Asphalt Hardening in Sprayed Seals

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A low-cost pavement that consists of a sprayed surface seal over a thin granular base is widely used in Australia on low-volume roads. The average life before a reseal is required is of the order of 10 to 15 years. The main reasons for such long service lives are considered to be (a) the design procedures used in Australia, (b) the selection of materials, particularly the durability of the asphaltic cement (asphalt), and (c) the high degree of control of the construction operation. Information on each of these factors is given. The Australian Road Research Board (ARRB) Asphalt Durability Test is described. Full-scale road trials that were placed in a range of climatic conditions and observed for up to 10 years have shown the test to be a good indicator of the resistance of an asphalt to hardening in sprayed seals. Road trials in which additives were evaluated to improve asphalt durability, such as hydrated lime and lead diamyldithiocarbamate (LDADC), are also being monitored. A simple predictive model of asphalt hardening has been developed. Only the following inputs are needed to calculate asphalt viscosity at a particular site: (a) the average temperature at the site, which can be obtained from the closest weather station, (b) the ARRB Asphalt Durability Test result for the fresh asphalt, and (c) the age of the seal. The model can be used to test the effects of asphalt durability on field hardening at particular sites and to identify climatic areas in which asphalt hardening will be particularly rapid. If it is further developed, the model could be usefully incorporated into pavement management systems.

The need to establish and maintain an all-weather road network in Australia, which has an area that is 80 percent that of the United States, but a population only 7 percent that of the United States, has led to the development of a particularly efficient type of pavement. This pavement typically consists of a base of unbound crushed rock or natural gravel about 200 mm thick that is placed on a compacted natural subgrade and covered with a sprayed seal surface treatment.

These light granular pavements give excellent service in conditions that range from a hot desert in central Australia and a tropical rain forest in northern Australia, to the cool climate of the south. The condition that is generally absent is the freeze-thaw cycle, which can be so destructive to pavements in North America.

Australia's total road network comprises about 800,000 km, of which 200,000 km are classified as sealed (*1*). This term generally indicates a sprayed seal surfacing, although thin, asphaltic concrete surfacings are common in urban areas. Concrete is used very little. By far the greatest proportion of Australia's road network services rural areas. Traffic volumes are very light; many roads carry less than 100 vehicles per day (vpd). Occasional heavy vehicles are common, however.

A number of different terms are used to describe sprayed seal surfacings. These include surface treatment, flush seal, spray and chip seal, and surface dressing. In this paper, the term sprayed seal is a surfacing that consists of a thin film of asphaltic cement (asphalt) that is sprayed hot from an asphalt distributor and covered with a single layer of approximately one-sized stone chippings.

Because of the importance of this type of surfacing, Australian State Road Authorities have refined design procedures and construction methods in such a way that average lives of 10 years are normally reported for seals with chippings (aggregate) 10 mm in size. In some areas, the average life of the seal can rise to 15 years.

For lives of this order to be obtained, a durable asphalt must be specified and care must be taken during the construction operation. Information on asphalt durability and the essential features of the spray sealing operation are given in this paper. It is likely that a more widespread adoption of the techniques and practices described could lead to a substantial improvement in the service life and performance of low-volume roads in many countries.

SPRAYED SEAL DESIGN AND CONSTRUCTION

General

A sprayed seal provides a dust-free running surface for vehicles and is characterized by a high skid resistance and good light reflectance properties under wet conditions. Although it may not appear so, the design and construction of a sprayed seal surfacing require more experience and skill to achieve a satisfactory result than is the case for a hot-mix (asphaltic concrete) surfacing.

In cases in which a seal is placed over an unbound base, its water-sealing properties are most important, particularly if the materials in the base or subgrade are water-sensitive. If appreciable cracking or stone loss occurs in a seal, which is normally associated with hardening of the binder with time, water can enter the pavement structural layers and rapid deterioration and failure can occur. The normal practice is to apply a reseal before this stage is reached.

Design Procedure

The design procedure used in Australia is based on a method first developed in New Zealand by Hanson (*2*). It depends on the assumption that, after traffic rolls and orients the particles, the aggregate particles in a seal will lie closely packed as a single layer with their least dimension vertical. The average thickness of this layer is the average least dimension (ALD) of the stones. The intention is to fill a predetermined proportion of the voids in this layer with binder.

Details of the design method are given in a publication of the National Association of Australian State Road Authorities (NAASRA) (*3*). The essential steps of the method are as follows:

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1. The ALD of the sealing aggregate is determined by using a simple sieving procedure (*3*).
2. The percentage of the theoretical surface voids to be filled by asphalt depends on the degree of traffic compaction the surfacing will receive. This percentage is obtained from a table that gives values for traffic levels that range from less than 50 to over 2,000 vpd (total of both directions) (*3*).
3. The asphalt application rate, expressed as L/m^2, is calculated from a simple expression that involves the two factors in Steps 1 and 2.
4. Adjustments to the application rate are made to allow for the absorbtivity of the surface to be treated.
5. For traffic flows of less than 500 vpd, a fluxing oil, normally diesel fuel, can be added to the asphalt to lower its viscosity and compensate for the reduced traffic embedment of the aggregate.
6. The aggregate application rate is calculated from the ALD; an allowance is made for imperfect spreading and initial losses due to traffic action.

The calculated application rates can be modified further, depending on local experience with the materials used. Minor adjustments can be made for large jobs based on the appearance of the early work.

Construction Practice

Asphalt

The grade of asphalt normally used for sealing in Australia is Class 170. The class number is the asphalt viscosity measured in Pa.s at 60°C (170 Pa.s = 1700 poises). The properties of the asphalt are listed in Australian Standard 2008 and are similar to the U.S. requirements except for a provision to permit the specification of asphalt durability (*4*). This subject is described in detail later.

Aggregate

Crushed rock is normally used to seal aggregate but in the more remote areas natural gravel may be the only source available. In this case, it is normal to specify that at least 75 percent by mass should have two or more faces that were produced by crushing.

It is important that the particles be as close to a cubical shape and as single-sized as possible. Simple tests are used to measure and control particle shape and grading. The aggregate must be able to resist decomposition on exposure and must have sufficient strength and resistance to wear for the expected traffic conditions. Information on the range of aggregate tests used is given by Dickinson (*5*).

Sealing aggregate is normally precoated with a proprietary agent (tar, asphalt, or oil-based) or, more commonly, with diesel fuel. The main purpose of this is to wet any dust on the surface of the aggregate and to allow penetration of the asphalt binder to the surface of the aggregate after spraying. The rate of application of precoat depends on the size, cleanliness, type, and dampness of the aggregate being used. The rate for diesel fuel is normally in the range of 6 to 12 L/m^3. Adhesion agents may be added, depending on the possibility of rain during or shortly after construction. These agents are preferably added to the precoat but may be added to the asphalt shortly before spraying.

Equipment

A number of different designs of asphalt distributor are currently in use. They all, however, employ slotted jets in a triple-overlap pattern. All sprayers used by State Road Authorities are calibrated annually to ensure uniformity of distribution and accuracy of application rate (*3*).

Aggregate is normally applied from the tip truck that is used to transport it to the site. A box spreader is attached to the rear of the truck and is used to control the application rate. Self-propelled, multi-wheeled, pneumatic-tired rollers are used to start the aggregate orientation process, which is completed by traffic.

The Laying Operation

The asphalt distributor begins its run when sufficient aggregate trucks are on site to cover the entire sprayed length. The distributor starts and finishes spraying on a paper strip that is removed to give a clean transverse joint. The driver uses a special low-speed tachometer to enable him to maintain constant speed. All details of the run, including spray tank dippings, area covered, additives used, and asphalt temperature, are recorded.

The rate of wetting of the aggregate particles by the asphalt film determines the rate at which a bond is formed. To ensure that the wetting rate is sufficiently high, the viscosity of the binder film is controlled by the addition of a volatile diluent (cutter), which is normally kerosene. The proportion of cutter added is determined by the road surface or air temperature and is adjusted throughout the day.

The aggregate truck is reversed over the sprayed binder film while an operator, walking alongside, adjusts the aggregate spread rate. The formation of a dense, interlocking mosaic of aggregate particles is essential for a sprayed seal to resist and endure the forces imposed by high-speed traffic. The orientation of particles to form such a mosaic is started by rolling during construction but is completed by low-speed vehicle tires.

A recently reported study on the particle orientation process has shown that most orientation occurs during the first three passes of a pneumatic tired roller and that very little improvement can be measured after the sixth pass (*6*). The surface improves immediately when the road is opened to normal traffic. Traffic speed should be restricted for a short period immediately after construction by, for example, leading a convoy through behind a roller.

Discussion

The previous section outlined some of the precautions necessary to obtain a high-quality sprayed seal. Further information is given in an NAASRA publication (*3*) and the process is further discussed in a book by Dickinson (*5*). Detailed information is given in a two-volume manual produced by the Road Construction Authority (formerly Country Roads Board) of Victoria that covers all aspects of asphalt surfacing work (*7*).

The quality of a sprayed seal depends on the skill and experience of the supervisor and members of the spraying crew. A spraying crew will normally be self-contained and can operate from a small base camp in a remote region, if necessary. The equipment used is generally simple and can be maintained

and repaired on site. Local equipment, such as aggregate trucks, and material, such as kerosene cutter, is used whenever possible.

ASPHALT HARDENING

Mechanism

Provided that a sufficiently durable aggregate has been used and that the pavement remains structurally sound, the life of a properly constructed seal critically depends on the life of the asphalt binder.

The common distress mode is for the asphalt to harden with time until it can no longer withstand the movement caused by diurnal temperature variations when it cracks, or when its adhesive bond to the aggregate particles fails. Ingress of moisture through cracks, or gaps in which stones have been lost, can quickly lead to pavement failure unless a new waterproofing layer is immediately applied. In practice, a new seal, or reseal, is normally placed before the asphalt hardens to this level.

Australian asphalts are derived almost exclusively from Middle East crudes and their method of manufacture ensures that very little volatile material is left in the final product. Under normal conditions all the hardening that occurs on the road is caused by the oxidation of the asphalt.

Although the sunlight-catalyzed reaction of asphalt with oxygen from the air (photo-oxidation) occurs rapidly, asphalt is a good light absorber and this reaction is confined to the top 5 μm of exposed material (*8*). The effect of photo-oxidation on paving asphalts is therefore considered to be slight and the bulk of the hardening in the road situation occurs through a slower thermal reaction mechanism. The rate of this reaction roughly doubles for every 10° C rise in temperature (*9*).

The rate of hardening of the asphalt binder in a sprayed seal depends on (a) the temperature of the surfacing, (b) the thickness of the asphalt film, and (c) the intrinsic resistance of the asphalt to oxidative hardening. This latter property is measured by the Asphalt Durability Test.

ARRB Asphalt Durability Test

The slow field hardening of asphalt can be accelerated in a laboratory test by (a) increasing the temperature, (b) reducing the film thickness of the exposed asphalt, and (c) increasing the oxygen pressure.

A combination of methods (a) and (b) is used in the ARRB test. The test temperature is set at 100° C, because this temperature is considered to be sufficiently high to produce a test result in a reasonable period of time but not so high that the character of the laboratory and field oxidation reactions will be markedly different. Maximum temperatures of about 70° C are encountered in pavement surfacings (*9*).

The test procedure is based on one first developed by the California State Highways Department (*10*). The important feature of the ARRB test is the use of a specially designed oven that permits precise temperature control to be maintained over a long period of time.

The test is fully described in Australian Standard 2341.13 and the main steps follow (*11*).

1. The asphalt is first subjected to the Rolling Thin Film Oven (RTFO) Test, in which it is heated as a rolling film in bottles on a rotating rack for 85 min in an oven set at 163° C. This procedure simulates the slight hardening that occurs when asphalt is hot-mixed to produce asphaltic concrete.
2. A portion of the RTFO-treated asphalt is deposited from toluene solution as a thin film (approximately 20-μm thick) on the inner walls of glass bottles.
3. The bottles are then placed in the durability oven, which may be the same oven that is used to perform the RTFO exposure, and are exposed to air, in the absence of light, at 100° C. The rack that holds the bottles rotates in the vertical plane to ensure that each bottle experiences the same temperature environment.
4. At selected treatment times, the bottles are removed and the asphalt is scraped from the walls. The apparent viscosity of the recovered asphalt is then measured on the Shell sliding plate microviscometer at 45° C and a shear rate of $5 \times 10^{-3} s^{-1}$. The viscosity determination procedure is described in Australian Standard 2341.5 (*12*).
5. Apparent viscosity is plotted against time of treatment. The time to reach an apparent viscosity of 5.7 log Pa.s (the critical viscosity) is determined by interpolation. This time, in days, is the durability.

Relationship Between Durability Test Result and Field Hardening

Since 1969 a series of sprayed seal road trials was laid with asphalts of widely differing durabilities at sites in Australia that covered a wide range of climatic conditions. Information on the placing of the trials has been reported, their performance has been monitored, and samples have been taken periodically for testing in the laboratory (*13*).

Asphalt from field samples is recovered for testing by a solvent extraction technique and the apparent viscosity of the extracted asphalt is measured at 45° C by use of a Shell sliding plate microviscometer. An analysis of the results obtained up to 1981 has been reported (*15*). It was concluded that the durability test correlated with the hardening observed for different asphalts in sprayed seal road trials and is a useful tool for predicting the rate of hardening in this application.

Asphalt Hardening Prediction Model

As the sites aged and more information became available, it became possible to combine data from all the sites to present an overall picture of how asphalt hardened in sprayed seals. Multiple linear regression of the data resulted in the development of a simple mathematical model (*16*).

Information from the road trials has now been supplemented with data from selected nonexperimental sites in which asphalt properties, including durability, were measured at the time of construction. The current data base is composed of 10 full-scale road trials and 13 nonexperimental sites. A total of 125 data points that cover 45 different asphalts have been used to construct the model.

$$\log \eta = .0476\ T\ Y^{0.5} - .0227\ D\ Y^{0.5} + 3.59 \qquad (1)$$

where

η = the viscosity of asphalt recovered from the seal (Pa.s),
T = the average temperature of the site calculated from Equation 2,
D = the ARRB test result (days), and
Y = the number of years since the seal was constructed.

$$T = (TMAX + TMIN)/2 \quad (2)$$

where

$TMAX$ = the yearly mean of the daily maximum air temperature, and
$TMIN$ = the yearly mean of the daily minimum air temperature.

The variables $TMAX$ and $TMIN$ are obtained from published tables of climatic data (*17*).

If log η is to be calculated in poises, the equation remains unchanged except for the constant term, which becomes 4.59.

A number of other predictor variables and combinations of variables were tested in the regression and only the addition of a term containing the original viscosity of the asphalt before spraying was found to produce a statistically significant improvement. However, the term has been excluded from the model presented here to maintain simplicity and because its contribution is very small.

The Pearson multiple correlation coefficient for Equation 1 was 0.93 and the standard error of estimate of log η was 0.19 log Pa.s. The following were obtained for the coefficients in the equation:

	Standard Error of Estimate
For the $T\ Y^{0.5}$ term	1.76×10^{-3}
For the $D\ Y^{0.5}$ term	1.68×10^{-3}
For the constant term	7.24×10^{-2}

Figure 1 is a plot of the values of viscosity that were predicted from Equation 1 against the viscosity actually measured for all points in the data set.

The model is applicable to properly constructed seals in which the asphalt hardens through thermal oxidation. Additional hardening that is caused by other reasons, such as a loss of volatile oils in the asphalt that were not removed during refining, is not predicted. The model only applies with the stated precision to points that lie within the range of the data base that was used to construct it. The range of the variables is given in Table 1.

The temperature variables were obtained from statistics published by the Meteorological Bureau for the measuring station that was closest to the site (*17*). The values of the variables are long-term averages over periods of at least 15 years. Although the range of the temperature parameter (T) appears small, it covers a wide range of climatic conditions. Sites are located between latitudes 17° and 37° S, and both in-land and coastal regions are covered.

With only one exception, the asphalts in the data base are of Middle East origin. They do, however, cover a range of manufacturing procedures, including straight-reduced, air-blown, and propane-precipitated asphalts. The range of the durabilities of the asphalts is great. State Road Authority specifications commonly limit asphalts to a durability of 9 days or more.

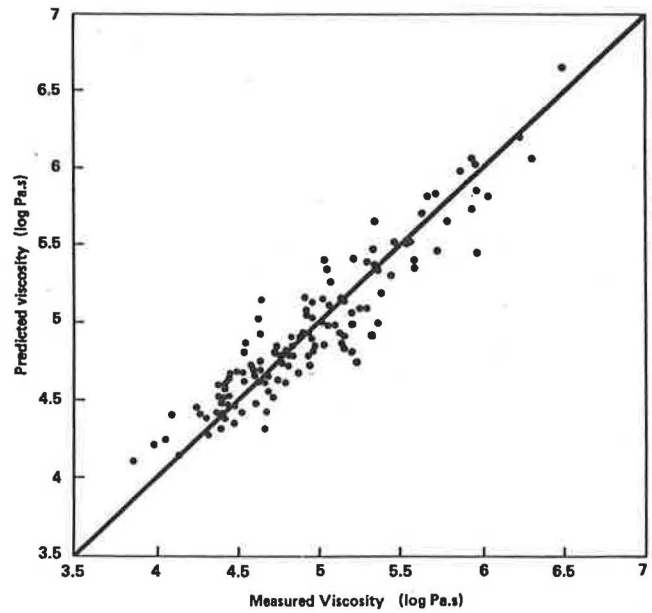

FIGURE 1 Plot of predicted versus measured viscosity.

TABLE 1 RANGE OF THE VARIABLES IN THE DATA BASE

Variable	Minimum	Maximum	Range
log η (Pa.s)	3.86	6.48	2.62
Y (years)	1	10.4	9.4
D (days)	3.4	21.0	17.6
TMAX (°C)	16.2	30.1	13.9
TMIN (°C)	8.2	21.2	13.0
T (°C) (equn. 2)	13.7	23.6	9.9
Viscosity of original asphalt before spraying (Pa.s at 60°C)	30	413	383

Uses of the Model

The model can be utilized to test the effect of using asphalts with different durability values at particular sites. Figures 2 and 3 are examples of asphalt-hardening graphs that were calculated for a medium- and a high-temperature site.

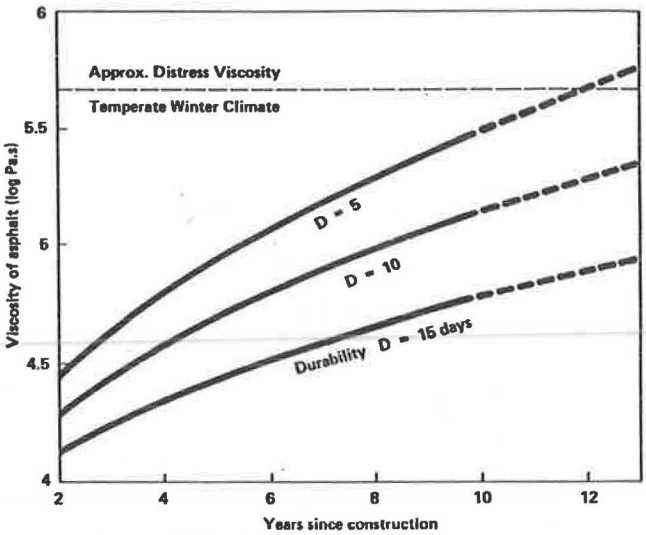

FIGURE 2 Asphalt hardening graph at T = 15°C.

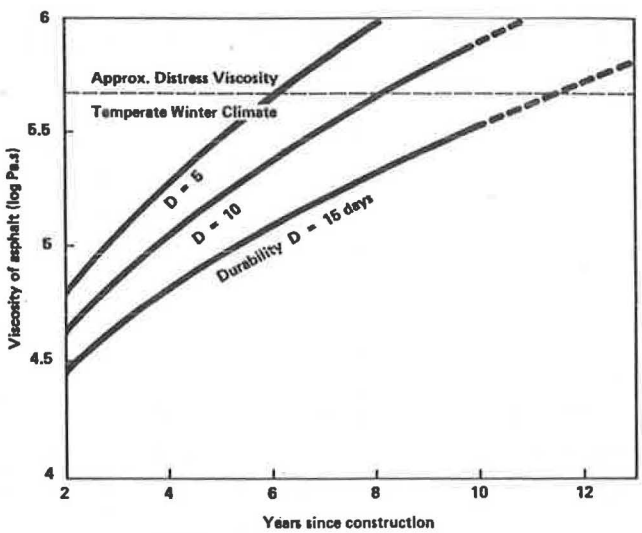

FIGURE 3 Asphalt hardening graph at T = 20°C.

Data are currently insufficient to reliably determine the viscosity level at which distress occurs in a sprayed seal. Although the level may be affected by traffic volume and rainfall at the site, Dickinson has suggested that the mean value of the minimum daily air temperature for the coldest month of the year (MIN MMAT) may be a good predictor (*9*). The distress viscosity level shown on the graph is the level that is based on the results of a survey of seals in a temperate climate area (MIN MMAT 7°C) (*18*).

As more information on the viscosity level associated with seal distress in different climatic areas becomes available, it should be possible to predict maximum achievable seal life for a particular climatic area and asphalt supply. Such relationships could be usefully incorporated into pavement management systems. Climatic areas in which asphalt will harden particularly rapidly can be easily identified by use of the present model.

Measures To Reduce the Rate of Asphalt Hardening

As can be inferred from Figures 2 and 3, seal life on low-volume roads in which structural inadequacy is not a critical factor can be substantially increased by the specification of a durable asphalt. The source of crude and the method of manufacture are the major factors that influence asphalt durability (*5*).

In cases in which durability cannot be increased by changing the source of crude or the refining procedures, it might be possible to incorporate an additive into the asphalt cement to improve durability. Two such additives, hydrated lime and lead dimethyldithiocarbamate (LDADC), are being evaluated by ARRB.

Hydrated lime that is mixed with asphalt at concentrations of up to 15 percent by mass has significantly improved asphalt durability in laboratory testing. The modified binder is now being evaluated in road trials at a number of sites.

The antioxidant LDADC has produced increases in durability of up to 100 percent in laboratory testing. The material is a liquid that is soluble in asphalt and is thus easy to incorporate. Two full-scale, sprayed-seal road trials have been laid that incorporate the additive in concentrations between 1 and 5 percent. Hardening of the modified binder sections will be compared with the control sections (same asphalts with no antioxidant) over a number of years.

HARDENING IN ASPHALTIC CONCRETE

This study is concerned with the performance of sprayed seals, but some types of low-volume roads are surfaced with asphaltic concrete (a.c.). Asphalt hardening in thin a.c. surfacings is briefly discussed in the following paragraphs.

The rate at which the binder hardens in an a.c. surfacing that is laid at a particular site depends on a number of factors, including the following:

- The air void content of the surfacing,
- The degree of interconnection of the air voids,
- The durability of the asphalt binder, and
- The thickness of the binder film that coats the aggregate particles.

The air void content of a mix immediately after construction could be well above its Marshall design value, depending on the thickness laid, the temperature of the base on which it was laid, and the amount of compaction applied. The surfacing may densify after construction because of the action of traffic. For example, the air void content on a highway that carries 15,000 vpd was observed to fall from 9.4 to 5.3 percent in the wheel path area and to 8.2 percent between the wheel paths over a period of 5 yrs (*15*).

This indicates that the situation is probably too complex to allow a general hardening model for asphaltic concrete mixes to be developed. It also means that it is extremely difficult to perform experiments to study, for example, the effect of an additive on asphalt hardening. This is because the other variables that affect the rate of hardening cannot be adequately controlled. A sprayed seal is preferred for such trials.

Although it is difficult to determine the precise effect of asphalt durability on the rate of asphalt hardening in an a.c. surfacing, it will nevertheless be a controlling factor unless air voids in the region of about 5 percent or less are achieved

uniformly across the surfacing at the time of construction (*19*). It is therefore just as important to select a durable asphalt for a.c. work as it is for sprayed seals.

CONCLUSIONS

- Sprayed seals laid on low-volume roads can have service lives of between 10 and 15 years provided they are properly designed and constructed, and a durable asphalt is used.
- Observation of full-scale road trials laid at sites with a range of climatic conditions, and monitored for periods of up to 10 yrs, has shown that the ARRB Asphalt Durability Test result is a good indicator of the long-term field hardening of Australian asphalts.
- An asphalt hardening model has been developed for sprayed seals. The model can be used to predict asphalt viscosity given the age of the seals, the durability of the original asphalt, and the site temperature, which can be obtained from published meteorological data. This model has been developed from testing of sprayed seals that were manufactured from Australian asphalts that were derived from Middle East crudes with an initial viscosity in the range from 30 to 400 Pa.s (300 to 4,000 poises) at 60° C.
- When the viscosity level at which seal distress occurs is known, the model can be used to predict seal life for adequately constructed low-volume roads. This relationship could be incorporated into pavement management systems.
- In cases in which durable asphalts are not available, laboratory testing has indicated that hydrated lime and the antioxidant lead dimethyldithiocarbamate could be used to reduce the rate of asphalt hardening. Road trials have been laid to confirm these findings for long-term pavement service.

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