by the following equation:

$$\sigma = A\left(\frac{\Delta h}{H_o}\right)^{-a} \qquad (4)$$

in which

σ = tensile strength;
H_o = film thickness;
Δh = amount of deformation to failure, assumed to be constant in a given asphalt;

A = constant related to rheological properties of asphalt; and
a = constant related to composition and type of asphalt.

A similar equation can be obtained by relating the maximum stress and the strain:

$$\frac{\sigma_m}{\sigma} = \left(\frac{\epsilon}{\epsilon_m}\right)^a \qquad (5)$$

In this equation, ϵ_m is the maximum strain at the maximum stress, σ_m, and ϵ corresponds to strain at stress σ. Eq. 5 can also be written as:

$$\frac{\sigma_m}{\sigma} = \left(\frac{h_m}{h}\right)^a \qquad (6)$$

in which σ_m and h_m are maximum film strength and optimum film thickness, respectively. σ corresponds to film strength at any other film thickness, h. The constant a in these equations is positive when $h < h_m$ and negative when $h > h_m$. In the region where a is positive, the secondary bond forces are strong and probably cause orientation of the molecules. In the region where a is negative, however, the secondary bond forces diminish with increasing film thickness. The constant a is also a measure of the degree of packing of molecules in the film.

As Eqs. 4, 5 and 6 indicate, the film thickness influences the tensile strength of asphalt films. As the film thickness increases, the tensile strength increases to a maximum and then decreases with further increase in film thickness. In addition, the tensile strength and the strength-thickness relationship is affected by the electrochemical and the molecular forces in the asphalt. The constant a in those equations, as reported by Mack, varies from 1.484 for coal tar pitch to 0.253 for Venezuelan oxidized asphalt. Mack also indicates the optimum film thickness for the different materials studied varies from 25.8 to 51.4 μ.

Discussion and Limitation of Theory.—The theory of potential energy and cavities, according to Mack's deductions can be used to explain the behavior of thin films of asphalts subjected to tensile stresses. His theoretical and experimental observations indicate that when tensile strength is plotted against film thickness on a logarithmic scale, it increases linearly with film thickness up to an optimum thickness, then decreases linearly with further increase in film thickness. At this optimum film thickness, the constant a in Eqs. 4, 5 and 6 changes from positive to negative, indicating the occurrence of changes in the secondary bond forces. In films thinner than optimum, secondary bond forces are stronger and probably cause the orientation of asphalt molecules. In films thicker than optimum, the secondary bond forces diminish with an increase in film thickness.

According to the basic assumptions, this theory is applicable only when no flow occurs in the asphalt. The asphalt film behaves as a solid. It is known from the hydrodynamic theory that in very thin films where flow is restrained, the material would be subjected only to tensile stresses. Therefore, this theory might be applicable only to very thin films where, due to the restraint of flow, the shortcoming of the hydrodynamic theory is obvious. Moreover, it is assumed that the amount of deformation-to-failure (Δh) is a constant for a given asphalt.

Other Theories.—To explain the extraordinary behavior of materials in thin films, other theories such as those of oriented molecular layers, probability of flaws, and internal stresses have been suggested. The theory of oriented molecular layers (20) is based on the extent to which molecules in a liquid are oreinted when they are in contact with a solid. In thin films, the oriented layers may extend well into the material, whereas in thick films, such layers only occur in a limited depth of film. From this, it is expected that thin films would be stronger than thick ones. The theory of probability of flaws (3) relates the tensile strength of a thin film to the number of flaws in the specimen. This theory states that there is a greater chance of finding severe flaws in a thick film than in a thin film. The third theory is the theory of internal stresses (21) which suggests that internal stresses developed in the specimen are responsible for the behavior of materials in thin films.

The applicability of these theories to materials such as asphalts is limited. It is indicated that the range of surface forces of solids which affects the orientation of molecules in an asphalt film is not quite significant (7, 9, 13, 14, 16, 18). Similarly, theories of probability of flaws and internal stresses are not applicable to asphalts which by their internal viscous flow neutralize any developed stresses (8, 14, 22).

Factors Influencing Strength-Thickness Rule

Because many of the factors influencing behavior of other materials might identically affect the behavior of asphalts in thin films, a review of these is quite important. The factors listed in this section are, however, limited only to those influential factors encountered in the literature, i.e., type, viscosity, and surface tension of asphalt; type and surface roughness of adherends (materials bonded by adhesive film); specimen arrangement; shape and size of specimen; rate of loading; and temperature.

MATERIALS

The bituminous material used in this investigation was a paving grade asphalt produced by Shell Oil Company. The properties of the asphalt are as follows:

Penetration at 77 F	72
Ductility at 77 F	150 cm +
Specific gravity at 60 F	1.015
Flash point COC F	600
Spot test	Negative
Percent soluble in CCl_4	99.86
Avg. molecular wt (20 samples)	1,056

APPARATUS AND TESTING PROCEDURE

The asphalt specimens were prepared by a standardized procedure. A small amount of the asphalt was placed between two aluminum blocks of known area and weight. Test blocks were carefully cleaned with n-pentane and accurately weighed to the nearest 0.0001 g on an analytical balance. Test blocks and asphalt were gently heated to allow suitable flow to provide better adhesion and to eliminate any air bubbles which might be trapped in the asphalt. To obtain uniform film thickness, test blocks with the asphalt between them were placed under an apparatus which, by its head weight, kept the test blocks in a parallel position. After the films were formed, specimens were allowed to cool for at least one-half hour to reach room temperature. Excess asphalt was removed and the sides of the blocks were carefully cleaned with solvent. After weighing the prepared specimen, the weight of the asphalt was obtained by subtracting the weight of the test blocks from the total weight. Because the area of the blocks and the specific gravity of the asphalt were known, the thickness of the asphalt film could be calculated.

The specimens were then placed in a controlled-temperature water bath for a period of at least one-half hour to make sure that the asphalt reached the desired temperature. After this period, the specimens were placed on the testing apparatus which was surrounded by a small constant-temperature water bath.

Special apparatus was developed for use in testing the circular shape specimens arranged as butt joints. In this apparatus, cylindrical test blocks, 1 in. high and 1 in. in diameter, were used to hold the asphalt specimens. These aluminum blocks had matched surfaces machine polished, and could be screwed to two vertical rods connected to the platforms of the hydraulic machine. Special spherical head arrangements were provided for the connection of the rods to these two platforms (Fig. 1). To control the temperature of the specimens during testing, a small water bath made of Plexiglass was placed on the lower platform. To prevent leakage from the water bath, the bottom rod passing through the bottom of the bath was sealed by a rubber membrane. A microscope equipped with a measuring rectile and adjustable hairline was mounted on the lower platform (stationary platform) to measure the deformation of the film (Fig. 1).

A Riehle hydraulic testing machine with a load capacity of 60,000 lb and a calibrated accuracy of 2 lb was utilized in this investigation. All tests were carried out with a constant rate of extension ranging from 0.005 to 1.0 in./min. In addition to a strain pacer that was an integral part of the machine, an Ames dial was connected to the machine to measure the speed of testing.

EXPERIMENTAL RESULTS

To study the tensile properties of asphalts in thin films and verify the hypotheses and theories, a laboratory investigation was conducted on thin asphalt films under controlled test conditions. The variables studied were selected from the available information related to the general behavior of materials in thin films. These variables were film thickness, rate of extension and temperature. All experiments were conducted over a range of film thicknesses from 10 to 1,000 μ and by varying one factor at a time while holding the other constant. The rates of extension studied were 0.005, 0.02, 0.1, and 1.0 in./min; the temperatures used were 32 F (0 C), 68 F (20 C), 77 F (25 C), 86 F (30 C), 95 F (35 C), and 113 F (45 C).

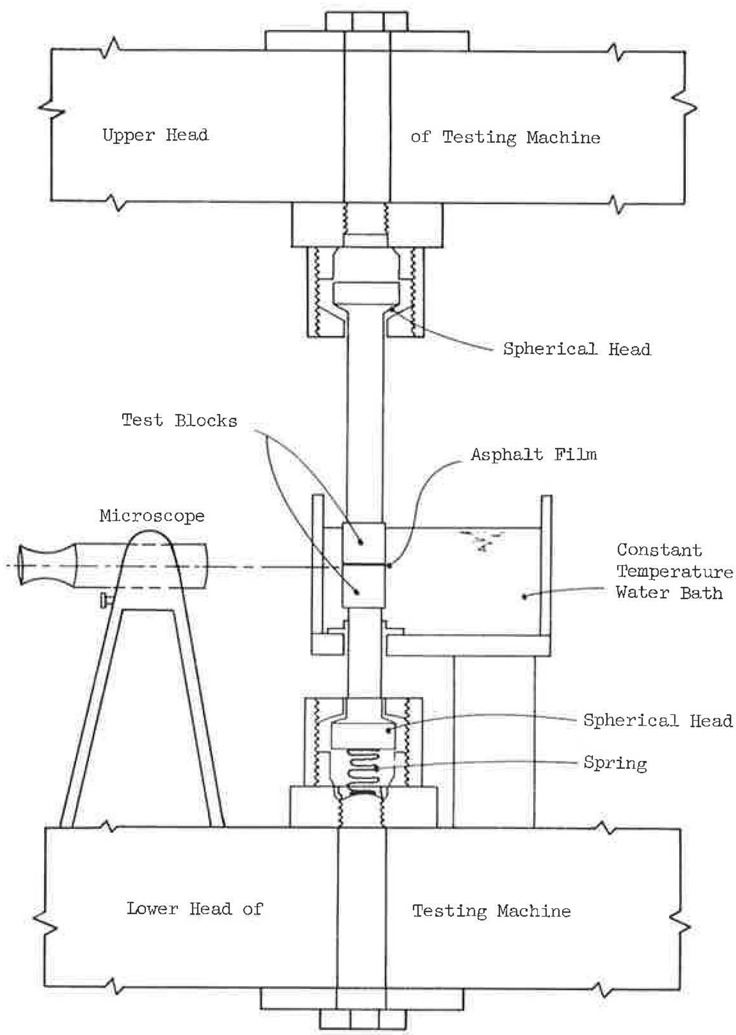

Figure 1. Schematic diagram of test apparatus for butt-type specimen arrangement.

It might appear that the consistency and type of binder were not considered as a variable in this investigation and, consequently, the conclusions would be seriously limited. The study did include these variables, but these data were not reported. The conclusions and theoretical considerations presented herein, however, were verified by the study of the different binders.

Load-Deformation Characteristics and Failure of Asphalt Films

The load-deformation characteristics of viscoelastic materials such as asphalts are known to be dependent on the rate of loading and the temperature (23). (Viscoelastic materials are those materials which, under various conditions, will act both elastically and plastically. The load-deformation characteristics of these materials are time dependent.) However, when the material is tested in thin films, the load-deformation characteristics, as indicated by laboratory test results, are also significantly influenced by film thickness (Figs. 2 and 3).

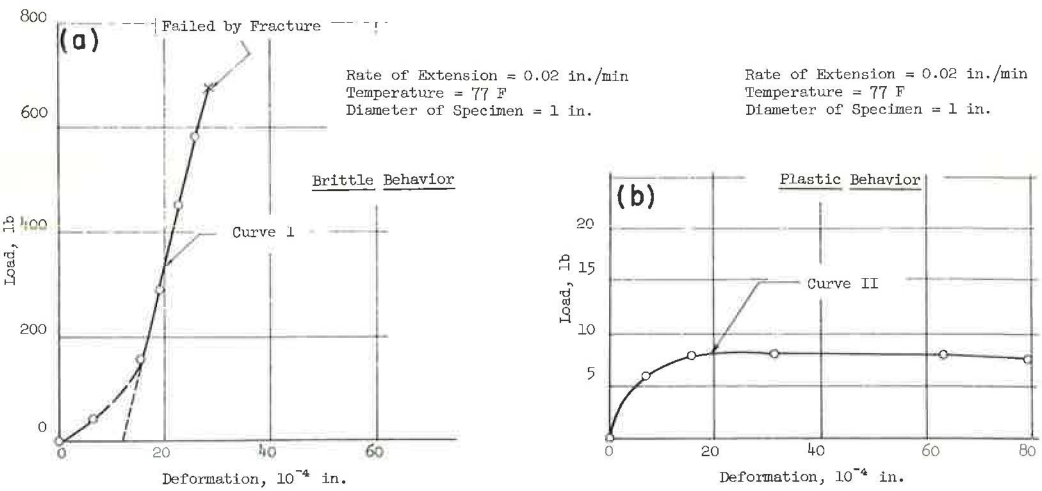

Figure 2. Typical load-deformation curves: (a) extremely thin (21.5 μ) asphalt film, and (b) extremely thick (1,490 μ) asphalt film.

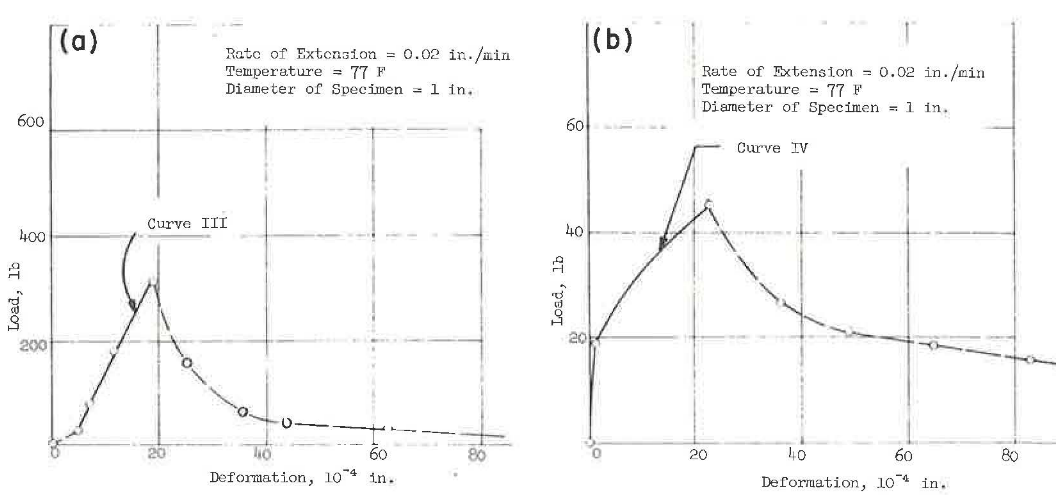

Figure 3. Typical load-deformation curves for intermediate asphalt film thicknessess: (a) 119 μ, and (b) 711 μ.

In Figure 2a, Curve I indicates that under the conditions shown, the asphalt present in a thin film (21.5 μ) behaved as a brittle material and the specimens separated instantaneously after the load reached the maximum. This type of behavior and linear load-deformation curve are characteristic of thin films of asphalt. The range of film thicknesses at which specimens fail by a brittle fracture depends on the test conditions and constitutes a "brittle" zone. The thickest film which may fail by brittle fracture is chosen as the limit of brittle fracture and is denoted by H_B.

Under identical conditions of temperature and rate of extension, asphalt behaves as a plastic material when tested in very thick films (1, 490 μ). Curve II (Fig. 2b) indicates that, in contrast to brittle films, the load-deformation curve is not linear because after the load reaches the maximum, plastic flow occurs in the specimen. This type of failure, characterized by beginning of flow and necking in the asphalt films, was observed only in thick specimens. The range of film thicknesses at which such a type of failure was observed depends on test conditions and constitutes a so-called flow zone. The thinnest film which may fail by flow is chosen as the limit of "flow condition" and is identified by the notation H_F.

In Figure 3, two other distinct types of load-deformation curves are shown. Curve III (Fig. 3a) corresponds to the load-deformation curve of a relatively thin (119 μ) film of asphalt which is slightly thicker than H_B. This curve is a typical load-deformation curve obtained for films which failed predominately by tensile rupture. The load-deformation curves of these film thicknesses were linear, and there was a rapid decrease in load after the maximum load was reached. In contrast with very thin films, no fracture occurred in the film, and the specimen, after reaching the state of failure, could still carry a reduced load. Curve IV (Fig. 3b) is a typical load-deformation curve for films slightly thicker than H_F which fail predominately by flow. The load-deformation curves of these films were no longer linear. However, the load continued to decrease gradually after reaching maximum load. The behavior of such films is in transition between the behavior shown by Curve III and that shown by Curve II. Because flow and necking also occur to some extent, in these films this transition zone has been combined with the flow zone to differentiate between the failure by flow and failure by tensile rupture. That is, films thinner than H_F fail by tensile rupture, whereas those thicker than H_F fail predominately or entirely by flow.

In types of failure shown by Curve III (Fig. 3), when the material reached the state of failure, cavitation occurred in the film due to localized failure by separation. As a result of cavitation, filaments were formed which carried a reduced load for greater deformation. Fewer cavities and filaments were observed in thicker films than in thin films. In fact, in very thick films, represented by Curve II (Fig. 2), no filaments were observed; rather, the film flowed inward and necked to a single thread which broke after a very large deformation. When the filaments formed in thin films were broken and the test blocks were completely separated, a honeycomb pattern was observed on the surface of the film (Fig. 4). The depressions seen in the honeycomb pattern are associated

Figure 4. Failed specimens.

with the cavities or the small rupture planes in the film, whereas the ridges are formed by filaments receding to the surface. The size of these honeycombs as well as the number of such impressions in the surface depends on the thickness of the specimen. In thinner films, the size of honeycombs is smaller, whereas the number of these impressions increases as the thickness decreases.

Figure 4 shows the surface pattern of films after failure and separation of the test blocks. The film of Specimen 1, tested at low temperature and a high rate of extension, failed by brittle fracture. The film of Specimen 2 failed by tensile rupture and the honeycomb pattern may be seen on the surface. Specimen 3 consisted of a thick film which failed by flow and necking.

Amount of Deformation at Failure

The amount of deformation at failure, part of the load-deformation characteristics of the asphalts, requires a separate and more detailed investigation. The theoretical information available concerning the amount of deformation to failure (18) indicates that in the very thin films such a deformation is a constant for a given asphalt. This has been attributed to the molecular attractive forces of the asphalt and to the distance that molecules should be separated before rupture occurs in the film. In this regard, the experimental data collected in this investigation indicate that some unique relationships exist between the amount of deformation at failure and the variables studied. The amount of deformation at failure (Δh) is defined as the strain at maximum load. When corrected for intial curvature of the stress-deformation curve and plotted against film thickness, Δh appears to be less scattered and linearly related to film thickness (Fig. 5). (This initial curvature at small deformations is believed to result from seating and adjustments in testing apparatus.)

In Figures 5 and 6 the amount of deformation to failure has been plotted for different temperatures and rates of extension. These figures indicate a linear relationship between the amount of deformation to failure and film thickness. Moreover, the amount of deformation at failure seems not to be significantly influenced by the variables studied. Statistical analysis of these data indicates no significant difference in the amounts of deformation. Thus, for all practical purposes, the amount of deformation at failure

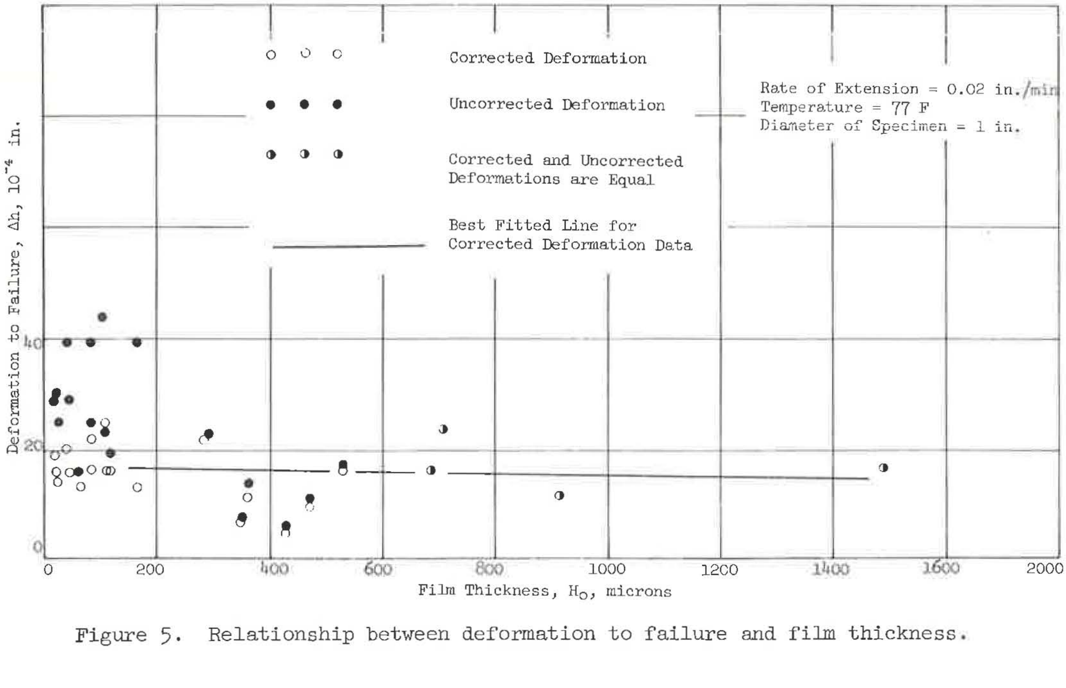

Figure 5. Relationship between deformation to failure and film thickness.

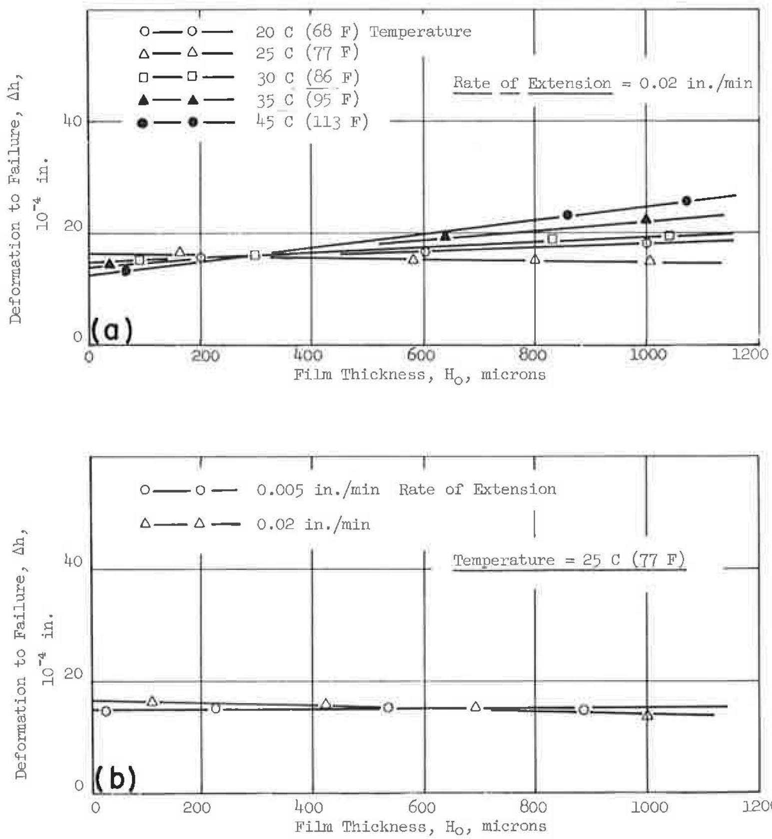

Figure 6. Calculated relationship of corrected amount of deformation to failure with film thickness: (a) effect of temperature, and (b) effect of rate of extension.

can be assumed constant regardless of film thickness, the rate of extension or the temperature.

Influence of Film Thickness on Tensile Strength

The shape of tensile strength-film thickness curves indicates a variation in the behavior of the asphalt at different film thicknesses. Figure 7, which is on an arithmetic scale, shows the relationship of tensile strength to film thickness at 77 F and 0.02 in./min rate of extension. According to this figure, the rule that "the thinner the film the higher the tensile strength" also holds true for asphalt films. In Figure 8, the same experimental data have been plotted on logarithmic scales. Lines A and B correspond to the predicted tensile strength by the hydrodynamic theory and the theory of potential energy and cavities, respectively. These lines will be discussed later. It is observed that there is a straight line relationship between the film thickness and tensile strength in the thick film range when data are plotted on these log-log scales.

When the experimental data plotted in Figure 8 are plotted on semilogarithmic scale (Fig. 9), a unique relationship is obtained. In this plot the upper curved portion of Figure 8 which corresponds to thin film range is represented by a straight line. This straight line, as will be explained later, corresponds to the range of film thickness at which failure appears to be predominately due to pure tensile stresses. The curved portion in Figure 9, however, corresponds to the thick film range where the asphalt films failed predominately by flow. Whereas behavior of thick films of asphalts can be predicted by the hydrodynamic theory, the behavior of asphalts in thin films can be

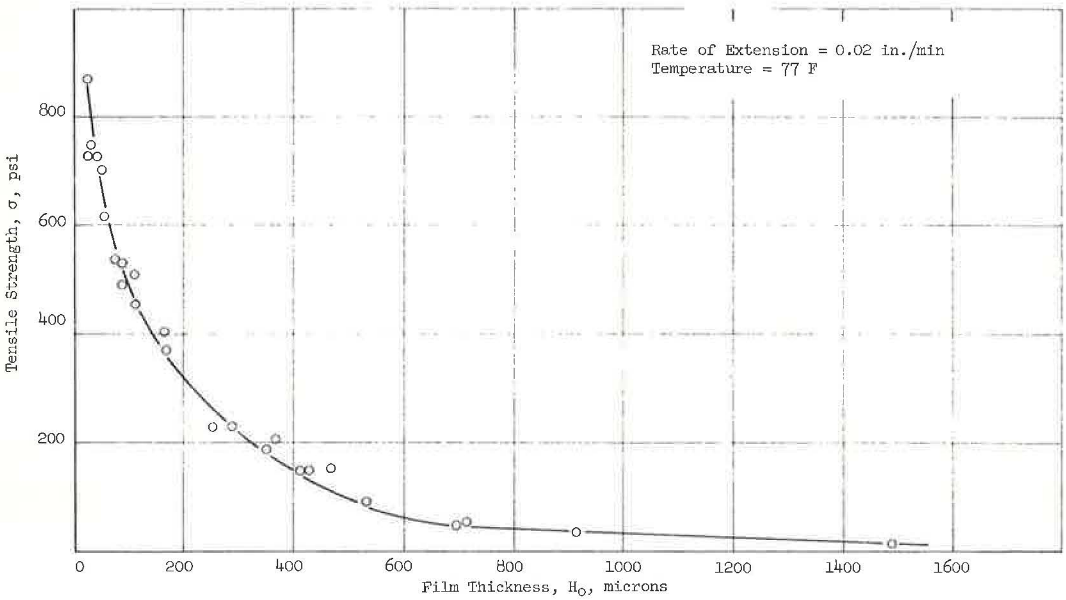

Figure 7. Influence of film thickness on tensile strength.

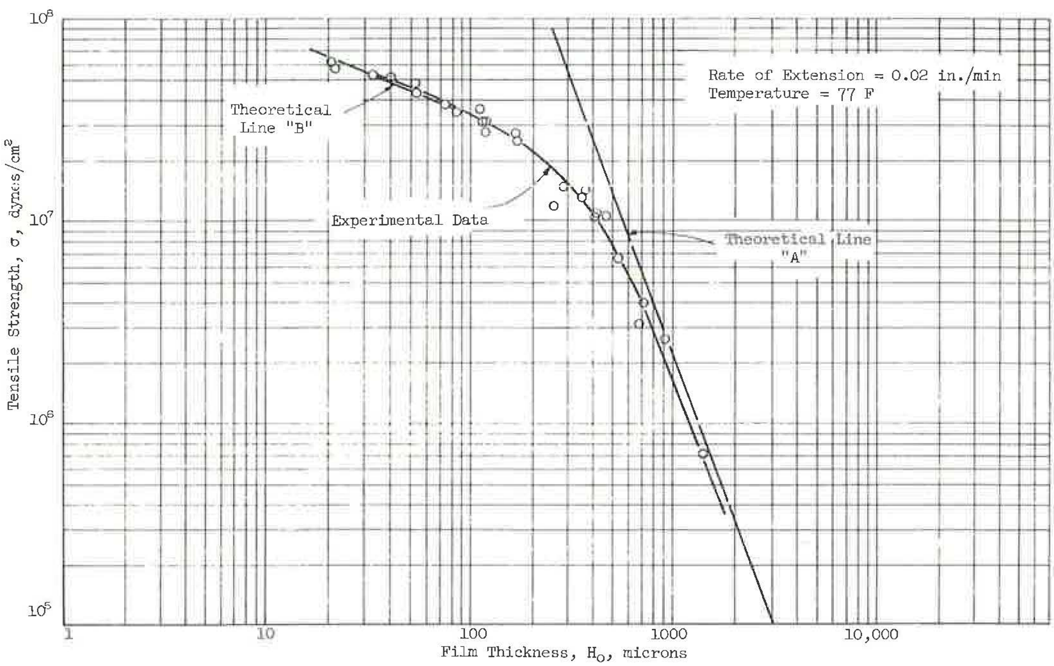

Figure 8. Influence of film thickness on tensile strength.

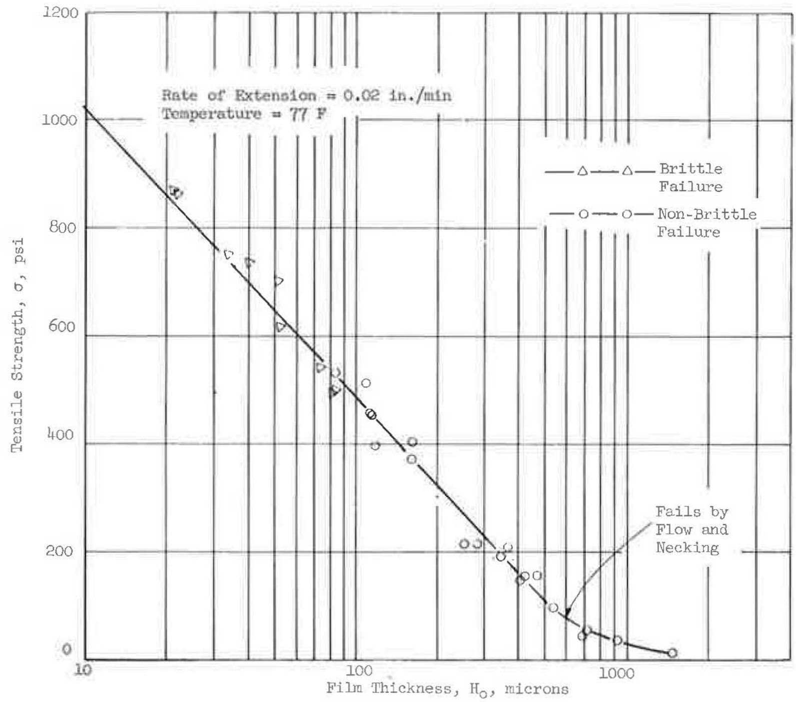

Figure 9. Influence of film thickness on tensile strength and types of failure.

predicted by a general equation derived for the straight portion of the curve on a semi-logarithmic plot. For example, the equation of the straight part of the curve in Figure 9 is:

$$\sigma = 1568.09 - 538.25 \log H_o \tag{7}$$

in which

σ = tensile strength of asphalt film (psi), and
H_o = film thickness (μ).

H_o is limited by H_F and should only be smaller than or equal to H_F.

Influence of Rate of Extension on Tensile Strength

To study the influence of rate of extension on tensile properties of asphalt films, tests were conducted with different rates of extension, varying from 0.005 to 1.0 in./min and at a temperature of 77 F. The experimental data presented in Figure 10 indicate that the tensile strength is considerably influenced by the rate of extension. The higher the rate of extension, the greater is the tensile strength. Furthermore, the straight lines representing the relationship of tensile strength to film thickness in thin films are parallel for all rates of extension. This figure shows that the limit of brittle failure zone extends to the thicker film range as the rate of extension increases. The curved portion occurring in the thick film range of the strength-thickness relationship is also shifted to the thicker film range as the rate of extension is increased.

Statistical analysis indicates that the slopes of strength-thickness relationships for thin films are parallel to each other. The equation obtained for these series of lines is as follows:

$$\sigma = 1972.4\, \dot{\delta}^{0.064} - 537.75 \log H_o \tag{8}$$

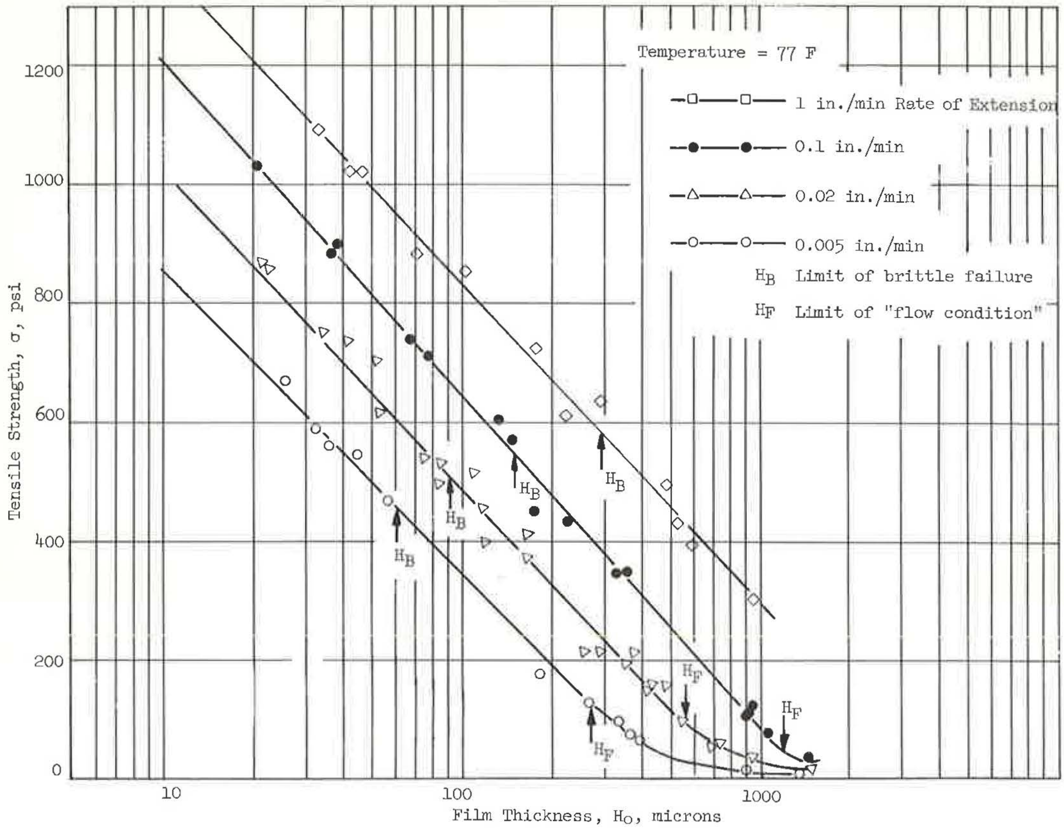

Figure 10. Influence of rate of extension on tensile strength.

in which

σ = tensile strength of asphalt in thin films (psi), and

$\dot{\delta}$ = rate of extension (in./min).

This numerical equation enables the prediction of the tensile strength of the asphalt in thin films at a temperature of 77 F. However, the general form of this equation might be used for all types of asphalts to predict the variations of tensile strength with film thickness and the rate of extension.

In Figure 10, the limit of brittle failure, H_B, and the limit of flow condition, H_F, are also plotted for different rates of extension. The asphalt in all films thinner than H_B behaves as a brittle material. All films thicker than H_F failed by flow. The film thicknesses at H_B and H_F are plotted in Figure 11. It is observed that as the rate of extension increases, H_B and H_F are shifted to the thicker film range. In this figure the lines representing H_B and H_F appear to be straight lines on a logarithmic scale.

Influence of Temperature on Tensile Strength

The effect of temperature on tensile properties of asphalt films was also studied. Tests were carried out over a temperature range of 0 to 45 C (32 to 113 F) with a constant rate of extension equal to 0.02 in./min. Figure 12 represents the relationship existing between the temperature and the tensile strength of asphalt for varying film thicknesses. Films of the same thickness have greater tensile strengths at lower temperatures. In this figure, it is also observed that the relationship existing between the tensile strength and the logarithm of film thickness is linear in the thin film range.

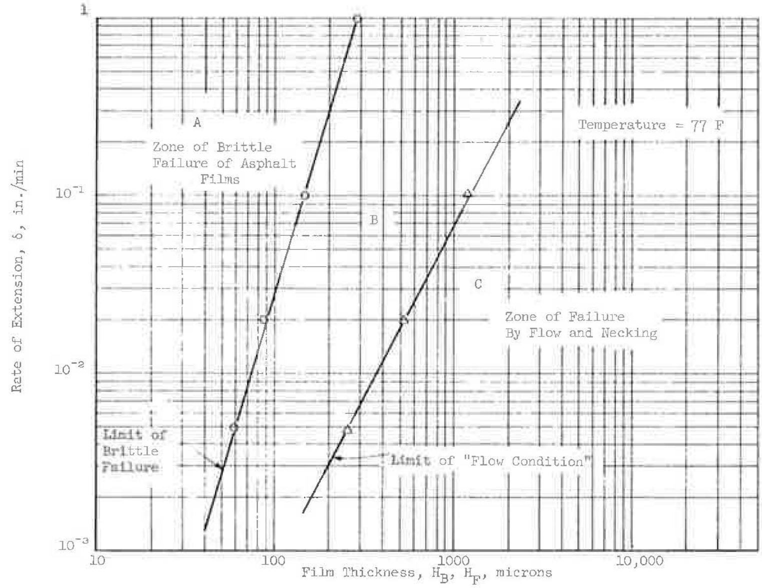

Figure 11. Influence of rate of extension on types of failure.

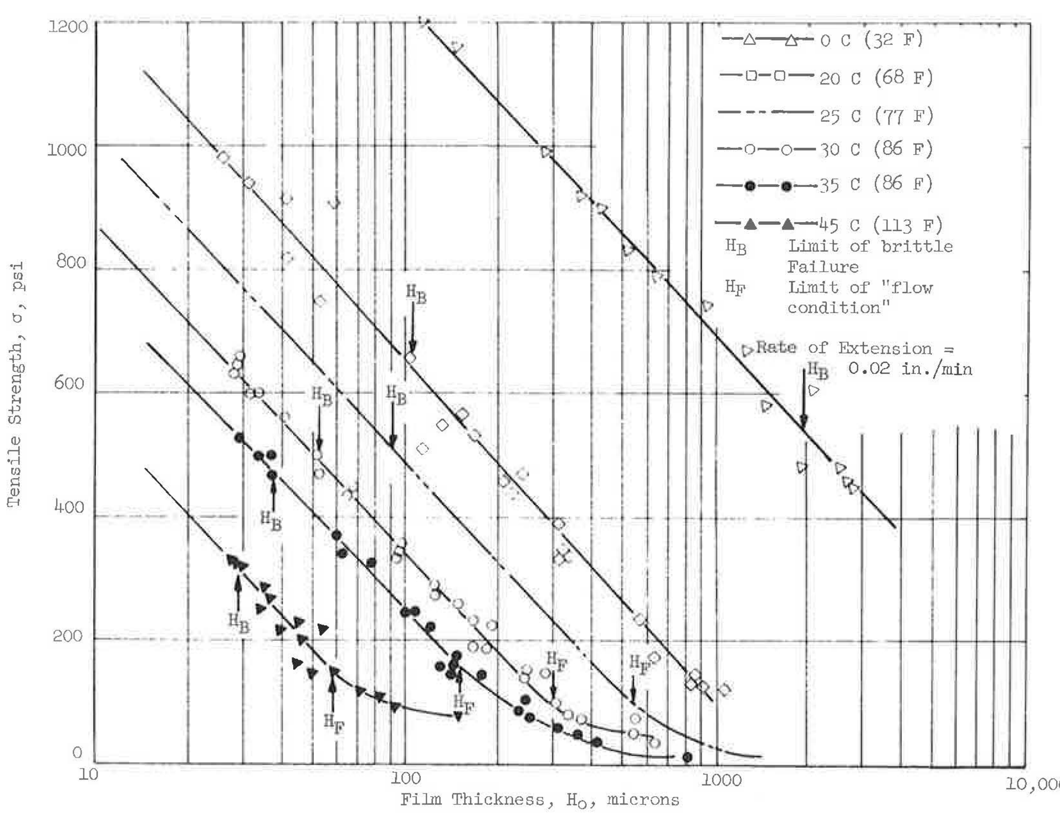

Figure 12. Influence of temperature on tensile strength.

The curved portions in the graphs corresponding to the different temperatures indicate the range of the film thickness at which the failure of asphalt is characterized by flow. The straight portion of the tensile strength-film thickness relationship corresponds to the range of film thickness at which asphalt films failed by either brittle fracture or tensile rupture. An analysis by covariance methods indicates that temperature significantly influences the location of these lines; however, the slopes of the linear portion of the lines are not affected by temperature and can be assumed equal.

In Figure 13, H_B and H_F are plotted for different temperatures. As temperature decreases, H_B is shifted to the thicker films. H_F is similarly affected by the temperature; that is, as the temperature decreases, the limit of "flow condition" extends to the thicker film range.

THEORETICAL EXPLANATION OF BEHAVIOR OF ASPHALT FILMS UNDER TENSILE STRESSES

In this section, an attempt is made to explain theoretically the behavior of asphalt films subjected to tensile stresses based on the concepts derived by the authors.

Explanation of Failure Mechanism

The experimental results clearly indicated that the failure of asphalt films subjected to tensile stresses could be placed in three distinct categories:

1. Asphalts in thick films, depending on the test conditions, behaved as a plastic material and failed by flow or shear.
2. Asphalts in thin films, depending on the test conditions, failed by brittle fracture.
3. Asphalt in intermediate film thicknesses failed by tensile ruptures which were characterized by the formation of small rupture planes (cavitation) and filaments.

The mechanism responsible for the occurrence of these different types of failure can be related to the extent to which the lateral deformation of the film is restrained

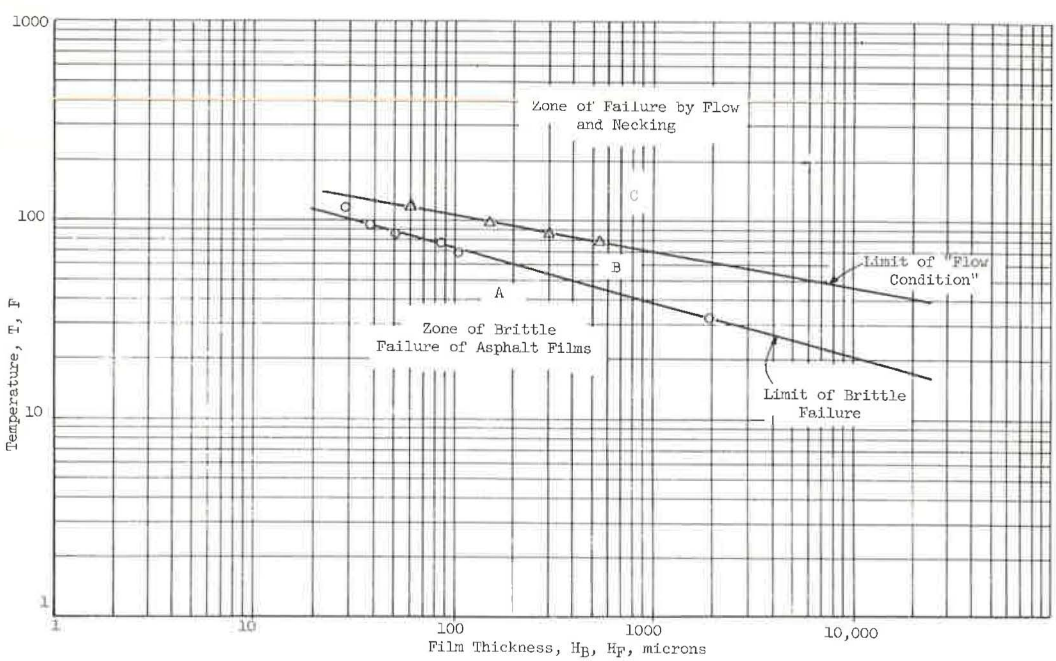

Figure 13. Influence of temperature on types of failure.

by the boundary conditions. To explain the failure mechanism, it is desirable that the failure of an asphalt specimen whose lateral deformation is not affected by the boundary conditions be examined first. When a long specimen (ratio of height to diameter more than three) is tested in tension, in addition to tensile stresses, shear stresses that can be quite large are also developed in the material as a result of lateral contraction of the specimen. Because the shear strength of asphalts, as well as other ductile and plastic materials, is smaller than its tensile strength, failure may be expected to occur because of shear stresses. However, in a shorter specimen where the material in contact with the boundary is prevented from deforming laterally, the relative amount of shear stress in the film decreases. This shear stress reduction can be attributed to transverse tensile stresses which are developed in the material as a result of the restraint of lateral deformation. When the transverse tensile stresses are superimposed with the simple tension that exists in a long specimen, a state of triaxial tension exists and results in a smaller shear stress in the asphalt. Therefore, as the lateral contraction is increasingly restrained with thinner films, the shear stress in a specimen is reduced and, thus, the tensile strength of the material is expected to increase. In a specimen which is considerably restrained from deforming laterally, the material would be subjected to more or less pure tensile stresses. In this condition, the failure of the specimen is by brittle fracture and is affected by the physical properties of the material such as flaws and cavities.

The three types of failure of the asphalt films observed in this investigation can be explained by this mechanism. In thick films, the amount of shear stress produced in the asphalt as a result of applied tensile stresses would be sufficient to cause the specimen to fail by flow or shear. However, as the film thickness decreases to an intermediate thickness, the transverse tensile stresses increase and the shear stresses in the specimen are reduced. The failure of specimens in these thicknesses, which is predominately due to tensile stress, is characterized by the formation of small rupture planes in the films. In very thin films where the lateral deformation is considerably reduced, the hydrostatic tension developed in the specimens would cause the films to fail by brittle fracture. The specimen, in this case, behaves more as a solid, and any flaws and cavities present in the material would cause stress concentration in the film which, in turn, would influence the fracture stress. Because the number of flaws in the material decreases with a decrease in film thickness, the tensile strength is expected to be higher for thinner films. In thick films, however, the stress concentration developed by the cavities and flaws are nullified by plastic flow. Thus, flaws do not significantly influence the tensile strength of thick films.

During the experimental work, three distinct types of failure were observed in the material: brittle fracture, tensile rupture and shear flow. Each type of failure occurred in a range of film thicknesses which constituted a failure zone. It was found that the brittle zone corresponds to the thin film range at which asphalt fails by brittle fracture as a result of excessive tensile stresses. In this investigation the limit of the brittle failure zone is represented by the notation H_B. The flow zone corresponds to the zone in which films fail predominately by flow and shear. Because the limit of this zone, in contrast to the limit of brittle failure, is not well defined, the thinnest film thickness at which the tensile strength plotted on semilogarithmic scale gradually levels off was assumed as the limit of flow condition, H_F. The experimental data indicate that the failure of films thicker than H_F is predominately or entirely due to shear stresses. The failure of films located between these two zones, however, is predominately by tensile stresses and is characterized by the formation of rupture planes or cavities in the specimens. In this type of failure, in contrast to brittle rupture, the specimen can still carry a reduced load after the maximum load has been reached.

This explanation for the failure mechanism can also explain the variation observed in the results of H_B and H_F. Figures 11 and 13 indicate H_B and H_F that are affected by the rate of extension and temperature. As the rate of extension increases, the film thicknesses which correspond to H_B and H_F are shifted to the thicker films. Likewise, the lower the temperature, the greater would be the thickness of the film at which these limits occur. Because asphalt is a viscoelastic material at higher rates of extension or lower temperature, the shearing resistance and, thus, the viscosity of the material is increased. Therefore, the magnitude of the shear stress which would cause flow in a specimen tested at a slow rate of extension or at a high temperature would no longer be sufficient to produce a shear flow in the film. Thus, the H_F is shifted to thicker films where there is less restraint of lateral deformation and where sufficient shear stresses for failure can be developed in the specimen. Similarly, at high rates of extension or low temperatures, H_B is also shifted to the thicker films where the decreased tensile stresses resulting from the lowered restraint of lateral deformation are not sufficient to cause brittle fracture in the specimen.

Explanation of Load-Deformation Curves

The different load-deformation curves shown in Figures 2 and 3 are typical curves associated with different types of failure. The load-deformation curves corresponding to brittle failure are linear until an instantaneous separation of the film occurs as the load reaches the maximum. This type of load-deformation curve is observed in all films which fail by brittle fracture and behave more like a solid than a plastic. Curve I in Figure 2 is a typical load-deformation curve for this type of behavior. In very thick films, however, the load-deformation curves are no longer linear. In this type of load-deformation curve, shown by Curve II in Figure 2, after the load reaches a maximum, plastic flow occurs in the film. This type of load-deformation curve is observed in films which fail by flow and necking. Because in thick films the lateral deformation of the specimen is less affected by the boundary conditions, the nonlinear load-deformation curves and the plastic flow can be attributed to the presence of sufficient shear stresses in the asphalt to produce the characteristic flow.

In Figure 3, two other typical load-deformation curves are shown. Curve III is a typical curve for films failing by tensile rupture and formation of cavities. In this type of failure, the load-deformation curve is linear initially but, in contrast to brittle films, no instantaneous breaking occurs in the specimen. After the specimen reached the state of failure, the filaments which formed as a result of cavitation still can carry a reduced load, for greater deformation. This type of load-deformation curve was observed for all specimens located between H_B and H_F. For films slightly thicker than H_F, another distinct type of load-deformation curve is observed. The load-deformation curve obtained for such films is no longer linear, but still a slight drop of the load is observed in the specimen after the load reaches the maximum. Curve IV is a typical load-deformation curve for films slightly thicker than H_F. As it is observed, this curve is more similar to Curve II (Fig. 2), which was obtained for flow-type failure, than to Curve III. That is, as the film thickness increases, the shape of Curve IV approaches the shape of Curve II obtained for flow-type failure. Therefore, it can be concluded that the load-deformation curves for films thicker than H_F are predominately or entirely affected by the occurrence of flow in the specimen.

Explanation of Tensile Strength-Film Thickness Relationship

In explaining the tensile strength-film thickness relationship, different failure mechanisms observed in the asphalt films must be considered. Each of the three types of failure have significant influence on the behavior of the asphalt film subjected to tensile stresses. In other words, in the range of film thicknesses where the films fail by shear flow, the behavior of the asphalt film is different from the behavior in the range at which failure is characterized by brittle fracture or in the range where tensile rupture occurs.

In the flow zone, where the material fails predominately or entirely by shear flow, the hydrodynamic theory given previously was found to be in agreement with experimental results. In Figure 8, Line A has been drawn based on this theory and its equation is as follows:

$$\sigma^n = \frac{dh}{dt} \frac{A^{\frac{(n+1)}{2}}}{\pi^{\frac{(n+1)}{2}}} \frac{K(2n)^n (n+2)}{(3n+1)^n} \frac{H_o^{\frac{3n+1}{2}}}{(H_o + \Delta h)^{\frac{5n+5}{2}}} \tag{9}$$

in which

σ = tensile strength of film (dynes/sq cm);

$\frac{dh}{dt}$ = rate of extension (cm/sec), which is equal to 8.46×10^{-4} cm/sec (0.02 in./min) in this case;

H_o = initial film thickness (cm);

Δh = amount of deformation to failure (cm);

A = area of specimen (sq cm);

n = constant related to non-Newtonian behavior of asphalt, which for this asphalt is 1.06708, obtained from the equation $\dot{\delta} = \tau^n/K$ (for Newtonian materials, n = 1); and

K = constant related to viscosity of asphalt (dynes-sec/sq cm), which for this asphalt is equal to 3.108×10^6 dynes-sec/sq cm).

Eq. 9 is similar to Eq. 3 presented previously. If in Eq. 3 the term related to force, F, is divided by area, A, to be in the form of stress, σ, and H is subdivided by H_o and Δh, Eq. 9 is obtained. Up to H_F, the part of the experimental plot which is approximately tangent and parallel to Line A (Fig. 8) indicates that the material, in thick films, tends to behave according to this theory.

In the equation derived from the hydrodynamic theory, if the rate of extension and the constants n and K, which are related to the type and viscosity of the asphalt, are known, the tensile strength of the asphalt in thick films can be predicted. The constants n and K in Eq. 9 were obtained from the results of shear tests conducted on the asphalt at 77 F.

The experimental results indicate that as the film thickness decreases, the difference between the theoretical tensile strength predicted by hydrodynamic theory and the observed strength increases. That is, in thin films, the failure of the asphalt films occurs at much smaller loads than those predicted by this theory. Because, in thin films, as a result of restraint of the lateral deformation, the magnitude of shear stresses decreases, a greater magnitude of tensile stress is required to develop sufficient shear stresses for producing flow in the film. However, when this tensile stress exceeds the tensile strength of the asphalt films, the failure occurs by tensile rupture before any appreciable flow can be produced in the film. Therefore, the failure can no longer be assumed to be a failure by flow, and, thus, this theory is invalid for thin films of asphalts. The experimental data indicate that H_F is the thinnest film thickness whose strength can be predicted by this theory.

In very thin films, where the lateral deformation of the specimen is considerably restricted, the asphalt films behave as solids and fail by brittle fracture. This type of failure is attributed to hydrostatic tension which is developed in the specimen as a result of restraint of lateral deformation. In films failing by brittle fracture, the cohesive strength of the material and the cavities and flaws present in the specimen influence the tensile strength of the film. The theory of potential energy and cavities which was given previously might predict the tensile strength of the films behaving as a solid. In Figure 8, Line B was based on this theory and its equation is as follows:

$$\sigma = A \left(\frac{\Delta h}{H_o}\right)^{+a} \tag{10}$$

in which, for the experimental data obtained at 77 F and rate of extension equal to 0.02 in./min,

A = a constant for these test conditions, equal to 4.782×10^7;

Δh = amount of deformation to failure (cm), the average amount of which assumed for the film thicknesses located in the brittle zone is equal to 41.4×10^{-4} cm; and a = constant related to cavities and molecular forces of asphalt, which for films thicker than the optimum film thickness (see the assumptions of theory) is equal to 0.397.

In this equation, the constant A depends on the rate of extension, temperature and consistency of the asphalts. This constant, for tests conducted at 77 F (25 C) and 0.005 in./min rate of extension, is equal to 3.80×10^7. For tests conducted at 0.02 in./min rate of extension and temperatures of 20, 35, and 45 C, A is 5.65×10^7, 3.10×10^7 and 1.87×10^7, respectively.

To predict the tensile strength of thin films of asphalts by the theory of potential energy and cavities, certain assumptions should be made:

1. The relationship of tensile strength to film thickness for the very thin films (the films located in the brittle zone) is a straight line on a logarithmic scale. The experimental data plotted in the upper portion of Figure 8 indicate that such an assumption can be made without introducing any appreciable error.

2. As predicted by the theory, there is an optimum film thickness in the tensile strength-film thickness relationship. However, because no optimum film thickness was observed in any of the experiments conducted in this investigation, the validity of this assumption remains unclarified. Therefore, the experimental data plotted in Figure 8 corresponds to the right side of the optimum and the sign of the constant a, as was discussed previously, is negative.

3. A constant value needs to be assumed for the amount of deformation to failure. According to Mack's assumptions, the amount of deformation to failure (Δh) remains constant for a given asphalt. The experimental results indicate that the amount of deformation to failure is not significantly influenced by the test variables, and, moreover, its variation with the film thickness is very small. Therefore, an average value can be assumed for the amount of deformation to failure for the range of film thicknesses studied.

The experimental data plotted in Figure 8 indicate that as the film thickness increases, the deviation of the theoretical Line B from the experimental results becomes greater. Moreover, it is observed that for a range of film thicknesses thicker than the limit of brittle failure, the tensile strength-film thickness relationship can no longer be assumed to be linear on logarithmic scales. Therefore, this theory, similar to the hydrodynamic theory, is only applicable to a limited range of film thicknesses. Thus, according to the basic assumptions discussed previously, the theory of potential energy and cavities is only applicable to films which behave as solids.

In the explanation of the tensile strength-film thickness relationship, only the three different types of behavior which are observed in the experimental work were discussed. However, there is a fourth type of behavior predicted by the suggested failure mechanism, even though it has not been observed in the experimental results. According to the hypothesis given for failure mechanism, as the film thickness decreases, the restraint of deformation and the resulting transverse tensile stresses increase. Therefore, it is expected that in extremely thin films, the lateral deformation is completely prevented and purely tensile stress is developed in the specimen. In this case, the asphalt film which is subjected to equal tensile stresses in all directions (pure hydrostatic tension) would also fail in a brittle fracture. Because the number of flaws and cavities which might be present in the asphalt film has been considerably reduced in the extremely thin films, it is expected that the tensile strength might not vary with film thickness. That is, in extremely thin films the tensile strength would gradually reach an ultimate value and remain constant regardless of the thickness of the asphalt film. Therefore, the general form of the tensile strength-film thickness relationship would be that of an S-shaped curve. The difference between this fourth type of behavior and the behavior of films in the brittle zone which was previously discussed is due to the variation in the number of flaws and the degree that lateral deformation is prevented. Thus, it might be concluded that in extremely thin films, the tensile strength might reach an ultimate value determined by the cohesive strength of the asphalt molecules. However, the difficulties associated with preparing such extremely thin films in the laboratory make it impossible to study this fourth type of behavior.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to study the tensile properties of asphalts in thin films. Attempts were made to explain theoretically the behavior of asphalts, as well as to derive relationships for such behaviors. Two theories that seemed to predict the tensile properties of asphalts in very thin and very thick films were investigated. It was found that these two theories can closely predict the tensile strength of asphalts in very thin and very thick films. In addition, an hypothesis was developed which tends to explain the general behavior of asphalt films. Laboratory investigations were conducted, and the influences of a selected group of variables on the tensile properties of asphalts were determined in order to verify the suggested hypothesis and theories.

The data reported herein were limited to one type of asphalt and a selected number of influential factors. However, other types of asphalt have been investigated and similar results were obtained. Therefore, the conclusions drawn from this study are limited primarily to the test conditions used. The conclusions reached from this investigation are as follows:

1. The tensile strength of asphalts in thin films varies with the film thickness. The tensile strength decreases as the film thickness increases, and, finally, the tensile strength approaches a constant value that does not change as the film thickness is increased. For the type of asphalt studied, it is observed that the tensile strength-film thickness relationship for thin films of asphalts is linear on a semilogarithmic scale. In thick films, however, depending on the test conditions, the tensile strength gradually approaches a constant value that is quite small.

2. It appears that the hydrodynamic theory can be used to predict the tensile strength of thick films of asphalts. According to this theory, the tensile strength depends on the type of asphalt, viscosity, and the rate of extension. It is indicated that this theory can be used for those films of asphalts which fail by shear flow and necking. However, this theory is not applicable to very thin films of asphalts which fail predominately by tensile stresses. For such thin films, the tensile strength predicted by this theory is much greater than the observed strength.

3. The theory of potential energy and cavities, with certain assumptions, can be applied to very thin films of asphalts which tend to behave as solids. According to this theory, there is an optimum film thickness in the tensile strength-film thickness relationship which varies with the type of asphalt. However, in the type of asphalt studied in this investigation, no optimum film thickness was observed. Thus, to apply this theory it must be assumed that all experimental data are of film thickness greater than optimum. Moreover, this theory is only applicable for thin films of asphalts. For thick films, the tensile strength predicted by this theory is much greater than the observed strength.

4. It is believed that the restraining action of the boundary conditions produces transverse tensile stresses in the specimen which change the state of simple tension to a state of triaxial tension. This change, occurring gradually as the film thickness decreases, is partly responsible for the different types of behavior observed in the asphalt films. In addition, the flaws and cavities that might be present in the asphalt films also influence the behavior of the material. However, the influence of flaws and cavities on the behavior of specimens is more pronounced in thin films where the material behaves more as a solid than in thick films where asphalt behaves more as a plastic material. It appears that this hypothesis can explain the behavior of asphalts over a wide range of film thicknesses.

5. Three types of failure are observed in the asphalt specimens; these are brittle fracture, tensile rupture, and failure by flow and necking. Depending on the test conditions, brittle fracture occurs in thin films, whereas thick films fail predominately by flow and necking. The failure of intermediate film thicknesses is by tensile rupture which is characterized by the formation of cavities and filaments in the film. These types of failure observed in the asphalt specimens can be explained by the suggested theoretical failure mechanism.

6. It is indicated that the range of film thicknesses at which different types of fail-

ure occur depend on the variables studied. Thus, the limit of brittle failure and the limit of flow condition, which are the limits of different zones of failure observed in the asphalt films, vary with such variables as rate of extension, temperature, and size of specimen. As the rate of extension increases or the temperature decreases, the limits of brittle failure and flow condition are shifted to the thicker film range. The variations observed in these limits can be explained by the suggested theoretical failure mechanism. Furthermore, the equations derived from these limits might be used to predict the type of failure of an asphalt film.

7. Rate of extension and temperature significantly influence the tensile strength of the asphalt films. The tensile strength increases as the rate of extension increases or as temperature decreases. It is indicated that when tensile strength is plotted against film thickness or a semilogarithmic scale, the slope of the straight line relationship existing in thin films is independent of the rate of extension and temperature for a specific asphalt.

8. The amount of deformation at failure tends to remain constant in the asphalts studied. The amount of deformation at failure is practically a constant regardless of the thickness of the specimen. The amount of deformation at failure also does not appear to vary significantly with the rate of extension and temperature.

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