Research in Asphalt Quality Control

PART I: CONSISTENCY OF ASPHALT

What is it and how is it measured?

This is the first in a series of five articles by Dr. Traxler on one of the more important research studies underway at the Texas Transportation Institute of the A & M College System for the Texas Highway Department. The A & M College System has been conducting a cooperative program of research for the Highway Department since January 1953. Some 23 formal research projects have been initiated under this cooperative program with the T.T.I., nine of which have been completed with a final report. There are presently fourteen active projects, including four utilizing Federal fund participation.

This series of articles will present the progress of one phase of a coordinated research program being conducted by the T.T.I. in conjunction with the asphalt section of the Materials and Tests Division of the Highway Department, aimed at developing ways of improving the quality of asphaltic paving in Texas.

The properties of asphalt which offer resistance to deformation by an applied force are called its consistency. Two kinds of deformation are involved—viscous and elastic. Any elastic deformation which occurs will eventually disappear after the applied force is removed. Viscous deformation, on the other hand, is not recoverable. Most asphalts show both elastic and viscous behavior, depending on the rate at which the force is applied. When a bitumen is deformed rapidly (at a high rate of shear) the stresses established will tend to result from deformation of elastic elements within the asphalt. At low rates of deformation the stresses are likely to be due predominately to viscous flow. In most paving asphalts elasticity becomes evident only in vibration of the material.

Basically, the viscosity of any fluid depends upon the internal friction, which resists deformation or flow when a force is applied. This is known as the coefficient of viscosity, or more simply, the viscosity of the material. Viscosity expressed in units of length, weight, and time can be measured in properly designed equipment. The metric unit is the poise, expressed in grams per centimeter-second. The English unit is the reyn, expressed in pounds per inch-second. One reyn equals 6,900,000 poises.

The stresses normally exerted on a pavement by moving vehicles are of the order of 10^7 dynes per square centimeter. While there usually is some elastic deformation under such stress, the highway engineer is most concerned with the viscous deformation (viscosity) of the asphalt at any given temperature. Stress in a pavement is also caused by soil movement and thermal contraction. These forces are sometimes more pronounced than those produced by traffic. Since the *rates of shear* brought about in an asphalt road by excessive cooling are

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Dr. R. N. Traxler

extremely low, the stresses so developed will be related to the viscous elements in the binder. Thus, in many situations the permanent or viscous flow may overshadow the non-permanent or elastic deformation. If the viscosity of the asphalt is greater than about 8 to 10 million poises at 77°F the pavement is likely to crack because of the stresses developed at low temperatures.

Although other factors are involved, the life of a bituminous pavement will depend to a great extent upon the consistency of the asphalt at any given temperature. Since the viscous element of consistency is of such great importance, it is essential that the viscosity-temperature coefficient be maintained as low as possible in roadbuilding asphalts. This is commonly expressed as the need for a material possessing a low temperature susceptibility. It is required that the binder be soft enough that the road will not crack at low temperatures because of traffic, soil, or thermal stresses. But, the asphalt also must be hard enough at maximum service temperature (160°F) to give stability to the highway under traffic. Finally, the binding material must be sufficiently fluid at temperatures that can be economically and satisfactorily used during transportation and mixing with stone. A hot-mix pavement must be prepared at a temperature low enough to prevent damage to the asphalt. The mixing temperature required to give a satisfactory film of asphalt on each piece of aggregate is very important. That temperature will depend on the consistency of the bitumen.

At this point it may be well to briefly review the history of asphalt and the methods developed for evaluating its consistency. Asphalt has been used by man longer than any other material related to or derived from petroleum. His first acquaintance with this black adhesive came with the discovery of surface deposits of soft bitumens, which could be used without processing. The early artisan paid little attention to the consistency of the asphalt other than to select a material which could be conveniently used for a particular application.

By the latter part of the Nineteenth Century, the pressure for paved streets and sidewalks resulted in an increased demand for native asphalts. It then became evident that proper use of most native asphalts required a modification of their hardness or consistency. This was accomplished by fluxing or softening the native asphalt by heavy oils or residues resulting from the distillation of petroleum. The heavy bottoms from asphaltic or mixed-base crude oils were found to be most suitable as fluxes.

It was not too difficult to devise an apparatus for evaluating the consistency of the hot-fluxed asphalt. The material to be tested was placed in a vessel that could be maintained at a constant temperature. The receptacle had a round hole of fixed diameter in the bottom into which a stopper was inserted. After the entire assembly and contents were brought to the desired temperature, the stopper was removed and a record made of the time required for a fixed volume of the material to flow through the hole. This type of viscosimeter possessing different forms and dimensions became known as the Engler (Germany), Redwood (Great Britain), Barbey (France), and Saybolt (United States). The original American instrument is now called the Saybolt-Universal, and a modification with a larger hole has been given the name Saybolt-Furol. The latter instrument was developed for the rapid evaluation of *fuel oils and road oils,* from which the name Furol was derived.

These apparatus served to evaluate and control asphaltic materials at manufacturing and handling temperatures. But, the problem still remained of how to measure the consistency of an asphalt at service temperatures (below 120°F). To start with, a small lump of the finished asphalt was chewed like a piece of chewing gum. This was not such a bad idea since the human mouth is a fairly accurate constant temperature bath. With practice and experience an operator could become adept at evaluating the consistency of the asphalt at the temperature of his mouth (about 98°F). In fact, as late as 1920 men were supervising the manufacture of asphalt who put great trust in this procedure. They considered it more reliable than the "new-fangled" penetrometer being used by the laboratory "boys."

The penetrometer was first designed by H. C. Bowen at Columbia University in 1889. Acceptance of the apparatus was slow and awaited improvements by A. W. Dow, Clifford Richardson, and C. N. Forrest. These men were all pioneers in asphalt technology. By 1910 the penetrometer was an established instrument for evaluating the consistency of road-building asphalts at atmospheric temperatures. Gradually, the temperatures used were established at 32°F (0°C), 77°F (25°C) and 115°F (46.1°C).

During the past 50 years many millions of penetration tests have been made on asphalts of different kinds and consistencies. It has become common practice to grade asphalts by the ASTM (American Society for Testing Materials) penetration test at 77°F under a load of 100 grams for five seconds. However, as asphalt technology became less of an art and more of a science, the inadequacy of the penetration test became apparent. It did not tell all that should be known about an asphalt. Valiant efforts have been made to convert penetration data into absolute viscosities (centimeter-gram-second units). Also, attempts were made to interpret flow characteristics in terms of penetration values.

As was mentioned at the beginning of this article, viscosity is a fundamental property of any fluid. For asphalts it offers a truer picture than can be obtained by empirical tests such as penetration and softening point. Also, viscosity measurements are very sensitive and bring to light differences not detected by the empirical tests. During the past 25 years much effort has been devoted to the

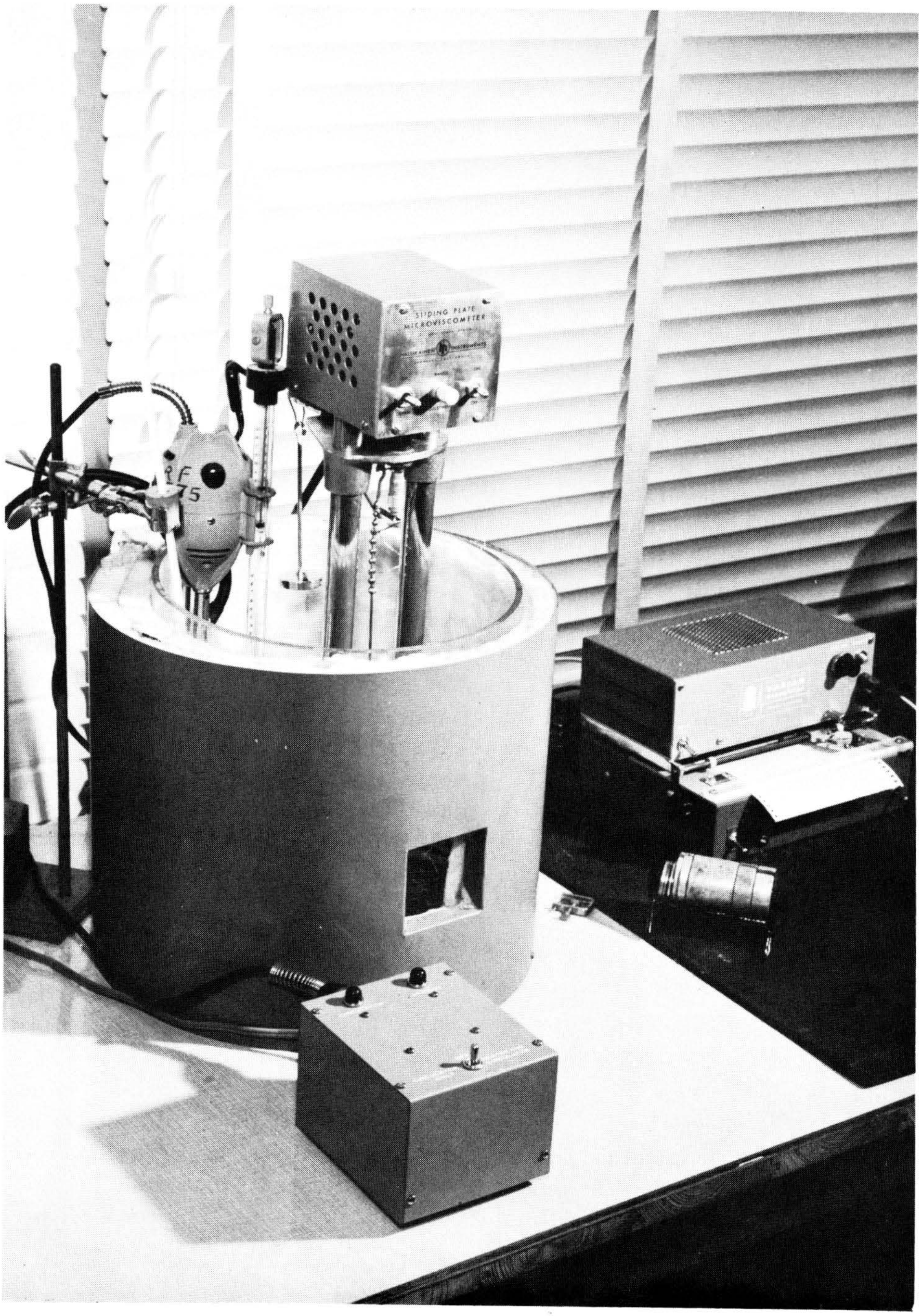

Figure 1—Microfilm viscometer and auxiliary equipment.

development of absolute viscometers for evaluating materials possessing a wide range of consistency. The consistencies of asphalts, caused by either differences in source, kind, and degree of processing, or temperature of test, may now be satisfactorily compared. Asphalt cements—either cold or hot, asphaltic cutbacks of all grades, asphalt emulsions, rubberized asphalts, and mineral-filled asphalts can all be compared on an equal basis. Viscosity in poises measured at some fixed rate of shear supplies the common basis for comparison.

Two or three types of viscometers now available make possible the evaluation of consistencies ranging from 0.01 poise (the viscosity of water) to about 10 billion poises. The best apparatus known by the author for measuring consistencies up to about 200 poises is one of the reverse-flow-type viscometers recommended by the ASTM for use with opaque liquids. Reference to and illustrations of these instruments may be found in "Tentative Method of Test for Kinematic Viscosity," ASTM D 445-53T, Appendices B and G. ASTM Standards Part 7, 212 and 226 (1958).

Higher viscosities can be determined in several different viscometers. One of the most modern types, the microfilm viscometer, with its auxiliary equipment, is shown in Figure 1. The viscometer is pictured alone in Figure 2. A uniform film of asphalt about 25 microns (1/1000 inch) thick is placed between two glass plates measuring three by two centimeters. The exact thickness of the asphalt film is determined from its weight and surface area (six square centimeters). The plates are inserted in the viscometer where one is held firmly in place and the other is moved by application of a weight. The plate is moved a very short distance. The weight required to cause a particular rate of movement depends on the viscosity of the asphalt. A few grams may be sufficient for a soft asphalt but several thousand grams may be required if a hard asphalt is being investigated. The movement of the plate for a given period of time is recorded on a chart. Knowing the weight applied and the rate of movement of the plate, it is possible to calculate in poises the viscosity of the thin film of asphalt. To avoid complications that may arise, especially with hard asphalts, the viscosities are always reported at the same rate of shear. A number of determinations may be made by one operator in a working day. It should be pointed out that viscosities obtained with the thin-film viscometer check with values obtained by other types of apparatus not discussed in this brief presentation.

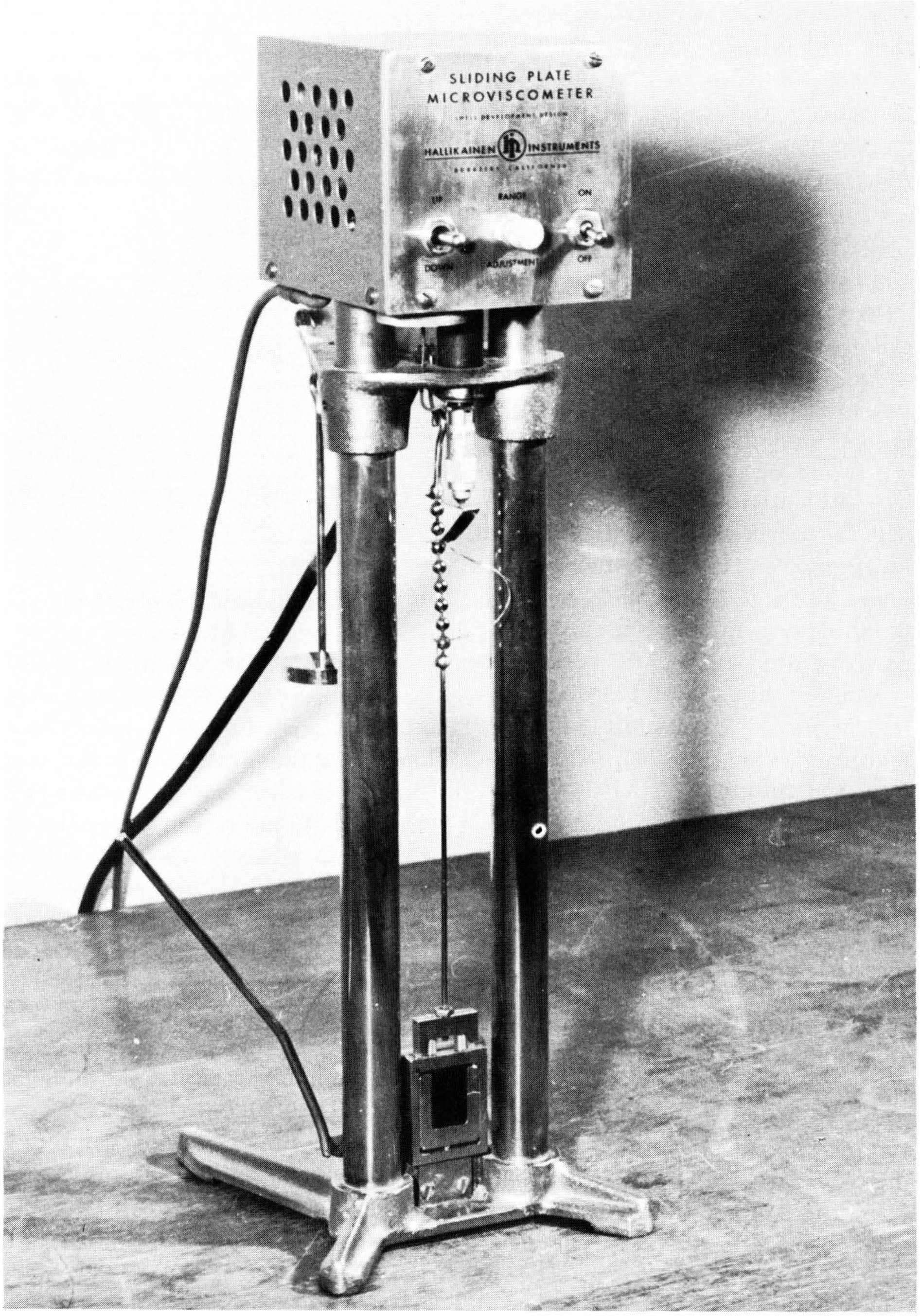

Figure 2—Microfilm viscometer.

Table I shows data on road-building asphalts made by ten different manufacturers. All are 85-100 penetration asphalts (OA-90) and the penetrations varied from 89 to 98 at 77°F/100 gms/5 secs. The viscosity values which were obtained by the thin film method vary from 700,000 to 1,300,000 poises at 77°F. It should be noted that Asphalt A with the hardest penetration (89) and almost the highest softening point (118°F) has the lowest viscosity at 77°F. Asphalt E with the softest penetration (98) and a fairly high softening point (116°) has a viscosity just below the average. Asphalt J which has about average penetration (93) and a high softening point (117°) has the highest viscosity (1.3 x 10^6 poises). Among the group of ten asphalts there is a spread of nine points in penetration, 8°F in softening point, and 600,000 poises at 77°F. Data similar to that given in Table I have been obtained by numerous investigators during the past two decades, and the conclusion is firmly established that consistency measurements in absolute units are more sensitive, precise, discriminatory, and informative than the penetration test.

Table I

Penetration and Viscosity at 77°F For OA-90 Asphalts

Sample	*ASTM Pen. at 77°F*	*Softening Point B&R °F*	*Viscosity at 77°F Million of Poises**
A	**89**	**118**	**0.70**
B	**93**	**115**	**0.80**
C	**94**	**117**	**0.80**
D	**90**	**115**	**0.85**
E	**98**	**116**	**0.90**
F	**92**	**111**	**0.90**
G	**92**	**119**	**1.00**
H	**92**	**117**	**1.10**
I	**90**	**117**	**1.20**
J	**93**	**117**	**1.30**

***Calculated at a rate of shear of 5 x 10^{-2} reciprocal seconds.**

The importance of the consistency at mixing temperatures has been mentioned. Table II again lists the ten asphalts and gives the penetrations at 77°F and the viscosity in poises at 280°F. Asphalts E (98 penetrations) and A (89 penetrations), which are the softest and hardest on the basis of penetration, both have about the same viscosity in poises at 280°F. The asphalts possessing low viscosities at this operating temperature have about average penetration values. The penetrations at 77°F show a range of about 10 per cent, but the viscosities at 280°F extend over a range of 80 per cent. It is evident that the penetration test cannot be used to obtain an idea of the consistency of an asphalt at normal handling and mixing temperatures. Absolute viscosity data are again more precise and discriminatory.

We must now consider another complication encountered during the complete and satisfactory evaluation of the consistency and flow properties of asphalt at service temperatures. This is the presence of internal structure in the asphalt which results in the appearance of complex or non-Newtonian flow. When an asphalt possesses any appreciable amount of internal structure an applied force tends to cause breakdown of the structure with a decrease in the measured viscosity. As the force is increased the measured viscosity decreases. Thus, the amount of structure present in an asphalt may be evaluated by measuring the viscosity at different shearing stresses (applied forces) or different rates of shear. Such information aids in understanding the behavior of asphalts under service conditions because all asphalts, with the passage of time and under service conditions, tend to deviate from simple viscous flow. The rate at which structure builds up in an asphalt is closely connected with its durability as a binder. An ideal material would show little or no hardening and slight change in complex flow with time.

The important point here is that the degree of complex flow present in an asphalt cannot be satisfactorily evaluated by the penetration test but can be measured in the proper type of viscometer. For evaluation of complex flow the viscosity is measured at three different rates of shear. The viscosity values are plotted against rate of shear, and the change in viscosity for a given change in rate of shear is calculated. When no change in viscosity occurs with change in rate of shear, the asphalt is essentially a viscous liquid. But, if a decrease in viscosity occurs when the rate of shear is increased, the asphalt possesses in-

Table II

Penetration at 77°F and Viscosity at 280°F for OA-90 Asphalts

Sample	*ASTM Pen. at 77°F*	*Viscosity at 280°F poises*
E	**98**	**3.6**
A	**89**	**3.5**
B	**93**	**3.5**
I	**90**	**3.3**
G	**92**	**3.0**
J	**93**	**3.0**
F	**92**	**2.3**
H	**92**	**2.3**
D	**90**	**2.0**
C	**94**	**1.9**

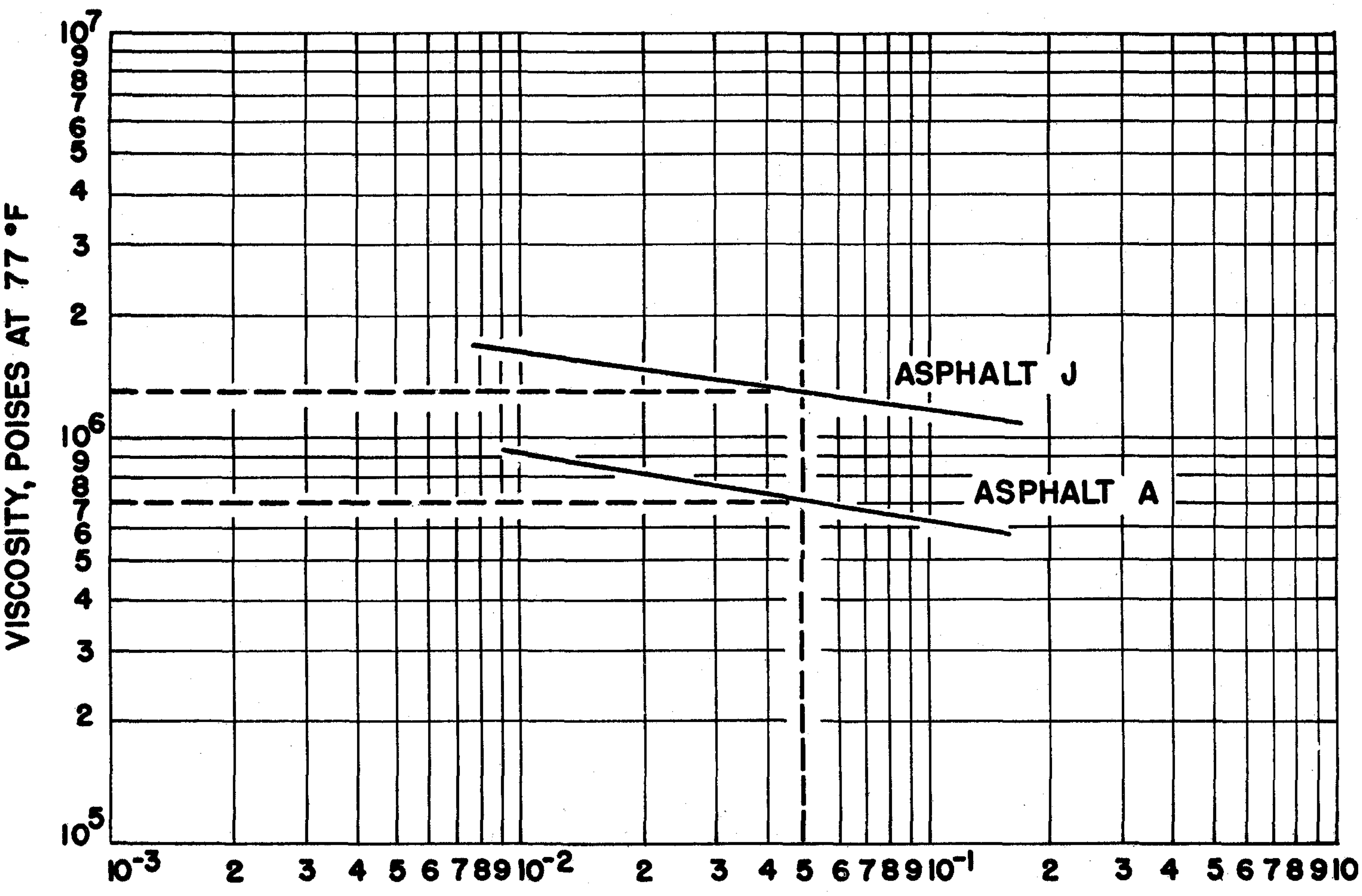

Figure 3—Absolute viscosities calculated at 5 x 10^{-2} reciprocal seconds.

ternal structure, and the amount is reflected by the change in viscosity. Also, to compare the viscosities of materials possessing complex flow, three experimentally determined viscosities for each material are plotted against rate of shear and the viscosity of each asphalt is calculated at a common rate of shear. Figure 3 is a log-log plot of the experimental data obtained for asphalts A and J at 77°F. The viscosity of each asphalt was determined at three different rates of shear. Each viscosity value was plotted against the rate of shear used in its determination. Since duplicate samples were tested, six values were used in obtaining the line shown for each asphalt. Figure 3 shows how the viscosity values for A and J were evaluated at a shear rate of 5 x 10^{-2} reciprocal seconds. These average viscosities at a common rate of shear are the values shown in Table I.

The facts presented above lead to the conclusion that empirical methods, such as the penetration and softening-point tests, for evaluating consistency have serious limitations. These methods are not sufficiently sensitive and are incapable of detecting important differences that may exist in the consistency and flow properties of paving-grade asphalts. These undetected differences may be responsible to a considerable extent for the success or failure of an asphalt in service. The asphalt technologist should know the consistency characteristics of the asphalt being used in a particular installation, and he should use the most precise and informative procedure for obtaining the necessary data. This requirement points to the use of an absolute viscometer.

Familiarity with the usefulness of absolute viscosity data at operating and service temperatures is increasing rapidly. Such understanding will eventually bring about general acceptance. The struggle for recognition of the viscometer as a working tool for the asphalt technologist seems to have reached a climax. Every reader of this brief discussion should give serious thought to the possibilities for advancing bituminous technology through exact evaluation of consistency.

The next article will discuss the susceptibility of different asphalts to hardening by oxidation. It will be shown how absolute viscosity measurements detect differences in hardening that cannot be detected by the tests generally employed at present.

Research in Asphalt Quality Control

PART II: SUSCEPTIBILITY OF ASPHALTS

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All asphalts harden to some extent during handling and mixing with aggregate because of volatilization and oxidation. The latter is the more important of the two factors. Then, in service the consistency of the asphalt continues to increase, because of further oxidation and the development of internal structure within the asphalt. In a pavement the oxidation of the thin films of asphalt on the aggregate is accelerated if the road is not sufficiently dense and well compacted to prevent entrance of air. Also, the oxidation of many organic materials, including asphalt, is accelerated by ultraviolet and the short wave lengths of visible light. The present paper will be limited to a discussion of accelerated oxidation of asphalt films and the resulting reduction of their usefulness as binders for road building.

Oxidation at elevated temperatures (450 to 550°F) is a method used by the manufacturer to change the physical, chemical, and flow properties of asphalt. Products so prepared are known as oxidized or air-blown asphalts, and are used mostly in the manufacture of roofings and specialty products. Some manufacturers, however, use small amounts of air-blown asphalts in the preparation of paving asphalts in order to meet certain specifications established by the customer. Studies of the oxidation of different kinds of asphalt at these high temperatures have resulted in the following general conclusions:

1. The consistencies of asphalts possessing high contents of unsaturated (naphthenic and aromatic) compounds do not increase as rapidly on oxidation as do asphalts containing low contents of cyclic compounds.
2. Increase in the consistencies of asphalts during the air-blowing process are caused mainly by removal of hydrogen from the asphaltic compounds. This results in the combining of smaller molecules to form larger ones. Thus, the oils and resins present are consumed to create asphaltic materials of more complicated chemical structure and higher consistency.
3. Oxygen-containing compounds are formed in the air-blown asphalts. Although the oxygen content of the asphalt may be low (1 to 2 per cent), up to 80 per cent of the molecules in the asphalt may contain oxygen.

Many similar reactions take place during handling and in the mixing of asphalt with stone in a hot mix, although the temperatures attained are not as high as in commercial air-blowing. Nevertheless, with every degree rise in temperature the oxidation process is accelerated and the asphalt hardened. It is essential that as low a temperature as possible be maintained during the mixing operation. Yet, the asphalt must be kept hot enough and fluid enough to result in complete coating of the stone and satisfactory laying and compaction on the road.

Asphalts from various sources, and made by different processes, react differently during the commercial air-blowing process. The same is true in the hot-mix plant, in the road during construction, and under service conditions. An asphalt which hardens

TO OXIDATION

Number 2 in a series of five articles by Dr. Traxler, Texas Transportation Institute, on the subject of asphalt quality control.

rapidly during handling and in service will have a short life as a satisfactory binder. Good service durability, on the other hand, can be expected from an asphalt which resists oxidation. Use of such asphalts will result in longer life and lower maintenance costs for the road, provided other factors do not overshadow the quality of the binder.

Much work has been done during the past 30 years on the development of accelerated methods for evaluating the effects of heat, oxygen, and light on different asphalts. No effort will be made here to review these numerous attempts to establish a measure for the durability of asphalt films. Only two procedures, developed recently, will be discussed. These methods show promise for evaluating the susceptibility of different asphalts to oxidation. They depend on contact of air with asphalt films at moderately high temperatures (225 and 325°F).

The first procedure to be discussed is based on the Lewis Thin Film Test developed at the Bureau of Public Roads in Washington, D. C. In this test a layer of asphalt about ⅛ inch thick is placed in an aluminum pan 5½ inches in diameter and ⅜ inch deep, and the pan containing the sample is placed on the revolving shelf of an oven maintained at 325°F. After five hours heating, the samples are removed from the oven, thoroughly mixed, cooled, and tested for penetration at 77°F, softening point R&B°F [ring and ball] and ductility at 5 cm/min, 77°F. The values obtained on the heated material are compared with the same tests on the asphalt prior to placing in the oven. Some preliminary work has been done in recent months at the Texas Transportation Institute on an elaboration of this test. First, the viscosities of ten different road-building asphalts (OA-90) were determined by means of the thin-film viscometer. The resulting data were given in Part I of this series of articles. Each of these same ten asphalts were then subjected to the Lewis Thin Film procedure and the oxidized asphalt tested as mentioned above. In addition, the absolute viscosity of each oxidized sample was determined. Then, the viscosity of each hardened sample was divided by the original viscosity of the asphalt to obtain a durability index, D, for the particular asphalt. Materials with low values for D harden less rapidly and, thus, should possess greater service durability. A value of 1.0 for D should be ideal, because it would mean the consistency of the asphalt was not changed during the heating and oxidation. The higher the durability index, the less satisfactory the asphalt should be in service because a high viscosity would be attained in a short time. As was mentioned in Part I, an asphalt possessing a viscosity of more than 10 million

TABLE I

Durability Indices from Lewis Film Test at 325°F

Sample	Durability Index, D, from Absolute Viscosity 5 hours	 10 hours	Percent Retained Penetration at 77°F* 5 hours	 10 hours
A	1.7	5.3	74	56
D	2.0	4.3	72	52
J	2.7	3.8	63	48
I	2.9	7.2	55	47
E	3.2	3.8	69	55
B	3.6	4.4	65	56
G	4.1	6.2	59	49
H	8.2	13.5	54	39
C	5.0	9.0	54	44
F	5.3	8.0	58	47

***Each of these asphalts are of the 85-100 penetration grade discussed in Part I of this series. (See the March issue of *Texas Highways*.)**

poises at 77°F is not a satisfactory binder, especially at low service temperatures.

Table I shows that the durability indices varied considerably. The investigation was extended by repeating the entire procedure, except that the heating period was increased to ten hours. As would be expected, the magnitude of the indices for all of the asphalts increased with time of heating, but the rate of increase varied with the different asphalts.

A review of the data in Table I shows that asphalts A, D, and J have low durability indices. From the standpoint of resistance to oxidation, these three products would be most likely to give satisfactory service in the road. Asphalts C, F, and H consistently show excessive hardening in air at 325°F and, consequently, would be expected to have the poorest durability under service conditions. The four remaining asphalts appear to be intermediate in their general reaction to the Lewis Thin-Film Test. Plots of heating time at 325°F versus durability index, D, are shown in Figure 1 for asphalts H and J.

Another procedure for evaluating the resistance of an asphalt to hardening by heat and oxidation is the Shell Thin-Film Test. In this test as usually conducted, films of asphalt about five microns thick are placed on 4 x 4 cm glass plates. The plates carrying these very thin films are heated for two hours in an oven at 225°F. After removal from the oven and cooling in a dessicator the film of asphalt is removed from the larger plate and placed between the 3 x 2 cm plates used in the microfilm viscometer. The viscosity is determined at 77°F. In the laboratories of the Institute, the films heated in the oven were fifteen microns thick and viscosities were determined on films of the same thickness. A film fifteen microns in thickness was selected because it approximates the optimum size of asphalt film on the aggregate in a bituminous road.

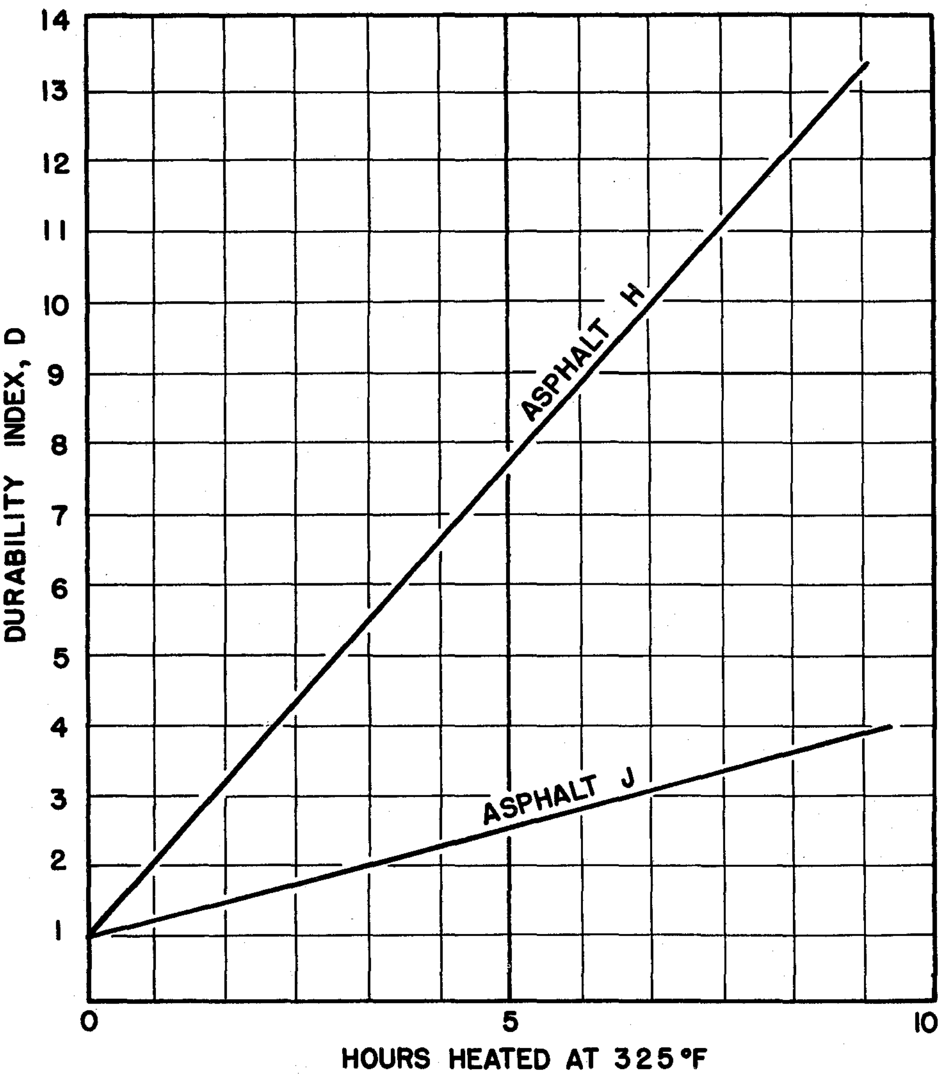

Figure 1—Time-durability index plots for one-eighth-inch films of asphalt heated in air at 325°F.

The test on each product was repeated except that fifteen micron films were heated at 225°F for four hours. Durability index, D, was calculated for each asphalt after heating for two and four hours. As in the Lewis Test these values were obtained by dividing the viscosity of the oxidized film

TABLE II

Durability Indices Obtained from Shell-Type Thin Film Test at 225°F

Sample	Durability Index from 2 hours heating	Durability Index from 4 hours heating
A	2.1	3.0
D	2.8	4.0
I	2.7	4.1
B	2.5	4.8
J	3.3	5.5
G	3.3	5.8
E	4.4	7.3
F	4.5	9.1
C	6.2	10.5
H	6.0	10.9

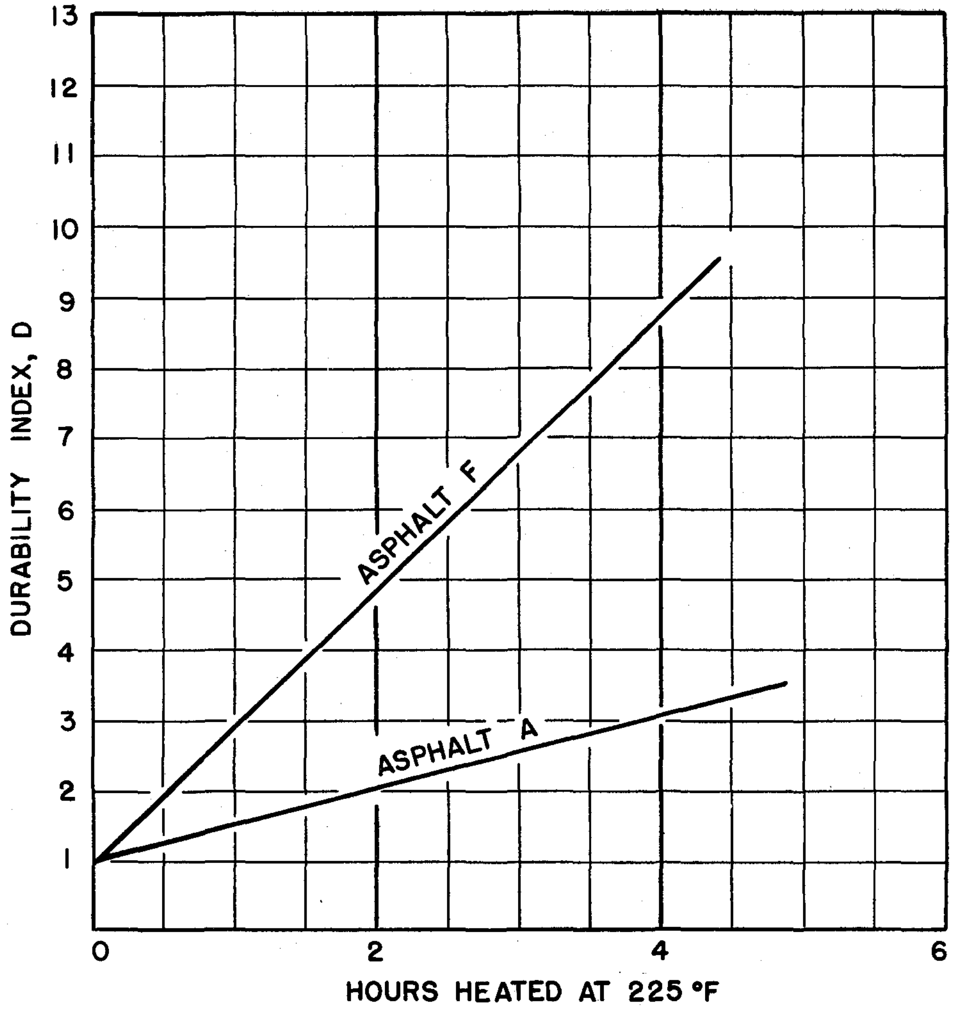

Figure 2—Time-durability index plots for fifteen micron films of asphalt heated in air at 225°F.

by the original viscosity of the asphalt. Table II gives the durability indices obtained by the Shell Thin-Film procedure. It is again clear that considerable differences exist in the resistance of the various asphalts to oxidation at 225°F. The same general relationship was found for these tests as for the thicker films heated to 325°F. Asphalts A, D, I, B, J, and G have low, and asphalts E, F, C, and H have high durability indices. Figure 2 is a plot of the time versus durability index for asphalts A and F, tested using fifteen micron films at 225°F.

From the data given in Tables I and II, it is evident that asphalts C, F, and H are subject to excessive hardening in both of the so-called thin-film tests. It would be justifiable to conclude that these three asphalts would probably be short-lived in the road. Asphalts A, D, and J have low indices from both tests, which indicates good resistance to hardening by oxidation. These asphalts should be long-lived in the road and a lower maintenance cost should be expected.

In the opinion of the writer, the results obtained by heating a fifteen-micron film are more reliable than those found by heating a $\frac{1}{8}$-inch (3000 micron) film. In the latter test the surface of the asphalt is oxidized and hardened during the heating period. Prior to testing, the hardened surface film is mixed with the softer, underlying portion of the asphalt, thus, the tests are made on a mixture of hard and soft asphalt, which even with the most careful blending may not be perfectly uniform. The fifteen-micron film test is susceptible to the same difficulty, but to a lesser degree.

A clearer understanding of the effect of oxidation on asphalts from different sources and methods of processing has resulted from this new approach based on measurement of consistency in absolute units. The differences in susceptibility to oxidation shown in Tables I and II cannot be detected by use of the less sensitive empirical tests such as penetration and softening point.

Examination of the data shows that some of the asphalts receive a lower durability index from one procedure and a higher one from the other test. A satisfactory explanation of such behavior is not yet available. It is interesting, however, to speculate on the causes for the differences in susceptibility to oxidation possessed by different asphalts. Work is in progress at the Institute on the chemical properties of the asphalts discussed above. Although the information now available is certainly inadequate to explain the underlying causes for the reaction of a particular asphalt to oxygen, we visualize that gradually the basic reasons will be brought into clearer focus. It is known that the asphaltenes (n-pentane insoluble portion of the asphalt) are readily oxidized when they are separated from the oily petrolenes (n-pentane soluble material). When the asphaltenes are mixed with petrolenes they are to a great extent protected from oxidation. It is a logical assumption that much of the resistance of an asphalt to oxidation lies in the chemical nature of the oils present. Increased knowledge concerning the chemistry of these components of asphalt will be important to the asphalt technologist, because the life of an asphaltic binder depends mainly upon retention of its original consistency under service conditions.

The next article in this series will discuss the causes for the development of structure in asphalt and the effect of such structure on the usefulness of road-building asphalts.

Research in Asphalt

PART III: STRUCTURE

The preceding articles in this series have dealt with (1) consistency and its measurement in terms of absolute viscosity [March] and (2) evaluation of the susceptibility of asphalts to oxidation [April]. Most asphalts are not simple liquids but possess some internal structure which affects their flow characteristics. Those which have structure are sometimes called non-Newtonian liquids to distinguish them from simple or Newtonian fluids. An asphalt selected for road building should possess essentially Newtonian characteristics. During service all asphalts harden and develop some internal structure. Thus, in building a road it is desirable to start with an asphalt that will harden and develop structure quite slowly. The degree of complex flow (non-Newtonian characteristics) possessed by a material may be most satisfactorily determined by viscosity measurements.

A short review of the procedure commonly employed for measurement of complex flow may be helpful. The viscosity of the asphalt is measured in an absolute viscometer (values are expressed in centimeters-grams-seconds) at three or four different shearing stresses or rates of shear. A plot of shearing stress versus rate of shear is called a rheology diagram. If the plot is prepared on arithmetic coordinates, simple (Newtonian) liquids give straight lines, but curved lines are obtained for asphalts possessing complex flow (non-Newtonian) characteristics. The greater the amount of internal structure, the greater will be the curvature of the line. If the rheology diagram is prepared using log-log cordinates, straight lines result for materials showing either simple or complex flow. Figures (1) and (2) illustrate the two types of rheology diagram. The log-log form is the most useful, because the line for simple liquids has a slope of 1.0, whereas the lines for complex liquids usually have a slope of less than 1.0. In special cases, where internal structure increases under increasing shearing stress, the value of the slope may be greater than 1.0. Such flow characteristics are unknown in asphalt.

The slope "C" of the log shearing stress versus log rate of shear curve is used to evaluate the degree of complex flow possessed by the asphalt. It is also an indication of the amount of internal structure in the material. Increased structure and resulting increased complex flow are both measured by a decrease in the value of "C." An increase in the value of "C" with increased shearing stress or rate of shear is caused by breakdown in the structure present. This change in internal arrangement results in a decreasing apparent viscosity as the asphalt is subjected to greater stresses or higher rates of shear. It will be recalled, from Part I, that the consistencies of asphalts are calculated at some common rate of shear (e.g. 5 x 10^{-2} reciprocal seconds) in order that the viscosities may be reported on a comparative basis.

Structure in asphalts may be influenced by a number of factors, most important of which are:

Source of the asphalt
Method of processing
Degree of processing

Quality Control IN ASPHALT

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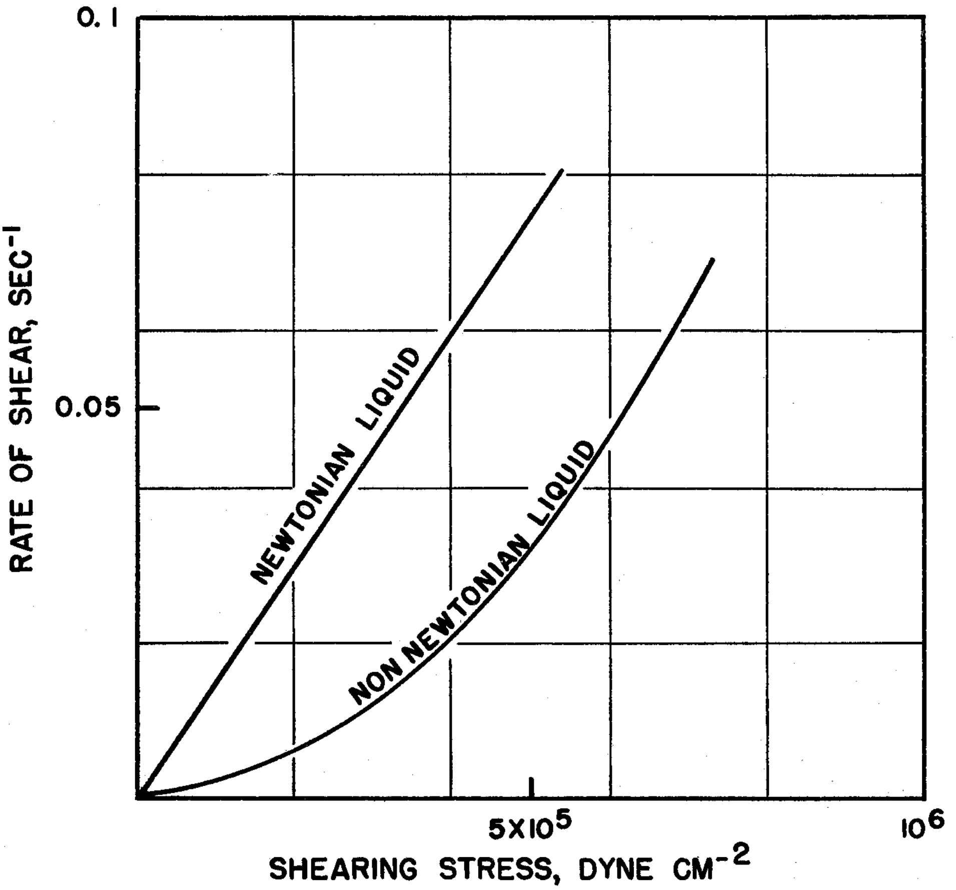

Figure 1—Rheology Diagram—Arithmetic Plot.

Heat and oxidation
Short wave lengths of light
Age hardening

These factors, responsible for the presence of structure in asphalts, will be discussed and illustrated by experimental data.

Source of the asphalt:

Crude oils used for the manufacture of high-grade asphalts are carefully selected, consequently, in reviewing the effect of source on the amount of structure in commercial road-building asphalts, only small differences are found. But, if asphalts from desirable and undesirable sources are investigated, large differences in their "C" values can be found Table I gives a good example of the magnitude of "C" to be expected from two asphalts from two different but satisfactory sources. These asphalts are quite different in rheological properties but are entirely suitable materials for certain uses.

The Gulf Coast asphalt has the

		Softening Point		
Source of Asphalt	Penetration @ 77°F	R&B °F	Megapoises @ 77°F	Complex Flow "C"
Gulf Coast	17	139	38	1.00
Venezuela	57	124	2.45	0.90

TABLE I

highest consistency (17 penetration and 38,000,000 poises at 77°F), but shows no complex flow and little, if any, internal structure. On the other hand, the much softer Venezuelan asphalt possesses some structure as indicated by the lower value of "C."

Method of processing:

The method of processing the asphalt from a given crude oil has a considerable effect on the amount of structure present. This is illustrated by Table II on two asphalts made from the same East Texas Crude by steam reduction and by air blowing.

		Softening Point		
Process	Penetration @ 77°F	R&B °F	Megapoises @ 77°F	Complex Flow "C"
Steam reduction	176	103	0.40	1.00
Airblown	196	106	0.32	0.85

TABLE II

Here, the steam-reduced asphalt, the harder of the two (176 penetration and 400,000 poises at 77°F), is essentially a viscous liquid with a "C" value of 1.00. The air-blown product is slightly softer but possesses considerable structure, as indicated by the "C" value of 0.85. Generally, an air-blown asphalt made from a given crude source manifests more complex flow than a steam-refined asphalt of the same viscosity prepared from the same oil.

Degree of processing:

Increased extent of processing also may result in an increase in the amount of structure present in asphalts made from the same source. The relationship between hardness and the degree of complex flow is illustrated by the properties of the following two steam-reduced asphalts prepared from an East Texas crude oil, shown in Table III.

		Softening Point		
Sample	Penetration @ 77°F	R&B °F	Megapoises @ 77°F	Complex Flow "C"
Soft	176	103	0.40	1.00
Hard	30	137	14.3	0.95

TABLE III

Although the hard asphalt has a viscosity 35 times that of the softer product, the amount of structure present is small ("C"=0.95). Extended air blowing produces, however, great differences in asphalts from the same source. Two asphalts air blown from a Northeast Texas crude are listed in Table IV to show the extensive amount of complex flow (structure) that may be developed in an asphalt by continued oxidation.

In this case, although the hard asphalt is only twelve times more viscous than the soft product, large amounts of structure are present ("C"=0.50). An increase in the extent of air blowing always results in a more exaggerated increase in structure than occurs with the same increase in consistency or hardness by steam reduction.

Heat and oxidation:

All asphalts show some increase in complex flow when heated for a prolonged time in air or oxygen. The extent of hardening will depend upon the temperature, time of heating, source, and method of processing the asphalt. In Part II of this series, data were given to illustrate differences in susceptibility to oxidation shown by a number of asphalts. The degrees of complex flow "C" for four of these are shown in Table V.

Heating and oxidation resulted in

Sample	Penetration @ 77°F	Softening Point R&B °F	Megapoises @ 77°F	Complex Flow "C"
Soft	149	112	0.64	0.90
Hard	49	162	7.9	0.50

TABLE IV

the development of internal structure within each asphalt and a decrease in the values of "C." It will be noted that the reaction is not the same for the various asphalts. A radical increase in the amount of structure (complex flow) is undesirable. In fact, it may be as serious as a marked increase in absolute viscosity on heating in air. Although Asphalt E has a moderately low durability index (4.0) after oxidation at 225°F for two hours, the rapid appearance of structure indicated by the 0.50 value for "C" is a warning that the asphalt will have a short life in the road.

Asphalt	Amount of Complex Flow "C"		
	Unexposed	15 micron film exposed at 225°F	
		2 hours	4 hours
A	0.90	0.80	0.75
C	0.90	0.75	0.70
E	0.85	0.65	0.50
H	0.85	0.80	0.75

TABLE V

Short wave lengths of light:

Figure 3 shows the effect of artificial sunlight on the viscosity and degree of complex flow "C" of Asphalt X. The asphalt unexposed to light had a viscosity at 77° of 6.5×10^5 poises at a rate of shear of 5×10^{-2} reciprocal seconds. The value of "C" was 0.90. This indicated that the asphalt possessed only a small amount of structure. Exposure of a fifteen-micron film to visible light at 180°F for 24 hours in the absence of air had changed the properties markedly. The viscosity at 77°F rose to 5.0×10^6 poises and the value of "C" decreased to 0.50. This excessive hardening and large increase in structure was caused by the light passing through Pyrex glass No. 7740. These results indicate what can happen to an unprotected film of asphalt exposed to the summer sun. The changes caused by the action of light vary among different asphalts.

Age hardening:

It was discovered many years ago that asphalts increase in viscosity on aging because of the development of internal structure. This effect takes place at a constant temperature and in the absence of light and oxygen. The age hardening phenomenon was first detected by the penetration test, but its real significance became apparent when means were found to measure high consistencies in absolute units. The procedure is quite simple for evaluating the age hardening of an asphalt. Six or seven viscometers, preferably of the rotating cylinder type, are filled with asphalt and stored in the dark at a constant temperature, e.g. 77°F. One instrument is removed from the constant temperature chamber after one hour and the viscosity evaluated at an established rate of shear. The remaining viscometers are maintained at the constant temperature and tested at approximately 24, 72, 190, and 1,000 elapsed hours. Examples of different degrees of age hardening are given in Table VI. Asphalt Y increased about 10 per cent in viscosity during storage for almost 1,000 hours at 77°F. Asphalt Z is quite different. During 700 hours of storage this material increased about 250 per cent in viscosity.

Most of the age hardening shown for asphalts Y and Z can be destroyed by mechanical working or heating to about their softening point, but a small per cent of the increase in viscosity is permanent. Heating may be done in the viscometer without subjecting the asphalt to either light or oxygen. Destruction of structure by mechanical working can be accomplished in the viscometer by applying high rates of shear for a considerable period of time. Of course, after shearing has ceased the structure will start to build up again and the viscosity will increase. Also, after a heated sample has cooled, the age hardening

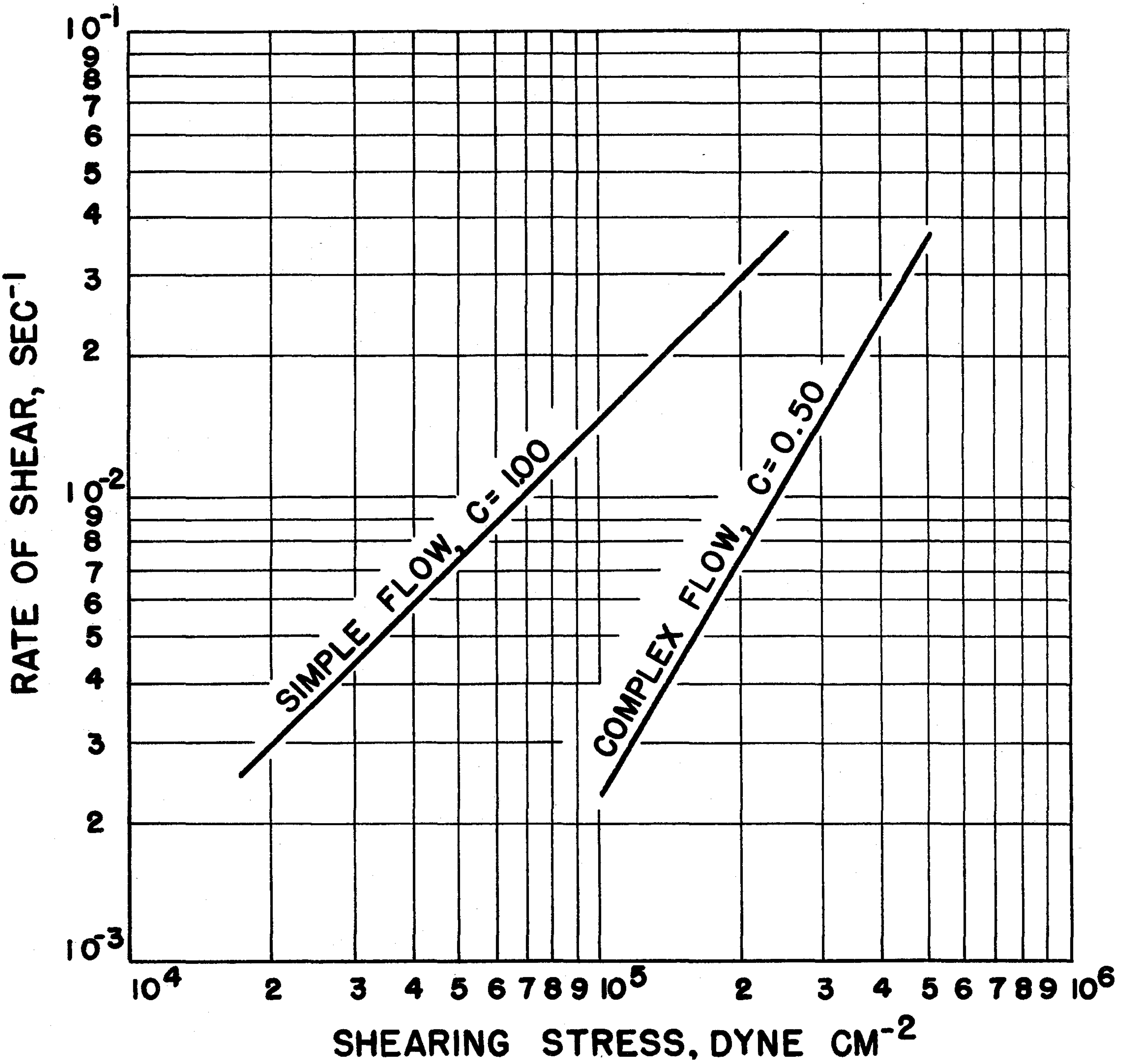

Figure 2—Rheology Diagram—Log-log Plot.

process will repeat itself. Permanent hardening will gradually increase as these processes are repeated. It is suspected that the ratio between non-permanent and permanent hardening may be an important characteristic of any asphalt. It is logical to conclude that an asphalt manifesting low age hardening should be a longer lived road binder than one which shows an excessive increase in consistency with the passage of time.

In summation, asphalts which oxidize readily, with a resulting increase in viscosity, and those which possess or develop excessive internal structure are likely to be a problem to the road builder. These changes in the asphalt, which reduce its usefulness as a binder for aggregate, can be evaluated by means of rheological methods based on the determination of absolute viscosity. Use of these precise and discriminatory methods of test will help clarify our understanding of the role of asphalt as a binder in the construction of highways.

The fourth article in this series will consider the adhesiveness of asphalts for the aggregates used in road building and will point out the problems which face the asphalt technologist in this field.

TABLE VI

Age Hardening of Asphalts at 77°F in Absence of Light and Air

ASPHALT Y		ASPHALT Z	
Time of Aging, Hrs.	Viscosity, Megapoises at 77°F	Time of Aging, Hrs.	Viscosity, Megapoises at 77°F
3	2.11	4	12.3
24	2.12	26	15.1
51	2.14	52	16.3
96	2.14	100	18.8
168	2.18	171	21.7
936	2.26	700	31.4
8834	2.49	1850	41.9

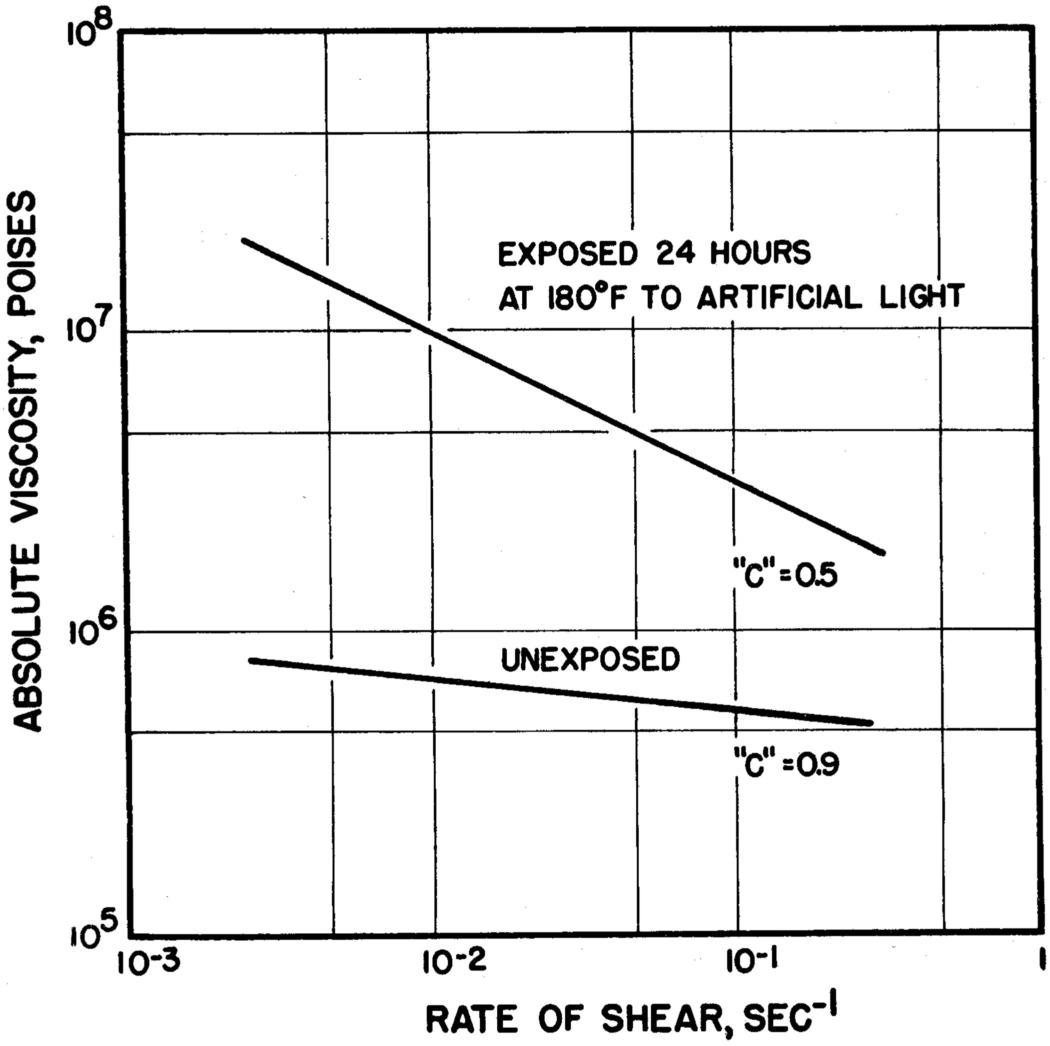

Figure 3—Hardening of Asphalt by Light in Absence of Air.

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Research in

PART IV

The effects of consistency and other flow properties of asphalt on its usefulness as a binder have been discussed in the preceding papers of this series. [See the March, April, and May issues of "Texas Highways" for the first three papers of this series by Dr. Traxler.] Included were illustrations of the hardening and development of structure in asphalt by heat, oxygen, and age. Knowledge of these properties are useful to the technologist interested in building a long-lived bituminous road. But, there is another characteristic of asphaltic binders which is extremely important to the highway engineer, namely, its adhesiveness for a stone surface. Moreover, this adherence must be retained under the most severe field conditions.

The problem of adhesion is especially difficult because of the number and nature of the factors involved. For example, the kind and history of the stone, and the chemical properties and consistency of the asphalt all influence the bond between the solid and liquid. In addition, the temperature of the stone and asphalt, and the presence of moisture and dust on the aggregate must be considered in any experimental approach to the subject. It is difficult enough to measure quantitatively the adhesion of a viscous liquid like asphalt to a uniform surface under ideal laboratory conditions. But, the problem is made much more troublesome by the large number of different aggregates used in road building and the far-from-ideal conditions encountered during construction. Practical experience has shown that the nature of the stone and the history of the solid surface (whether new or weathered) have a greater effect on adhesion at the solid-liquid interface than does the nature of the asphalt.

The interfacial force (interfacial tension) between a solid and a liquid is referred to as adhesion and may be evaluated by the contact angle the liquid makes with the solid surface. Asphalt spreads easily over most dry, solid surfaces and consequently presents a small angle of contact. Experimental work, using different asphalts and sands treated in a number of ways, has shown the contact angle to vary from 0 to 47°. The presence of chemically active (polar) materials in the asphalt lowers the angle of contact and increases the adhesion of the asphalt for the stone surface. Addition of nonpolar compounds (e.g., paraffin wax) to the asphalt decreases its adhesiveness to stone. Recent investigations have indicated that when the binder is fluid, its adhesion is controlled by the flow properties of the binder. However, as the consistency increases, because of a lowering of the temperature or for any other reason, the adhesion is influenced more by the molecular forces acting between the solid and liquid.

Adhesion of asphalt to a water-wet surface is poor, that is, the angle of contact is high. Also, when water enters a stone-asphalt interface during service the bond is decreased and may be broken. This tendency for water to prevent or destroy the adhesion of the asphaltic binder in a bituminous road is a constant source of irritation to the highway engineer. Another factor which influences the magnitude of the forces operating at the solid-asphalt interface is the adsorption of certain components of the asphalt by some types of stone. This action usually enhances the bond between the solid and liquid, although situations could arise which might be deleterious to the strength of the bond. Research is needed on this subject. For purely physical reasons the surface texture of the stone is important in determining its adhesion to

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ADHESIVENESS OF ASPHALT TO STONE

asphalt. A smooth surface will not hold an asphalt as tenaciously as a rough, porous surface, irrespective of the chemical natures of the solid and liquid.

Experience has taught that asphalt generally adheres more strongly to an alkaline stone (e.g., certain limestones) than to an acidic one (e.g., rhyolite or silica). This happens because asphalt is slightly acidic in nature and, thus, there is a certain amount of chemical affinity between the alkaline stone and the acidic asphalt. By increasing the chemical activity of the asphalt, its adherence to borderline or acidic stones can be enhanced. This is done commercially by the addition of small quantities of polar chemicals to the asphalt.

Stripping by Water

Destruction of the stone-asphalt bond by entrance of water has been the subject of many investigations. Unfortunately, most of the tests have been highly empirical. The first work of practical importance was done simultaneously in the United States and Germany about 25 years ago. Static stripping tests were first developed, but later dynamic tests were developed in which the asphalt-coated aggregate was agitated with water or an aqueous solution. In these stripping tests the stone of uniform particle size is mixed with adequate asphalt to completely coat each particle. If curing is specified, the coated stone is held for the required period of time at the stipulated temperature. The coated stone is then placed in water at a given constant temperature and for a definite period of time, or it is agitated under specified conditions. In some tests the water is drained from the stone, which is then examined visually for uncoated areas. The American Association of State Highway Officials has a prescribed standard method (T 182-57) for such a test. Their outline of the method is as follows:

"The selected and prepared aggregate is coated with the bitumen at the proper temperature indicated for the grade of material used. A curing period is given the bituminous coating except semisolid asphalts, depending upon the type of solvent (if any) contained. After curing, the coated aggregate is immersed in water for a definite period of time. At the end of the soaking period, and with the aggregate under water, the total area of the aggregate on which the bituminous film is retained is rated visually as *above or below 95 per cent.*"

The variety of stripping tests used by the various State Highway Departments is shown as Appendix I of A.S.T.M. Special Technical Publication No. 240 (1958). This publication is the result of a symposium on "Effect of Water on Bituminous Paving Mixtures." It comprises discussions of field and laboratory tests, aggregate characteristics, antistripping additives, and advanced test procedures.

The time of curing in all tests for adhesion is an important factor. Conditions used vary from no curing time to 24 hours at 140°F. With such a wide range in curing conditions it is possible to obtain a great variety of values for adhesion. Probably there exists an optimum temperature and time for best results, but so far no complete agreement has been obtained among asphalt technologists. It seems logical that the temperature used should be high enough and the time long enough to remove any moisture from the interface. This raises the important idea that, for hot-mix construction, the aggregate should be dried as thoroughly as possible, and the mixing temperature and time should be adequate to give perfect adhesion before the mixture is placed on the road. It is only when asphalt emulsions are used that the presence of moisture on the stone surface can be safely ignored.

Test tracks have been used for evaluating the adhesion of asphalt in paving mixtures, and in some cases excellent conclusions have been drawn from the results. In recent years the Immersion Compression Test has been recognized as promising for measuring the degree of adhesion at a stone-asphalt interface. This test is based on the idea that complete coverage of a piece of stone by asphalt does not mean that good adhesion

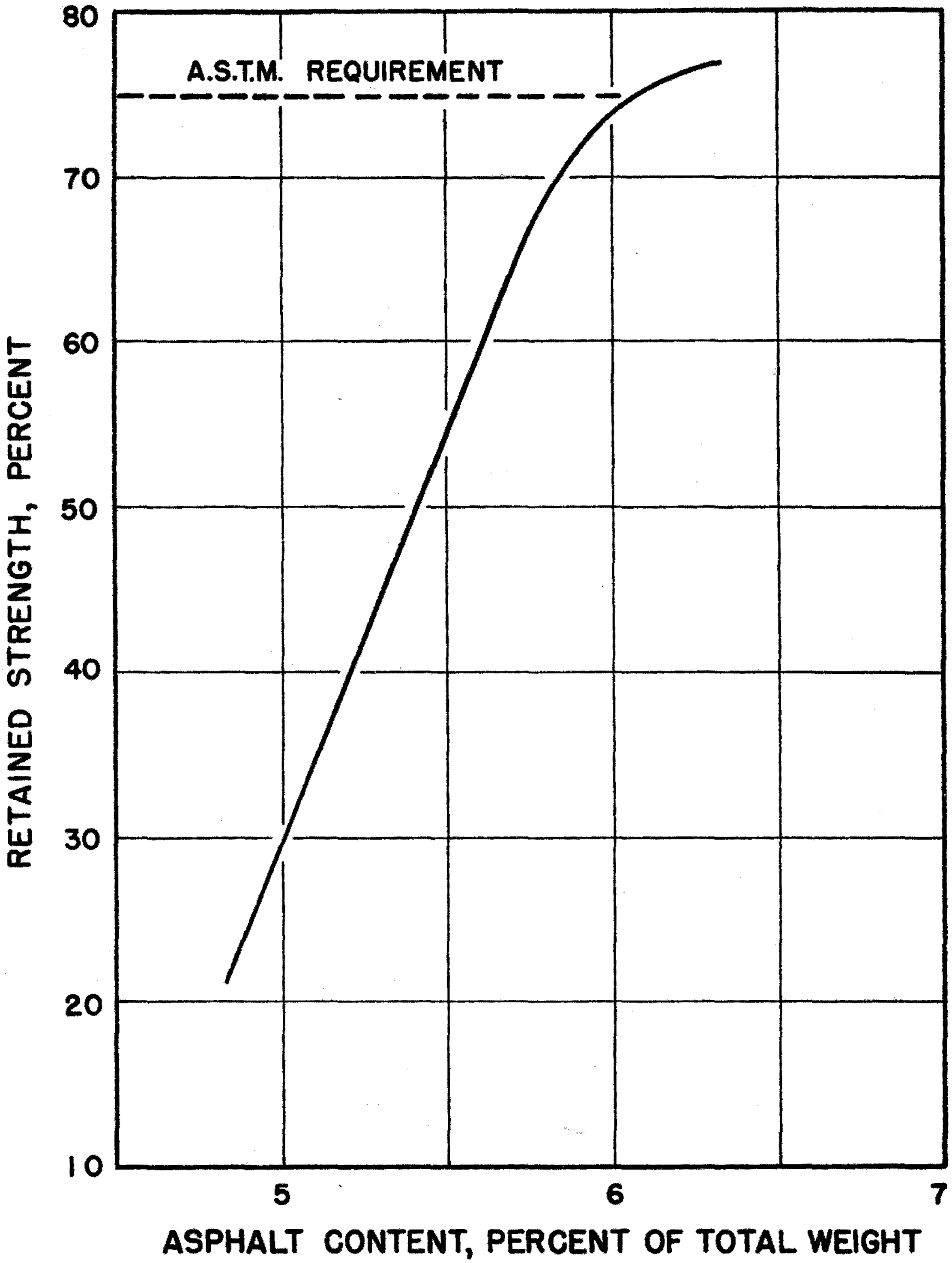

Figure 1

exists at the stone-asphalt interface. Although the asphalt may cover the stone so completely that no stone surface is visible, moisture may have entered the interface and destroyed the bond. Such insidious destruction of the adherence between the stone and asphalt can ruin to a great extent the value of the asphalt as a binder. The Immersion Compression Test was devised to detect the development of such weakness in a bituminous mixture. It has been used extensively by the Army Corps of Engineers and is advocated by the American Society for Testing Materials (Method D-1074-58T) for evaluating the adhesion between asphalt and road-building aggregates. In this test six briquettes four inches high and four inches in diameter are prepared and cured in air for 24 hours at 140°F. Three of the samples are then maintained at 77°F for five hours, after which time they are tested for compressive strength at 77°F. During compression the briquettes are unconfined. The other three samples are immersed in a water bath maintained at 140°F for 24 hours or at 120°F for 96 hours. At the end of the prescribed time, the soaked briquettes are placed in a water bath at 77°F and held at that temperature for at least two hours. Unconfined compressive strengths are then determined at 77°F. per cent of retained compressive strength is calculated from the experimental data. Amount of deviation from 100 per cent retention is considered a measure of the loss in adhesion caused by water action.

The plot in Figure 1 shows the relationship between per cent asphalt by weight in a mixture *versus* retained compressive strength of the mix after immersion in water for 24 hours at 140°F. The data shown were obtained on mixtures prepared from an OA-90 asphalt and a particular aggregate, possessing a sand equivalent of 30-35. Retained compressive strength is low (30 per cent) when 5 per cent asphalt is used to make the mixture, but the curve rises as the amount of asphalt is increased to 6 per cent. Above this value the curve tends to flatten and a considerable increase in asphalt content has a small effect on retained strength. A.S.T.M. specifies a retained compressive strength equal to 75 per cent of the value for the cured unsoaked material. Figure 1 shows that the use of adequate asphalt in a mixture decreases the possibility of excessive deterioration through water action at the stone-asphalt interface. The properties of the asphalt and the nature and grading of the aggregate also influence the results of this test. Caution should be used in drawing sweeping conclusions from immersion compression data. Some aggregates may show unexpected results. Dirty stone affects the experimental values adversely.

Additives to Improve Adhesion

During the past twenty years a large number of materials have been proposed as additives to improve adhesion of asphalt for stone. Most of the additives are complex compounds or mixtures which have a powerful wetting action on stone and metal surfaces. When present in asphalt (0.2 to 1.5 per cent) they possess the power to displace water from the solid surface and make it possible for a firm bond to be established between the stone and asphalt. One of the vexatious situations encountered early in the use of these asphalt adhesion additives was their deterioration by heat. When it was necessary to maintain the treated asphalt at a temperature of 125 to 250°F for a period of time, the additive lost much of its effectiveness. However, through extensive research by the additive manufacturers, this difficulty has been surmounted and now heat-stable formulations are available.

Recently, the commercial development of cationic emulsions appears to offer a solution for certain adhesion problems connected with the use of asphalt emulsions. The older, well-known anionic type of emulsion usually adheres quite well to alkaline stone. This is because such an emulsion carries a negative charge on the surface of the asphalt particles and the alkaline types of stone carry a positive surface charge. However, the anionic emulsions do not adhere too well to a stone carrying a negative surface charge (e.g., most acidic rocks). Since the particles in the newer cationic emulsions carry a positive surface charge, adhesion is good for acidic stones possessing a negative surface charge. The presence of water has no deleterious effect on the adherence of asphalt deposited from a cationic emulsion. Breaking of such emulsions, and deposition of the asphalt on the stone, is purely a chemical reaction and does not depend on the evaporation of water as is the case for the well-known anionic type. Thus, the newly developed cationic systems appear to offer considerable promise for solving the adhesion problem encountered in the application of emulsions. This is especially true in climates where the rainfall is heavy.

Summarizing this brief discussion, it is evident that the creation and maintenance of a strong bond between the stone and asphalt in a bituminous pavement is one of the most serious problems facing the road builder. The problem is unusually difficult because of the great variations in chemical nature, cleanliness and history of the aggregates, and the chemical properties of the asphaltic binders. Fortunately, methods have been developed which give quantitative data concerning loss of adhesion in a particular mixture. The knowledge obtained from such evaluations makes possible the avoidance of certain mistakes made in the past. Also, additives and procedures have been formulated which help prevent loss of adhesion at the stone-asphalt interface. Nevertheless, attainment of complete adhesion remains one of the most pressing problems in the field of asphalt technology.

The final article in this series will be a summary and discussion of the factors affecting the serviceability of bituminous highways, especially at low temperatures.

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Research in

PART V: FACTORS AFFECTING

In the preceding articles of this series we have discussed briefly (1) the consistency of asphalt and how it can be measured accurately, (2) the susceptibility of asphalt to hardening by oxidation, (3) the variables that influence the amount of structure in an asphalt, and (4) the adhesiveness or bonding of asphalt to stone. (These articles appeared in the March, April, May, and June issues of "Texas Highways.")

There are a number of factors that may influence the life expectancy or serviceability of a bituminous pavement. Some are not concerned directly with the properties of the asphalt but to a certain degree each may contribute to the durability of the binder and, thus, of the entire road. We will start at the beginning of the highway construction procedure and mention some of the factors that affect the serviceability of the final product.

Foundation or Base

Inaccurate or inadequate evaluation of the soil structures through which the road is to be built and failure to correct weaknesses that exist can result in serious reduction of service characteristics of the finished road. For example, if the foundation is composed of a clay, which expands and contracts with gain and loss of water, deterioration of the traffic-bearing structure can be expected to occur. The most satisfactory asphaltic binder cannot be expected to withstand the disruptive forces exerted by such severe soil movements.

Poor drainage frequently contributes to the deterioration of a roadbed. In addition to causing expansion of certain kinds of clay, as mentioned above, presence of water weakens the bond between the asphalt and aggregate. Excessive moisture may also cause certain aggregates to disintegrate. Water entering from the subgrade can cause serious deterioration of the road even when the best aggregates and asphalts are used. In subfreezing weather the presence of water in the foundation or road can become a serious problem because of ice formation, especially if there is present an excessive amount of fines in the aggregate. It is conceded by most road builders that the entrance of moisture into the foundation and surface layers is one of the important factors adversely affecting the serviceability of a bituminous pavement.

Road Surface

Assuming that a suitable foundation has been prepared and adequate drainage assured, deterioration of a bituminous pavement must be related to the road surface, which is composed of a mixture of stone and asphalt. Logically, the required thickness of the bituminous surface will depend upon the weight and volume of traffic it is expected to carry. Satisfactory serviceability cannot be expected if the design and/or thickness of the bituminous mixture is not adequate to support the traffic. Under such conditions, failure cannot be attributed to unsatisfactory properties of the asphalt per se.

A common cause of weakness is the use of a bituminous mixture, which after compaction is so open and porous that it permits the entrance of air and water. This can result in hardening of the asphalt and weakening of the bond between the asphalt and stone. An open, porous pavement surface, which is susceptible to rapid deterioration, may be caused by insufficient asphalt to properly fill the voids in the aggregate and/or by inadequate compaction of the asphalt mixture. Poor compaction may result from allowing the hot mixture to cool before compaction is started. Or, the rollers used may be too light in weight for the layer of mixture. In some cases too few passes are made with a heavy roller. The type of roller used may, also, have an important bearing on the degree of compaction. If, after all precautions have been taken, a porous surface results it is advantageous to apply a light seal coat. The increased durability gained by such an application is sound economy.

Aggregate

Quality of the aggregate used in construction of a pavement has an important part in its durability in service. First of all, the stone must be properly graded to give a mixture of adequate strength. Next, it must be hard enough to resist degradation during handling and compaction of the mixture and by the forces applied in service. Further, the aggregate should not be susceptible to disintegration

Asphalt Quality Control

SERVICEABILITY OF A BITUMINOUS PAVEMENT

because of reaction with water or air. Presence of deleterious fines adhering to the stone surface is a most undesirable condition because it interferes with a good bond between the asphalt and aggregate.

Use of a stone which is capable of absorbing some of the low viscosity components of the asphalt may result in reduced serviceability because of excessive hardening of the binder and reduction of the film thickness. The absorptive effect occurs only with a porous stone and is likely to be most serious with a "gel-type" or poorly dispersed asphalt. Such a binder can loose a considerable amount of oil to a porous stone through capillary attraction. In a well-dispersed or "sol-type" asphalt the oil is not so free to migrate into the pores of the stone. There are indications that the chemical compositions of certain aggregates accelerate the oxidation and hardening of asphalt films, but little is known about the effects that occur at the interface between aggregate and asphalt. This is a challenging problem in the field of asphalt technology.

Asphalt

We now come to our basic theme, namely the effect of the asphaltic binder on the service characteristics of a bituminous pavement. The form in which the asphalt is used is important. The binder may be blended with the aggregate as (1) an asphaltic cement, which must be heated to yield a viscosity low enough to permit handling and mixing, (2) a cutback in which the asphalt is dissolved in a hydrocarbon solvent to obtain a low viscosity, and (3) an emulsion, which is a dispersion of asphalt in an aqueous solution to give a reduced viscosity at atmospheric temperatures. Each of these forms are attractive and valuable to the road builder under particular circumstances but he must use considerable judgment in his selection. Of the 15 million tons of paving asphalt used in the United States during 1959, slightly over 50 per cent was in the form of asphalt cement, about 40 per cent was some type of cutback, and the remainder, less than 10 per cent, was asphalt emulsion.

Consistencies of the asphalt cements commonly used in road building vary from 200 to 60 penetration (0.2 to 10 million poises) at 77°F. Selection of the most suitable consistency for a particular job sometimes poses a problem. The argument usually advanced for use of a soft binder is that an asphalt of low viscosity will yield a pavement of long serviceability because a greater period of time will be required for the bitumen to attain a hard, brittle, nonadhesive condition. This argument appears quite logical but there are certain factors which oppose its complete acceptance. Assuming all other variables (aggregate grading, etc.) are maintained constant, it is possible to incorporate more hard asphalt into a mixture and obtain satisfactory stability, than when a soft asphalt is used. Attainment of a given set of engineering flow properties, such as stability and cohesion, with a soft asphalt means use of a limited amount of asphalt spread through the mixture in the form of thinner films than are obtained with a harder binder. The thinner films will harden at a more rapid rate than will the thicker, more viscous ones, thereby reducing the advantage obtained by starting with an asphalt of lower viscosity. The use of larger amounts and thicker films (obtained by employing harder asphalts) naturally results in a paving mixture that is better protected from the deteriorating action of entering air and water. Another phenomenon that tends to result in the more rapid hardening of a soft asphalt, thereby offsetting its original advantage, is the greater absorption of oily components by porous aggregate. When an absorbent aggregate is used, some of the lighter components are removed even from a 60 penetration (10 million poise) asphalt, but the effect is more pronounced and occurs over a longer period of time when a 200 penetration (0.2 million poise) asphalt is used. Thus, the advantages frequently mentioned for the use of a low-viscosity asphaltic binder are to a considerable extent reduced by a number of factors not usually contemplated. Consistency of the asphalt should also be considered in relationship to climatic conditions. There seems to be general agreement that road building in tropical or semitropical climates requires use of a somewhat harder asphalt than should be used for road construction in temperate or subarctic regions.

A disadvantage attached to the use

of some types of cutbacks is the low viscosity of the asphalt present in the mixture. This means that the amount of asphalt incorporated into the pavement must be reduced to obtain the necessary stability. As mentioned above, the films of soft asphalt are thin and subject to rapid hardening. Because of the fluidity of the liquid in contact with the aggregate, extensive absorption may occur if a porous stone has to be used. These effects vary, naturally, with the grade of cutback and the kind of asphalt used in its manufacture. It may be pointed out here that medium-curing cutbacks (made with a soft asphalt) are most widely used, but the rapid-curing materials (containing somewhat harder asphalts) follow closely in tonnage consumed.

Asphalt emulsions for road building are usually prepared from soft asphalts (about 0.2 million poises at 77°F) and, thus, are subject to the factors influencing the behavior of the same consistency asphalts used in the form of cutbacks or cements. The use of asphalt emulsions and cutbacks in the construction of soil-stabilized roads also raises another problem. When the soil contains certain types of clay, *adsorptive* forces may enter the picture. In this situation the highly adsorptive mineral surface removes the harder components (asphaltenes) from the asphalt and leaves as a binder a softer material than was originally mixed with the soil.

For various reasons the road builder may use too little asphalt in the design of his mixture. This situation can develop through his attempt to attain a set of engineering characteristics that will assure satisfactory behavior under the anticipated traffic load. He may have been embarrassed in the past by building a road that shoved under traffic or exuded asphalt and became slippery during rainy weather because of too much asphalt for the aggregate used. The result of such an experience is a tendency to play safe and use too little rather than too much binder. Use of a low-viscosity asphalt will tend to accentuate this trouble. There is less risk involved in the use of a high viscosity binder. The road builder can, to some extent, escape the dilemma posed above by using an asphalt possessing a viscosity slightly above one million poises (below 90 penetration) because he can put more asphalt and thicker films into his mixture. He, thereby, obtains a more durable road because it is less subject to deterioration under service conditions. Use of a high-quality asphalt cannot entirely overcome the deteriorating effect resulting from the presence of even 0.5 per cent too little asphalt in the paving mixture.

Now that we have discussed some of the conditions responsible for a change in binder consistency, let us turn our attention to the asphalt itself. Road-building asphalts, all of which fall within present consumer specifications, can vary widely in composition and in behavior under service conditions. In recent years, advances have been made in procedures for evaluating asphalts in respect to their anticipated resistance to deterioration during construction and use in a highway. It has been shown in Part II of this series that different asphalts, meeting standard requirements of specific gravity, penetration, softening point, and ductility, may vary widely in their susceptibility to hardening when subjected to the effects of heat, oxygen, actinic light, and aging. What is the cause of this difference in behavior among various asphalts? The explanation most likely will be found in the colloidal characteristics of the bitumens, which in turn, are linked to their chemical composition. To obtain a long-lived pavement, an asphalt should be used which possesses the chemical composition required to give a well-dispersed system capable of resisting to the greatest degree the hardening and deteriorating influences encountered during construction and service. In addition to possessing low susceptibility to hardening by heat, oxygen, and sunlight and the development of limited internal structure upon aging, the binder must exhibit adequate adhesion for the aggregate. The strength of the bond between the binder and aggregate depends on the chemical composition of both the asphalt and the stone. Bonding strengths of paving asphalts for aggregates have been improved by the use of small amounts of adhesion additives.

It is evident that the failure of a bituminous pavement to give the ultimate in serviceability may be caused by any or all of a number of factors involving design and the quality of material. These may be operating as complimentary or conflicting effects. Although quality of the asphalt—especially in respect to its ability to resist hardening and loss of adhesiveness—is most pertinent, it is only one of many elements contributing to the service life of the bituminous pavement. The asphalt should not be made the whipping boy for all of the failures that occur. However, a vigorous and sincere effort should be made to supply the road builder with the best binder it is possible to manufacture.

Many different types of failure in bituminous pavement could be illustrated; only one has been selected for use here. The particular example is a hot-mix asphaltic concrete overlay on a portland cement concrete base. After about eighteen months of service, the surfacing material had eroded away in places. Figure 1 shows one of the eroded spots. The asphalt used met OA-90 specifications. A stock sample from storage at the plant possessed a penetration of 87 (1.2 million poises) at 77°F. Quality of the asphalt was about average in its resistance to hardening by heat and oxygen.

A few pounds of the surfacing material were removed from a location adjacent to the eroded area shown in Figure 1. Benzene was used to extract the bitumen from this sample and the asphalt was recovered from the benzene solution by the standard Abson recovery procedure. The asphalt obtained from the deteriorating surface course had a penetration of 30 at 77°F. Thus, by this test it had hardened about threefold in the preparation and laying of the hot mixture and during eighteen months of service. Viscosity of the recovered asphalt was found to be 19 million as compared with 1.2 million poises for the original asphalt, or a 15.8 fold increase in hardness by this method for evaluating consistency. These values offer another example of the greater sensitivity and precision obtained by using viscosity for the measurement of consistency.

What were the causes for the failure of this surface and for the excessive hardening of the asphalt? The answer probably can be found among the following factors:

(1) The asphalt possessed somewhat inferior resistance to the action of heat, oxygen, and sunlight.

(2) The films of asphalt on the stone were overheated and oxidized during preparation of the mixture.

(3) Insufficient asphalt was used in the mixture.

(4) The mixture cooled on the road before compaction was started, resulting in an open, porous surface.

(5) Improper compaction techniques were used, resulting in a low-density surface.

(6) Inadequate compacting equipment was used.

(7) A poor grade of aggregate was employed.

From observation of the road it was apparent that the surface was open and had allowed air and moisture to enter, which accelerated the hardening of the asphalt and weakened or destroyed the bond between the aggregate and binder. The stone did not appear to be of high quality. A careful scrutiny of any road failure should bring to light one or more of the factors mentioned above as responsible for poor durability.

Summary

These short discussions concerning the properties of road-building asphalts began, in Part I, with a review of the methods used for evaluating their consistencies. It was shown, by recently obtained data, that consistency measurements expressed in absolute units of viscosity are more sensitive, discriminatory, and informative than the commonly used penetration test. An up-to-date microfilm viscometer for measuring the viscosity of thin films was illustrated and discussed.

Part II described procedures for evaluating the susceptibility of a paving asphalt to oxidation. The viscosity of an asphalt before and after heating films of various thicknesses in air at temperatures from 225° to 325°F were measured in the microfilm viscometer. It was shown that a group of commercially available OA-90 asphalts varied widely in their resistance to the hardening effect of heat and oxygen and presumably to their durability in the road. The thesis was advanced that the susceptibility to oxidation and hardening is dependent upon the chemical composition of the asphalt.

The causes for the development of structure in an asphalt were considered to reside in (1) source of the asphalt, (2) method of processing, (3) degree of processing, (4) effect of heat and oxygen, (5) effect of short wave lengths of sunlight, and (6) age hardening. Examples of each were shown in Part III. Evaluation of internal structure in asphalts by rheological (flow) measurements was described.

The practical importance of a good bond between the asphalt and aggregate was pointed out in Part IV. Available methods for evaluating adhesion were mentioned, and the difficulties encountered were stressed. An example of the type of data obtained by the Immersion-Compression method was given. The use of adhesion additives was cited and the recently developed cationic type of asphalt emulsion was discussed because of the good adhesion obtained with acidic types of stone.

Finally, in this current section, a brief review has been made of the numerous factors that influence the durability of a bituminous pavement. Poor design, low-quality aggregate, inferior handling of the materials during mixing and application to the road and, finally, the use of asphalts that are not sufficiently stable and resistant to hardening are the most important causes for failure.

The purpose of this series of articles has been to present in the briefest possible form some of the latest advances in asphalt technology. The author will be happy if he has inspired the reader to a constructive train of thought concerning the problems involved in the construction of high-quality bituminous pavements.

Man has used asphalt for several thousand years, but only recently has he learned a little about its unique characteristics. The current investigations on asphalts and bituminous pavements at the Texas Transportation Institute are directed expressly to a fuller understanding of this adhesive material and to the practical problems encountered in the improvement of its quality for use in pavements.

Figure 1—Eroded spot in a hot-mix asphaltic overlay on a portland cement concrete base after eighteen months' service.