The most profitably used basic engineering property of liquid asphalts and asphalt cement is the thermo-plasticity. The change of viscosity or fluidity with temperature is one of the most important engineering properties of asphalts.

When asphalt first came in use, its hardness was determined by chewing a small portion. It soon became evident that consistency was a very important property of bituminous material. The highway engineer now uses consistency values to select a bituminous binder for a particular use and also as a basis for adjusting certain construction operations.

Consistency is an important property to study the ultimate performance and durability of pavements. Asphalt specifications relating to consistency have occupied a static state for the past forty years. It is only during recent years that the asphalt technology has been trying to lift asphalt testing and use out of the realm of the arts to one of science and engineering. The present specifications are, for the most part, arbitrary physical properties.

The situation with respect to highway construction is changing faster than ever. Highways must now be built
to accommodate faster and more frequent traffic; there is a demand to permit heavier loads; and the economic conditions require that the highways last longer. To accomplish these aims, more research is needed. The fundamental principles of pavement design and the properties of the materials used must be determined more precisely.

Viscosity is the scientific measure of consistency as portrayed by the resistance to flow caused by molecular friction. For years, the value of the viscosity test has been clouded by the use of an arbitrary method, viz. Saybolt Furol viscosity test. The other arbitrary tests of consistency measurements are: (i) Float test, (ii) Ring and ball softening point test, and (iii) Penetration test. These tests have inherent weakness in them and measure consistency in a wide variety of units, viz. time, length and temperature. There has been a long felt need for adoption of fundamental units of viscosity as a replacement for the empirical values. The standard penetration test at 77°F despite its recognised limitations, does serve to differentiate between various grades of asphalts. But it is now known that two asphalt cements from different crudes, of same penetration at 77°F have quite different viscosities throughout the entire range of service and construction temperatures. Yet these are
commonly used in widely divergent climatic areas. Saybolt furol viscosity tests are required to be run at different temperatures to control liquid grades of asphal tic products. It is only very recently that liquid asphalts are graded by kinematic viscosity at 140°F in U.S.A. Measurement and reporting of consistency by the same method at all temperatures fosters a clear understanding of viscosity - temperature properties of asphalt and their influence on mixing, rolling, traffic compaction, rutting and tenderness at summer time temperatures common in tropical countries. There will also be a reduction in test repeatabilities.

Viscosity grading at 140°F presents a more realistic specification than the conventional penetration grading at 77°F. The Highway Research Board, The Asphalt Institute, The Bureau of Public Roads, and the Sub-Committees of the American Society for Testing and Materials of Committee D-4 are deeply concerned to use fundamental units in asphalt specifications. Precise temperature control and use of accurate viscosity measuring instruments have enabled to grade liquid asphalts by kinematic viscosity at 140°F.

It is not quite easy to classify the asphalt cements from various sources (crudes) and of various
penetration grades by viscosity grading at one particular temperature, since many complex factors come into play while attempting to grade them by viscosity. Viscosity measurements at proper shear rates corresponding to various pavement conditions should be attempted to predict the rheological behaviour of asphalt cements under such conditions. Asphalts from different crudes have different chemical composition (asphaltene content) and different rheological characteristics in relation to stress, deformation and time. In the past few years considerable research is undertaken to examine critically the shear and temperature susceptibility, viscosity changes in bituminous materials, rheological characteristics of asphalts, and possible relationship of viscosity with empirical tests. These properties need to be studied well before any viscosity specifications are adopted. Also exact relationships of fundamental properties of asphalts with those of asphalt mixtures yet remains to be investigated.

The problem before the asphalt paving technologists today is the design of one single instrument which can be used to measure the viscosities of asphalt cements at various important temperatures. In absence of such a unique instrument available commercially, today different techniques are used to measure the viscosity of asphalts
at different temperatures. Precision evaluation is invariably essential before recommending the use of any research instrument for routine laboratory testing programme. It helps the instrument designer to evaluate the degree of precision and to know if any changes in its design, control and fabrication are essential. It is the objective of this investigation to know the limit of precision of each of the instruments employed, as the precision varies from instrument to instrument. Thus, it is obligatory to know whether the instruments give concordant results while correlating viscosity measurements at various temperatures and also to compare their performance and suitability. It is also thought that it would assist in establishing the standards of precision possible with these instruments to formulate the specifications. At lower test temperatures especially, the application of proper statistical analysis seems to be extremely essential.

It is also investigated if there is a suitable correlation between penetration and viscosity of twenty-eight asphalt cement samples of two groups, viz. 85-100 and 120-150 penetration grades. It is also investigated how far these asphalts fit in the revised study specifications of Asphalt Institute, U.S.A. Besides, a study of
shear susceptibility, temperature susceptibility, degree of complex flow, etc. was also made at ambient and lower temperatures.

The results of the investigation show that there is a good agreement between the results of viscosity repeatability as obtained by the A.S.T.M. D-4 (old) format and A.S.T.M. D-2 format. The new A.S.T.M. D-4 format should be used when the number of observation is quite large. At 140°F the repeatability of pooled data is close to 3 per cent by any format used. There is also good correlation between penetration and viscosity at 77°F, i.e. when both are reported at the same temperature. Grading of asphalt cements by viscosity is possible as seen from the results.
VISCOSITY AS A CHARACTERISTIC PROPERTY

(A) FUNDAMENTAL VISCOSITY

It is well known that viscosity is the resistance offered by a fluid to the relative motion of its particles, internal friction. If this resistance is measured in fundamental units of length, mass and time, it is known as the 'fundamental viscosity'. Viscosity is the ratio of shear stress and rate of strain. The strain rate generally known as 'shear rate' is the velocity gradient, i.e. rate of change of velocity with the distance from the wall. Thus, 'absolute' or 'dynamic' viscosity of a Newtonian liquid is the tangential force on unit area of either of two parallel planes at unit distance apart when the space is filled with liquid and one of the planes moves relative to the other with unit velocity in its own plane. The c.g.s. units of absolute viscosity is the 'poise' which has the dimension grams per centimeter per second. 'Kinematic viscosity' is the quotient of the dynamic viscosity divided by the density both at the same temperature. The c.g.s. unit of kinematic viscosity is 'stoke', which
has the dimension square centimeters per second. Newtonian fluids have constant viscosity for linear flow conditions, whereas the viscosity of non-Newtonian materials is expressed as a function of rate of shear, since the viscosity is not constant (1).

Asphaltic materials are generally non-Newtonian but at temperatures usually above 140°F, they behave like Newtonian bodies. At lower temperatures and below a certain rate of shear, they may also behave as Newtonian bodies; for example, under these conditions, they have a viscosity known as 'initial viscosity'.

The primary interest in studying the fundamental viscosity and other fundamental properties of asphalts is to determine whether they can be correlated with the fundamental properties of asphalt paving mixtures. This study may help in understanding the behavior of asphalt concrete in the pavement during its span of service. It may also provide a better basis for improved asphalt specifications.

(E) IMPORTANCE AND RELATIONSHIPS

Research has shown that the logarithm of rut
depth per million wheel passes at the pavement temperature is linearly related to the log of asphalt viscosity at the same temperature. A four fold increase in the viscosity produces a two fold decrease in rutting. Stability increases with viscosity, but the rate of increase is less when pavements are compacted at higher viscosities (2). For asphalts of same viscosity regardless of the source or penetration grade, differences in the strength are greatest at 140°F for aggregates of different types, for example, sand, gravel and stone-mixtures (3).

Under the steady state conditions, flow and deformation depend upon the rate of shear and temperature. Viscosity is an important element in studying the rheological properties of asphalt and asphalt mixtures. The stress, strain, relaxation time and shear modulus of visco-elastic bodies are related to the viscosity. The relationship can be conveniently understood by analysing an appropriate mechanical model to represent the asphalt. This analysis is of great value in developing more insight in understanding the effect of such variables as type of asphalt, asphalt content, aggregate type and gradation, temperature, and confining pressure. The approach may further prove to be useful in the analysis
of flexible pavements, because time element can be accounted for.

(C) MEASUREMENT OF CONSISTENCY

The four principal areas encompassing the needs of research and development with regard to use of asphalt are:

(1) Consistency (2) Durability (3) Adhesion (4) Rate of setting as applied to asphalt cements.

Consistency is selected for undertaking research in this investigation. At present, we have only empirical measurements for consistency which have traditional acceptance. Research is needed, however, to provide basic means of measuring consistency for:

(1) more suitable application, control and (ii) better understanding and utilization of asphalt-aggregate combinations as affected by climate (4).

C-1. EMPIRICAL TESTS OF CONSISTENCY
MEASUREMENT - LIMITATIONS.

The empirical measurements of consistency are:
(i) the Penetration test which measures consistency in units of length, (ii) the Saybolt-Furol viscosity test which measures consistency in units of time, (iii) the Ring-and-Ball Softening Point test which measures consistency in units of temperature, and (iv) the Float test which measures consistency in units of time. All of these measurements are made under differing sets of arbitrary conditions.

C-1-1. SAYBOLT-FUROL TEST

Four temperatures 77°F, 122°F, 140°F and 180°F were used when measuring furol viscosity. At times, the temperature of 210°F had also been used for more viscous materials (5). The classification of liquid asphalts by S.F. viscosity is non-uniform, having unequal gaps between consecutive grades and some overlaps also, as shown in figure 1-1. The new specifications using kinematic viscosity appearing in this figure are more uniform (6).

S.F. viscosity is 0.5 times the kinematic viscosity, but this relation is not true at all temperatures (7),(8),(9). The values calculated from kinematic viscosities become progressively lower as the test temperature...
Comparison of present and new grades of liquid asphalts at 140°F

Fig. 1-1
is increased (10). Saybolt Furol is also an awkward measure if, for example, one must design manufacturing, storage, or handling systems for asphalt (11).

C-1-2. PENETRATION TEST

In the penetration test the variation in penetration numbers is principally due to the differences in frictional (shear) resistance which develops along the sides of the needle as it penetrates the asphalt. The area of needle becomes larger as it penetrates the asphalt and it increases at non-uniform rate. For asphalts of 62 penetration and less, the area subjected to shear varies with the changing surface area of the tapered cone. Besides, the energy required to displace the volume of the asphalt occupied by the needle increases throughout the test. This affects the penetration value (4). Highly elastic binders appear much softer in the penetration test (12). Besides, two asphalts of same penetration number at 77°F may have quite different viscosities throughout the entire range of service and construction temperature (13). A typical 85/100 penetration asphalt may have the penetration of 92 at 77°F, 25 at 60°F and more than 200 at 90°F. Thus, in a 30°F temperature
range, all of the penetration asphalt grades are encompassed. Yet this asphalt is commonly used in widely divergent climatic areas (14). As against penetration grading, a detailed discussion on viscosity grading is presented in article C-6 of this chapter.

C-1-3. SOFTENING POINT AND FLOAT TESTS

The Ring-and-Ball Softening Point test and the Float test also measure the consistency by arbitrary methods but not in fundamental and meaningful units.

C-2. CRITICAL COMPARISON OF GLASS CAPILLARY VISCOMETERS

The two types of viscometers now recommended for use for viscosity measurements of liquid and penetration grade asphalts at 140°F or above consist of: (i) Vacuum Capillary type and (ii) the Gravity Flow type. In the first type, Cannon-Manning vacuum capillary, Asphalt Institute vacuum capillary or modified Koppers vacuum capillary viscometers are suggested. These are shown in Figure 1-2. A further modification of these viscometers is suggested by the Cannon Instrument Company, State College, Pennsylvania, to construct a number of measuring bulbs in the length of capillary tube, as shown in
VARIOUS TYPES OF VACUUM CAPILLARY VISCOMETERS IN USE.

FIG. 1-2

A. STRAIGHT CAPILLARY (KOPPERS) TYPE

B. CANNON-MANNING TYPE

C. ASPHALT INSTITUTE TYPE
figure 1-3. In the gravity flow type, Cannon-Fenske reverse flow, Zeitfuchs crossarm, Lantz-Zeitfuchs, British Standard U-tube modified reverse flow type are being used as shown in figure 1-4. The use of gravity flow viscometer is limited usually to low viscosity fluids because the driving force is the hydrostatic head of the test liquid itself.

C-2-1. CANNON-FENSKE TYPE

The Cannon-Fenske viscometer requires an asphalt sample of 11 ml. The two efflux bulbs hold about 2 ml. sample. The kinetic energy correction is not quite significant (0.2 per cent). An efflux period below 200 secs. is used for all sizes (15).

C-2-2. ZEITFUCHS CROSSARM TYPE

Zeitfuchs crossarm viscometer is often called "The all purpose capillary viscometer". It has made possible the gradation of liquid asphalts at a single temperature of 140°F. The instrument has the advantages of higher precision, large saving in time, small sample sizes, less time required for attaining equilibrium temperature. But the greatest source of error in the
FIG. 1-3 PRESSURE AND VACUUM VISCOMETERS
SUGGESTED BY CANNON INSTRUMENT COMPANY.
(3) CANNON-FENSKE
(b) ZEITFUCHS CROSS-ARM
(c) LANTZ-ZEITFUCHS TYPE REVERSE FLOW
(d) U-TUBE REVERSE FLOW, TYPE B5/12/15

CAPILLARY VISCOMETERS FOR OPAQUE LIQUIDS
(FROM ASTM METHOD D445-60)

FIG. 1-4
use of this apparatus is due to careless drying. A very small amount of solvent can cause considerable error in viscosity measurements. The curvature of capillary in this instrument may introduce a small error (16).

Efflux time as low as 60 secs. is used in this instrument. The instrument has extremely high length to diameter ratio and a wide range - 0.6 to $10^5$ centistokes, compared to the Cannon-Fenske tubes - 0.4 to 16000 centistokes. The efflux bulb holds about 0.3 ml. of liquid. No special "master" viscometers are required for its calibration. It is estimated that the kinematic energy correction is 0.03 per cent and surface tension correction is less than 0.02 per cent. There is a very small change (0.03 per cent) in the constant of calibration with temperature due to expansion of glass (15).

C-2-3. **LANTZ ZEITFUCHS TYPE**

The Lantz Zeitfuchs type viscometer combines the features of simple and crossarm types. It has a viscosity range of 60 to $1.2 \times 10^5$ centistokes and range of capillary length of 200-490 mm. It needs 20 minutes for the sample to reach temperature equilibrium at test temperature (17).
C-2-4. B.S. U-TUBE MODIFIED VISCOMETER

The B.S. U.Tube Modified Reverse Flow viscometer has a viscosity range of 2 to $10^5$ centistokes. The capillary diameter varies from 0.5 to 10 mm and length of capillary from 185 to 210 mm. This type is not in common use in United States.

C-2-5. CANNON-MANNING VACUUM CAPILLARY TYPE

In this instrument a short length of precision bore glass capillary governs the rate of flow into the expanded measuring bulbs. It needs less time for temperature equilibrium compared to the Koppers vacuum capillary viscometer described in article G-2-6. The simplification of calculations and accuracy in the design of this instrument, is due to the fact that the capillary area is full of fluid during the entire timing period, whereas, in the other two types described further, the capillary area is changing during the timing period (18). With this instrument the detection of complex flow behaviour of asphalt requires at least two tests using different vacuum or two viscometers of different capillary sizes. However, limited test data indicate
that this instrument is most accurate and precise for use at 140°F compared to other viscometers currently available commercially (19). But, it needs exact calibration for use at vacuum other than 30 cm. of mercury for investigation of viscosity at higher shear rates.

C-2-6. MODIFIED KOPPERS VACUUM CAPILLARY VISCOMETER

This instrument has a separate filling tube and a precision bore glass capillary vacuum tube (17). Viscosity measurement with this instrument indicates the shear susceptibility of asphalt within a relatively narrow range of shear rates. The time required for preheating the sample to the test temperature is more than that in the Cannon-Manning vacuum capillary viscometer (19). The vacuum for best precision should be at least 10 cm. mercury and the flow time at least 50 secs. Viscosity is calculated from the dimensions of the capillary, the vacuum and the time of flow (1). It is required to use either the Bureau of Public Roads or Heithaus equation to calculate viscosity by this instrument. B.P.R. equation can be favourably used for lower values of vacuum (20), (21), (22), (23).
C-2-7. ASPHALT INSTITUTE VACUUM CAPILLARY VISCOMETER

One arm of this viscometer consists of a straight precision bore capillary divided into five segments of equal length. It is a combination of good features of both the above types of viscometers. The instrument is adaptable for the detection of the asphalt cement's complex flow behaviour using a single test, because of the wider range. The range available is 42 to 200,000 poises (19).

C-3. CORRECTIONS FOR ERRORS OF MEASUREMENT

Flow and Shear Rate Equations

Referring to figure 1-5, the quantity of fluid flow per unit time according to Poiseulle's law can be written as:

\[ V = \frac{\Delta p \times \pi R^2 t}{8 \sqrt{L}} \quad \text{For Cannon-Manning vacuum capillary viscometer,} \]

\[ \Delta p = \sigma_h g x (H-h). \]

Hence, \( \gamma = \frac{\Delta p \times \pi R^2 t}{8 L V} = \frac{\sigma_h g x (H-h) x g x \pi R^2 t}{8 L V} \)
LAMINAR FLOW THROUGH A CAPILLARY TUBE

NOTATIONS:

\(\beta_L\) = VISCOS RESISTANCE PER UNIT AREA
\(\Delta p\) = PRESSURE DIFFERENCE
\(R\) = RADIUS OF LIQUID CYLINDER
\(R_i\) = INTERNAL RADIUS OF TUBE
\(L\) = LENGTH OF THE TUBE
\(V\) = VELOCITY OF LIQUID
\(V\) = VOLUME OF LIQUID FLOWING IN TIME \(t\)

FIG. 1.5
The shear rate at the wall, 
\[ \frac{\Delta v}{\Delta t} = \frac{\Delta p x R}{2\eta L} \]

Thus, 
\[ \eta = K_2 (H - h) t \] (1)

The shear rate at the wall, 
\[ \frac{dv}{dr} = \frac{4Q}{\pi R^3} = \frac{4V}{\pi R^3 t} \]

Shear rate at wall, 
\[ \frac{K_1}{t} \] (2)

\( K_1 \) and \( K_2 \) are instrument constants which should be obtained by calibration (24).

For gravity flow viscometers,

Fluid head  =  \( F_f + F_e \), where \( F_f = \frac{8LV\eta}{g \pi r^4 t} \) and 
\[ F_e = \frac{g^n r^4 t}{m V} \]

Thus, 
\[ \frac{\eta}{8} = \frac{\pi g r^4 t}{8LV} (X_1 - X_2) - \frac{mV}{8\pi Lt} , \]

or 
\[ \frac{\eta}{8} = ct - \frac{B}{t} \]

C is a true constant (25).

But \( B \) varies with \( m \), which changes with
Reynold's number (16). 'm' approaches zero as Re approaches zero (m = 1 generally).

(1) Kinetic Energy Correction

Bell and Cannon suggested the equation:

\[ \frac{\eta}{\zeta} = Ct - \frac{E}{t^m}. \]

The kinetic energy correction, \( \frac{E}{t^m} \), decreases as t (efflux time) increases (25). Thus t less than 50 seconds should not be employed (27). Both C & E should be determined by calibration of the viscometer. The K.E. and surface tension correction are negligible in Zeitfuchs crossarm viscometer and hence viscosity as low as 0.5 centistoke may be measured. Elimination of drainage error in this instrument also permits measurement of viscosities ranging up to \( 10^5 \) centistokes.

(2) Viscous End Effects

Some energy is dissipated to overcome viscous forces at the entry and exit of capillaries, to account for change in velocity. Hence entrance and exit should be carefully designed to minimise friction loss caused by this end effects. A long capillary such as that of 200 length - to- radius has to be used so that the end
effects are negligible (15).

(3) Elastic Energy Correction

Elastic stresses are set up in the fluid, as it converges into the capillary. As it enters the capillary, these stresses begin to relax. The correction is more important for short capillaries (15).

(4) Surface Tension Correction

If the S.T. of the calibrating fluid differs from that of the fluid to be tested and bulb diameters differ above and below the capillary, a S.T. correction is required (28). This correction is usually less than 1 per cent of the driving force (29), (30).

(5) Heat Effects

Temperature gradient may result when a fluid flows at high level of shear stress. The thermal gradients affect the flow properties. When the experiment and calibration temperatures are different, the instrument constant K should be corrected for this effect.

\[ K = K' \times 0.996, \] where K & K' are constants at 100°F and 210°F respectively for Cannon-Fenske reverse flow.
The knowledge of correction factors is essential if the viscometers are to be calibrated in the laboratory. The Cannon Inst. Co. charges as much for the calibration as for the instrument.

The constants for Cannon-Fenske viscometer can be obtained at any temperature by interpolation or extrapolation between two calibrated values, usually at 100°F and 210°F. The constant for Zeitfuchs crossarm viscometer is the same at all temperatures. In case of Cannon-Manning vacuum capillary viscometers, the constant for the instrument is the same at all temperatures provided the specified vacuum (viz. 30 cm. of mercury) is not changed. It may be possible to calculate the constant at other vacuum heads, provided the average liquid head in the viscometer for each fill bulb is exactly known. In the case of Koppers vacuum capillary viscometer, the constants vary with the capillary lengths up to the various timing marks.

Cannon-Manning vacuum capillary viscometers
are calibrated by use of viscosity standards and hence no elaborate calculations are required for viscosity determination. If slight air entrapment occurs, the volume of the fluid may not correspond with the volume of fill bulb. This will cause appreciable errors in viscosity measurements.

C-5. VARIATION OF VISCOSITY WITH TEMPERATURE

There are various factors which cause a wide variation in the viscosity of asphalt cements from different crudes of the same penetration group. With rise of temperature various changes take place in the bitumen. These are as follows: (i) Reduction of the viscosity of the intermicellar liquid; (ii) Reduction of the volume of micelles reduces the viscosity of the system; at the same time, however, the high molecular-weight components that are dissolved increase the viscosity of the intermicellar phase and thus that of the system; (iii) Reduction of coherence between the micelles owing to which the viscosity of system is reduced; (iv) Change in elastic properties of the micelles or of the micelle structure. The sum of these effects determines the ultimate change in rheological properties. It is evident that it is only by a thorough knowledge of these effects in every
individual bitumen that this change can be calculated. This is, of course, beyond the scope of present investigation, but may be an answer to the cause of non-relationship of penetration and viscosity (31).

C-6. VISCOSITY GRADING OF ASPHALT CEMENTS

Asphaltic concrete is neither mixed at 77°F nor laid at that temperature. Thus, 77°F is not the critical temperature for either summer or winter performance of the pavement and has no significant relation with the critical temperatures affecting construction and service of a hot-mix asphalt pavement. Hence attempts are being made by The Asphalt Institute, the U.S. Bureau of Public Roads and other States of America to develop fundamental viscosity tests and viscosity limits to grade and specify asphalts. It will make common sense to mix at the proper viscosity, not at some arbitrary temperature which may have one asphalt too fluid and another not fluid enough for good mixing (13). Asphalts are natural products of great chemical complexity and their properties vary depending on the crude source. It is not possible to adjust the proportions of each of the different chemical species to obtain the same chemical composition and hence the same
temperature-viscosity curve. Requiring identical consistency at all temperatures would drastically narrow the availability of asphalt products. Cost would also increase (14).

Asphalt viscosity at mixing temperatures is important to obtain complete and uniform coating of the aggregate. The viscosity in the range of 190°F to 275°F is important for initial steel wheel compaction of the mix. Pneumatic tire rolling is usually conducted between 150°F and 180°F. Thus, toughness of the mix and its resistance to rutting is governed by the viscosity of the asphalt in the 100°F to 140°F temperature ranges (14).

Aside from improved uniformity, single standardization temperature for all asphalts and other commercial advantages claimed for viscosity grading, the technical advantages are:

(a) Direct calibration of the test equipment,
(b) Common units of measurement at all temperatures,
(c) Use of units that have engineering significance,
(d) Straight-line viscosity-temperature relationships that permit either graphical or numerical interpolation and extrapolation (currently arbitrary susceptibility factors are used). The relation between penetration at 77°F and viscosity at 140°F is poor. Natural asphalts, if at about equal viscosity at 77°F, will not behave the same at the 140°F temperature. This is the very reason for considering a new more functional temperature range. The current world-wide basis for grading paving asphalts is penetration at 77°F. The grades range from 40 to 300 penetration (14). The 140°F and 275°F viscosity-limits in the proposed specifications are intended for design, uniformity and workability. At present, the penetration at 77°F results in the asphalts having about the same viscosity at 77°F. Yet there is some divergence at lower temperatures. The proposed system makes the asphalt behave more alike at the 140°F temperature.

Hveem and Marshall stability tests are
made at 140°F. Accurate, reproducible vacuum capillary viscosity equipment can be used to measure viscosity at this temperature. The 275°F minimum viscosity is established to insure workability and to control the shape of the temperature viscosity curve (14).

Four grades proposed for classification are: AC-5 with a viscosity of 500-750 poises, AC-10 with a viscosity of 1000-1500 poises, AC-20 with a viscosity range of 2000-3000 poises and AC-40 with a range of 4000-6000. Soft grade may be used for such applications as sand seals, a somewhat higher grade for chip sealing, penetration macadam construction and for asphaltic concrete in very cold weather areas. A still harder grade, AC-20 will cover most major hot mix needs. A material of even greater cohesiveness, AC-40 is for such application as curbs, hydraulic uses and parking lot construction.

There are no basic reasons why the system could not be expanded to 5 grades or reduced to 3. The next step was to select the maximum boundaries for each grade. The current asphalt penetration system ranges from 1.4 to
2.2 when considered on a viscosity basis. Normally a 60-70 penetration asphalt has a range in viscosity of approximately 1.4 as does the 85-100 penetration asphalt. The 120-150 asphalt when considered on the basis of viscosity has a range of approximately 1.6 and the 200-300 grade of approximately 2.2. The proposed specifications will have a somewhat narrower range of viscosity in the softer grades while being about the same in the harder grades.

Producers currently supplying low viscosity asphalts will, under the new system, supply asphalts of a lower penetration. Thus some suppliers to meet the consistency requirements of AC-20 will supply an asphalt of about 60-70 penetration while others will supply an 85-100 penetration material. Actually such a shift to higher grades is not new since, in many areas, the higher viscosity 60-70 grade is already replacing the 85-100 grade as the most common grade. This trend has been developing fastest in urban areas where higher tensile strength is required. The new system provides a more rational approach to the trends already taking place in many areas. The new specifications are detailed in Table 1-1. Recently, the Asphalt Institute has
<table>
<thead>
<tr>
<th>Grade</th>
<th>AC-5</th>
<th>AC-10</th>
<th>AC-20</th>
<th>AC-40</th>
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<tbody>
<tr>
<td>Viscosity at 140°F, Poises</td>
<td>500-750</td>
<td>1000-1500</td>
<td>2000-3000</td>
<td>4000-6000</td>
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<tr>
<td>Viscosity at 275°F, Centistokes</td>
<td>150+</td>
<td>200+</td>
<td>300+</td>
<td>400+</td>
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<tr>
<td>Ductility Minimum at 77°F</td>
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<td>100+</td>
<td>100+</td>
<td>100+</td>
</tr>
<tr>
<td>Ductility Minimum at 60°F</td>
<td>60+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Solubility in CCl₄</td>
<td>99.5+</td>
<td>99.5+</td>
<td>99.5+</td>
<td>99.5+</td>
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<tr>
<td>Flashpoint, COC, °F</td>
<td>375</td>
<td>425</td>
<td>450</td>
<td>450</td>
</tr>
</tbody>
</table>

**Tests After TFOT**

- **Viscosity at 140°F after TFOT**
  - Maximum: 5
- **Viscosity at 140°F before TFOT**
  - Maximum: 5
- **Viscosity at 39.2°F in 10⁸ poises measured with shear rates between 10⁻² and 10⁻⁵ sec⁻¹**
  - 7.0  | 30  | 150  | 600  |
proposed grades AC-3, AC-6, AC-12, AC-24 and AC-48, as shown in Table 2 and has also suggested the approximate relation between viscosity and penetration of asphalt cements at 60°F (32).

According to current specifications, the penetration measurement variation between two laboratories should not exceed 8 per cent. Thus, it would be 1 to 1.08 for a 100 penetration product. When converted in terms of viscosity, it becomes 1:1.2. With the new viscosity method, the reproducibility works out to a ratio of 1:1.1. Thus, less difficulties are anticipated with the new system (14).

Most engineers feel that low temperature consistency can play a part in cracking and surface abrasion of asphalt pavements. The present proposed specifications do not include a viscosity test requirement at low temperatures. Research is under way in this direction. Some effort is made in this investigation also in measuring low temperature viscosity.

As reported earlier by Kofalt et al, more temperature susceptible asphalts of the same acceptance grade show higher stability values at lower temperatures.
TABLE 1-2.
RESEARCH SPECIFICATIONS FOR ASPHALT CEMENTS
AUGUST 17, 1965
THE ASPHALT INSTITUTE

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>AASHO TEST METHOD</th>
<th>ASTM TEST METHOD</th>
<th>GRADES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity at 140°F, poises</td>
<td>T 202 I D 2171</td>
<td>300±75</td>
<td>AC-3</td>
</tr>
<tr>
<td>Viscosity at 275°F, centipoises</td>
<td>T 201 I D 2170</td>
<td>80+</td>
<td>110+</td>
</tr>
<tr>
<td>Viscosity at 60°F, megapoises</td>
<td>T 51</td>
<td>D 113</td>
<td>30±</td>
</tr>
<tr>
<td>Ductility at 77°F, 5cm/min., cm</td>
<td>T 44</td>
<td>D 4</td>
<td>99.5±</td>
</tr>
<tr>
<td>Solubility in CCl₄, %</td>
<td>T 48</td>
<td>D 92</td>
<td>100±</td>
</tr>
<tr>
<td>Flash Point, COC, °F</td>
<td>T 179</td>
<td>D 1746</td>
<td>48±</td>
</tr>
<tr>
<td>Thin Film Oven (TFO) Test</td>
<td>T 179</td>
<td>D 1746</td>
<td></td>
</tr>
<tr>
<td>Viscosity at 140°F after TFO Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity at 140°F before TFO Test</td>
<td>5±</td>
<td>5±</td>
<td>5±</td>
</tr>
</tbody>
</table>

(1) For industrial uses and special paving applications.

(2) The maximum viscosity limits at 60°F apply when measured at shear rates of 0.05 sec⁻¹ or lower. In cases of dispute, viscosity shall be interpolated to a 0.05 sec⁻¹ shear rate.

(3) At present four test methods may be used for viscosity measurement at 60°F. These methods are described in ASTM preprint No. 33 S, published as information only, June 1965. Alternatively, the penetration test may be used to provide an approximate measurement of viscosity at 60°F. The conversion of penetration at 60°F, 100 gms., 5 sec. to viscosity in megapoises at 60°F at shear rates of 0.05 sec⁻¹ or lower may be made by use of the formula Log 3.617 Log pen.60. For convenience, a chart for making this conversion is attached.

(4) If the ductility at 77°F is less than 100-cm., the material will be acceptable if its ductility at 60°F is 60±cm.

(5) Except that carbon tetrachloride is used instead of carbon disulfide as solvent, Method No. 1 in AASHO Method T 44 or Procedure No. 1 in ASTM Method D 4.
Temperature susceptible asphalts at 39.2°F show greater stability values but lower shear susceptibilities. Asphaltene content (insoluble portion in n-pentene) governs to a considerable extent, the viscosity of asphalts, and has some relationship with it (33).

C-7. LIMITATIONS OF VISCOSITY GRADING

The range in penetration at 77°F for the asphalts of AC-5, AC-10, AC-20 and AC-40 has been noticed to be 80-250, 45-170, 25-120 and 15-80, respectively. Also, a wider spread is noticed in the low temperature properties of the asphalt cements from the results of penetration tests at 45°F and 60°F and viscosity tests from 39.2°F to 77°F when they are graded by viscosity at 140°F. Limitations should be imposed to narrow these differences (34).

AC-10 grade would probably include all of the three most commonly used current grades of paving asphalts, 60-70, 85-10 and 150-200 penetration. History provides evidence that softer grades are selected for asphalt pavements on weaker foundations and harder 60-70 grade asphalts are used for pavements on stronger foundations for heavy traffic. There are experienced engineers who
believe that in some cases at least, the pavement performances has been less satisfactory when they changed from SC-6 to the much harder 150-200 penetration grade. It is hard to accept the change without offering any substantial evidence from the field. There are a number of formulae available for converting penetration at 77°F to viscosity in poises at 77°F. Also, it has been shown that in general for paving asphalts used in Canada, the viscosity of an asphalt cement at 77°F for zero shear rate is normally less than twice its viscosity at infinite rate of shear. Although the rate of shear inherent in the penetration test is variable, both its range and its average value lie somewhere between zero and infinite shear rates. Consequently, in general, for asphalt cements used in Canada, the measure of viscosity provided by the penetration test, probably does not differ greatly from the viscosities actually developed by an asphalt cement for the rates of shear to which it is subjected in a pavement in the field (35).

C-8. EFFECT ON CUTBACK AND ASPHALT EMULSIONS

The residue from distillation of cutback asphalts at 680°F, and asphalt emulsions at 500°F would not have the specified range of viscosity less than that of AC-5. This may correspond to a range of penetration at 77°F
of 80 to 250, which is much wider than the currently specified penetration of 120 to 250. Similarly, the range of viscosity at 140°F specified for residue of R.C. cutbacks is not likely to be less than that of AC-10. This would correspond to a range of penetration at 77°F of 45 to 170. This is much broader than the range of 80 to 120 presently specified.

Values obtained by the penetration test on distillation residues of MC and RC cutback asphalts and of asphalt emulsions, do have a marked effect on the service performance of asphalt road surfaces made with these binders (35).

C-9. EFFECT ON LONG TERM PAVEMENT PERFORMANCE

Although grading the asphalt cements by viscosity at 140°F might facilitate construction operations at elevated temperatures, it would be detrimental to long term pavement performance. A temperature of 77°F is much closer to the average of the road surface temperature range, than is 140°F which is the upper limit of the service temperature. Consequently, the characteristics of asphalt pavements at 77°F can be expected to have a much greater influence on the actual performance of these pavements throughout their
service lives, than the characteristics of the same paving mixtures at the higher temperatures of construction stage. Dr. Norman W. Mcleod has a feeling that the asphalt industry is on a viscosity hinge at the present time, and in its head long rush to substitute viscosity for each of the well-known so-called empirical consistency tests, has temporarily lost its sense of proportion (35).

The state of Texas is placing these new specifications in use at the present time. The state of Pennsylvania also is installing trial sections of the "study" specifications (4).

The hardening of asphalt averages nearly 4 per cent (0-14.1 per cent) when measured by the penetration test and about 34 per cent (14.3 per cent to 44.2 per cent) when measured by viscosity test. A study to investigate the cause of hardness could possibly lead to the cause for vast differences in viscosity values for the asphalt cements of identical penetration value. It is believed a transition asphalt specification embodying viscosity can be written provided it is developed using penetration as a base and contains some controlling factors. It is also suggested that cement industry methods be considered as a guide. This would demand the testing of asphalt cement
and laboratory asphaltic concrete mixtures prior to acceptance of the asphalt cement, as is the case with Portland cement. The asphalt cements and mixtures would be tested under various specified conditions and temperatures.

D. RHEOLOGICAL CHARACTERISTICS

For a bitumen to be used successfully in road surfacing, (i) it must be capable of being made sufficiently fluid to coat and 'wet' mineral aggregate, (ii) be viscous at high pavement temperatures to resist deformation, (iii) be flexible to resist fracture and disintegration.

Bituminous binders have complex flow properties. Hence, it is desirable to study their viscous and elastic properties. Since the flow behaviour of bitumens is complex, they exhibit non-linear time and stress effects. Despite this, the present specifications are based on empirical control tests. Van der Poel's study indicates that for a wide range of bitumens and not too large strain, a linear relation in a constant load tensile test exists between the stress and the strain-time curve. This will define "stiffness modulus" which like viscosity would be
dependent on the temperature. The stiffness modulus in tension will, for bituminous binders, be normally equal to three times the modulus in shear. The similar modulus for shorter times of loading by dynamic tests (with Sinusoidal stress application) can be defined by ratio of stress amplitude to strain amplitude and referring to an effective time of loading $1/2 \pi f$, where $f$ is the frequency. The curve of stiffness function can be obtained by plotting logarithm of the stiffness modulus versus logarithm of time of loading. The stiffness modulii can cover a range of many decades of time of loading. Stiffness of the bitumen of high penetration index changes less with increase in time of loading than does that of the bitumen of low penetration index. Van der Poel has found that for bitumens of given penetration index, the ways in which the stiffness depends upon (a) its hardness at a given temperature, (b) the test temperature, (c) the time of frequency of loading, are interrelated in a fairly simple manner. The application of notion of stiffness would be to those circumstances when the duration of loading is small and the temperature is low (12).

Research has shown that a correlation exists between changes in asphalt viscosity and the mechanical properties of the mix. The temperature susceptibility
factor should be evaluated directly from bituminous concrete rheological data rather than from viscosity tests on asphalt phase alone. In the linear visco-elastic range of stress and in the thermo-linear range of temperature, an equation of state which correlates stress, strain, time and temperature exists, indicating that the time-temperature super position concept is applicable to asphalt mixtures. Mechanical properties of dense asphalt mixtures can be expressed to a useful degree of approximation (37).

The rheological properties can be studied by constant load creep test, stress relaxation test, and direct sinusoidal stress dynamic test. Stress relaxation tests are usually difficult to perform, direct dynamic test yields information applicable only at frequency used in the test. The creep test, however, is relatively easy to conduct and it yields in formation over a wider range of loading time or over a range of frequencies when transferred to frequency domain. In the visco-elastic theory, creep deformation consists of instantaneous elastic, time dependent elastic, and plastic deformation. The observation of rebound behaviour of the material after unloading should be observed to separate the elastic add plastic deformation from total
deformation. The phenomenon of mechanical conditioning can be analysed by repetition-of-load application (37).

The stress-strain-time relationships at normal service temperatures, at low levels of stress and deformation may be expressed as functions of frequency by means of complex parameters. Two complex modulii are required to describe an isotropic material fully, the Elastic and Transversa modulii, by means of both dynamic and static tests. If the analytical expression of the modulus is available, it is possible to picture the given modulus as a mechanical model or as a plot of its magnitude and angle as functions of frequency. The response of the model would approximate that of the material. It is of interest to correlate the rheological properties of asphalt cements with those of asphalt mixture (38).

A mechanism whereby Newtonian behaviour can be exhibited by molecules of high molecular weight is found in structural reorganisation. When the rate of exchange of parts between molecules making up a liquid is faster than the rate of the translational molecular motion involved in the flow, the whole molecule does not move as in flow but only the exchanging parts act as flow units (15). Non-Newtonian flow is found only in colloidal
and other particulate systems in which the concept of a colloidal particle includes large molecules. The non-linear flow curves observed from colloidal systems can be explained by interaction between particles, interaction with continuous phases and particle deformation(15).

For Newtonian bitumens, no elastic resilience occurs after release of the constant stress and is therefore non-colloidal or a sol-with non or slightly elastic particles. In sol type bitumens, the higher rate at the beginning of the deformation is due to the elastic properties. After release of stress, there is some elastic recovery. For a bitumen of gel structure, the rate of shear at constant shearing stress drops at the beginning, passes a minimum value and subsequently begins to rise when applied shearing stress is above a certain value(31).

Cracking and subsequent failure of bituminous surfaces can often be attributed to excessive tensile stresses induced in pavements by various causes (39),(40). 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 behaviour of asphalt, is due not only to simple tension or to simple
shear alone, but also depends on the behaviour of asphalt subjected to combined stresses. Thus, an understanding of the mechanism of failure and the rheological behaviour of the material in simple tension, as well as in simple shear, is required for the final evaluation of mix design. This, in turn, is affected by rate of loading, thickness of the film separating the particles of aggregates, and temperature (39).