Extending the Life of Thin Asphalt Surfacings

JOHN W. H. OLIVER

The scope for extending the life of asphalt surfacings in the United States is examined by comparing the durabilities of Australian and North American asphaltic cements. A model is used to estimate the effect of durability on surfacing life at a number of sites in the United States. Two approaches to reducing asphalt oxidative hardening are presented. In the first, a road trial of a gap-graded mix designed for surfacing lightly trafficked residential streets is described. After 10 years of service, the gap-graded mix had hardened much less than conventional ones. Sectioning of cores from the trial showed that all the hardening in the gap-graded mix had occurred at the surface; the interior of the mix had not hardened since construction. This is attributed to the low air void content initially obtained as a result of the ease of compaction of the mix. The second approach is reduction of the hardening rate of asphalt binders by addition of an antioxidant. The antioxidant lead diamyldithiocarbamate (LDADC) is being evaluated in two chip seal road trials in Australia. Binder hardening is well advanced at the trial in a tropical environment, and the results of sampling and testing 6 years after construction are presented. These results show that, for LDADC concentrations greater than 4 percent, a substantial reduction in binder hardening has occurred. LDADC has acted sacrificially and none now remains in any of the trial sections. Further observation of the trial will reveal whether the observed improvement continues to be maintained.

The author compares the durability of North American and Australian asphaltic cements and indicates how a reduction in binder hardening rate could translate into substantial increases in life for thin asphalt surfacings in North America. Two means by which such a reduction in hardening may be achieved are considered.

The first is by reducing the air void content of asphaltic concrete (AC) surfacings to prevent air ingress and subsequent oxidative hardening. A case study is presented of the development and subsequent performance evaluation of an easily compacted mix for surfacing lightly trafficked residential streets.

The second approach is by improving the durability of the binder itself through addition of an antioxidant. As in the first study, the asphalt antioxidant is being evaluated by means of long-term roads trials. Although laboratory experimentation may be used to identify promising new materials and rank them by means of simulative performance tests, the only reliable measure of field performance is behavior under actual road conditions. The complex interaction between the road environment and naturally occurring, and thus intrinsically variable, pavement materials cannot be satisfactorily duplicated in the laboratory.

BINDER HARDENING

Hardening Process and Durability Testing

The life of a correctly designed asphalt surfacing that is able to resist rutting and is placed on a structurally sound base depends to a large extent on the life of the binder. The binder hardens with time until it can no longer withstand the movement caused by diurnal temperature changes and cracking occurs or until the bond between the aggregate and the binder fails and stone particles are displaced by traffic.

Binder hardening occurs mainly through oxidation of the asphalt. Although the sunlight-induced photo-oxidation reaction proceeds rapidly, it is confined to the top 5 mm of the exposed surfacing and its overall effect is slight (*1*). Most asphalt hardening is caused by the slower thermal oxidation reaction. The rate of this reaction roughly doubles for every 10°C rise in temperature (*2*). Another factor that affects the rate of reaction is the diffusion of atmospheric oxidation into the binder films.

The Australian Road Research Board (ARRB) durability test is used to measure the intrinsic resistance of an asphalt to thermal oxidation hardening. The first stage of the test is the normal rolling thin film oven (RTFO) treatment (*3*) to simulate hardening during construction. The RTFO-treated asphalt is then deposited as a 20-mm film onto the walls of glass bottles, which are exposed in a special oven at 100°C. Bottles are withdrawn periodically, the bitumen is removed, and its viscosity is measured at 45°C. The durability of the asphalt is the time in days for it to reach an apparent viscosity of 5.7 log Pa.s.

The test has been used in Australia for more than 20 years, and most road authorities have a minimum durability requirement for asphalt. Full details of the test are provided in Australian standards (*3*).

To determine whether field hardening correlates with the durability test result, full-scale road trials were placed with asphaltic cements covering a range of durability at various sites in Australia. The trials were chip seal surfacings, which allowed the effect of binder durability to be easily studied. Asphalt mixes suffer from the disadvantage, from an experimental viewpoint, that binder hardening in an AC layer depends on air void content, which varies with location across the road and with time, as traffic densifies the mix.

The road trials were followed for up to 15 years, and a correlation between the durability test result and asphalt hardening was established (*4*). Further analysis of the data resulted in the development of a binder hardening model for chip seals that related binder viscosity to average site temperature, binder

---

Australian Road Research Board Ltd., 500 Burwood Highway, Vermont South Vic 3133 Australia.

durability, and age of the surfacing. Full details of the model are reported elsewhere (*5*).

Durability of North American Asphalts

There is wide variation in the properties of asphaltic cements in use across North America. The selection by the Strategic Highway Research Program (SHRP) of eight core asphalts provides a convenient means for overseas workers to obtain and test a cross-section of North American binders. The eight core SHRP asphalts were subjected to the ARRB durability test, and the results are presented in Table 1.

A high number of days in the durability test indicates a durable asphalt. Most Australian road authorities specify a minimum durability of 9 days for Class 170 (85/100 pen) asphalts. Only one of the eight SHRP asphalts met this requirement; several had extremely low durability values. Asphalt durability depends on the crude source used and, to a lesser extent, on the refining procedure. Australian asphalts are manufactured from Middle East crudes.

The effect of durability on the time to onset of distress in chip seal surfacings was estimated by Oliver for a number of U.S. cities (*6*). The results are presented in Table 2 for asphalt durability of 5 and 10 days.

The data in Table 2 refer to high-quality chip seals constructed on bases that remain structurally sound. As indicated in Table 1, the durability of some North American asphalts is less than 5 days, and the lives of seals constructed with these materials will be shorter than those shown in Table 2. The lives of AC surfacings are normally greater than those of seals, but the relative effect of asphalt durability will be of a similar order, unless a sufficiently low air void content is obtained at construction.

The information summarized here indicates the magnitude of the improvement in surfacing life that may be obtained by reducing the rate of oxidative hardening of asphalt binders. Two means by which this might be achieved are discussed in this paper.

TABLE 1 Results of Durability Testing of SHRP Core Asphalts (*3*).

SHRP Designation	ARRB No.	Durability (days)
AAA-1	458	5.1
AAB-1	459	4.7
AAC-1	460	8.3
AAD-1	527	2.4
AAF-1	462	2.7
AAG-1	463	10.4
AAK-1	464	1.8
AAM-1	465	3.8

TABLE 2 Estimated Time to Onset of Distress in Chip Seals

City	Seal Life (years)	
	Durability = 5 days	Durability = 10 days
Washington	13	>20
Houston	8	11
Oklahoma City	10	16
Phoenix	6	9
San Fransisco	16	>20
Wichita, Kansas	11	20
Nashville	11	17
Los Angeles	9	14
Jacksonville, Fla	8	11

DEVELOPMENT OF LONG-LIFE MIX FOR LIGHTLY TRAFFICKED STREETS

Design of Gap-Graded Mix

Although little attention is paid to the design and construction of surfacings for lightly trafficked residential streets, they nevertheless represent an asset of considerable size, with probably around 20 percent of Australian production of asphaltic cement devoted to this end. This value may be similar in the United States.

ARRB became involved in the topic in 1977 after a group of local government engineers expressed concern that residential street surfacings were fretting away, resulting in reduced service lives. An investigation showed that the most common failure mechanism was hardening of the binder, leading to disintegration at the surface. A clear trend was found for increased binder hardening rate to be associated with high air voids in the mix.

The highway type mixes normally used on residential streets do not usually get sufficient traffic compaction for the air voids to be reduced to a satisfactory level. Work was therefore begun to develop a mix that would have a sufficiently low air void content immediately after construction.

The design was based on a gap-graded mix (for which certain sizes of aggregate are deliberately omitted), which is easier to compact. Traffic loads are carried by the fine aggregate and binder mortar, and these mixes are liable to rut unless the properties of the fine aggregate fraction are properly controlled. Consequently, laboratory and pilot investigations were focused on defining the relative proportions of sand (rounded) and crushed rock (angular) fines to be used. Mixes of different composition were manufactured and tested in the laboratory at 55°C on a wheel tracking machine, and selected compositions were placed in the ARRB grounds and trafficked by a loaded truck to verify that rutting resistance was satisfactory. Information on the procedures used is provided elsewhere by Oliver (*7*).

Camberwell Road Trial

The selected gap-graded mix design was placed in a full-scale road trial in 1981. A Country Roads Board (CRB) (now Vicroads) light traffic mix (Type L) was placed in the same trial. The CRB Type L mix was based on conventional, continuously graded highway mixes, but a lower design air void content was achieved through small changes in aggregate grading and a small increase in bitumen content (around 0.5 percent). The mixes were placed nominally 25 mm thick over an old pavement that showed some cracking.

The standard mix used by the constructing authority, Camberwell City Council (CCC), was placed at the same site for comparison purposes. A mix with the same grading as the CCC mix, but with a softer bitumen (Class 80 equivalent to 200 pen), was also placed.

The composition of the trial mixes is presented in Table 3. As indicated previously, the performance of a gap-graded mix depends on the properties of the fine aggregate, particularly on the relative proportions of the rounded sand and angular crushed rocked fines fraction. This was controlled by specifying the proportions of mix components to be added to the cold feed line at the mixing plant, as indicated in Table 4.

Conventional paving equipment was used, and compaction was effected by a 10 t static steel-wheeled tandem followed by a 12 t pneumatic multiwheeled roller. The achieved layer thickness and air void content for each mix is presented in Table 5. The results shown for each mix are mean values of duplicate sections laid on adjacent streets.

Periodic Inspection and Sampling

The trial sections were inspected and tested in 1986 and again in 1991 and were found to be in generally good condition. The latter inspection showed that some loss of fine aggregate was occurring in the conventional mixes but not in the gap-graded one. All sections showed signs of cracking, believed to be reflected through from the underlying base, but this was not considered to be serious. None of the sections had rutted and there was judged to be considerable life remaining in all sections.

In 1986 two 100-mm-diameter samples were cored from each section, and the air void content was measured. Binder was recovered from each specimen using toluene as a solvent. Recovered binder was tested using a Shell sliding plate microviscometer to determine apparent viscosity at a temperature of 45°C and a shear rate of $5 \times 10^{-3}\ s^{-1}$.

In order to obtain information on the variation of binder hardening with depth beneath the surface, a more elaborate procedure was used in 1991. Three samples were cored in a transverse line approximately midway along the length of each section. Density measurements were made on the cores as before, and then each was cut into three sections: a top layer 3.6 mm thick, a middle layer 3.6 mm thick, and a bottom layer of variable thickness averaging 6.8 mm. The width of the saw cut was 5 mm, so the centers of the three layers were originally 1.8, 10.4, and 20.6 mm beneath the road surface.

The viscosity of the binder recovered from each layer of each core was measured as before. In order to compare these results with the 1986 results, the mean viscosity of the binder in each core was estimated from the observed viscosity gradient.

RESULTS

Change in Air Void Content with Time

The air void contents of the cores are presented in Table 5 and show that all mixes continued to densify slowly with time in spite of being placed in a low-traffic location. The gap-graded mix had a void content of 7.1 percent at construction, which fell to less than 6 percent within 4 years.

TABLE 4 Aggregate Composition of ARRB Gap-Graded Mix

Component	% by Mass of Total Aggregate
10 mm industrial sized crushed rock	30
Passing 3.2 mm industrial sized crushed rock fines	31
Earlston (rounded) sand	31
Cement kiln dust filler	8

TABLE 3 Composition of Road Trial Mixes

	Percentage Passing			
A.S Sieve (mm)	ARRB Gap-Graded	CRB Type L	CCC Standard	CCC with Class 80
13.2	100	100	100	100
9.5	98	99	98	99
6.7	77	81	78	78
4.75	68	60	61	61
2.36	64	45	48	50
1.18	48	35	36	37
0.6	34	25	25	26
0.3	21	16	16	16
0.15	11	8	8	9
0.075	7.4	5.6	5.5	6.0
Bitumen (% by mass of total mix)	6.8	5.9	5.7	5.7
Average film thickness (mm)	8.8	9.9	9.6	9.1

TABLE 5 Layer Thickness and Air Void Contents

Mix Type	Surfacing Thickness (mm)		Air Void Content (%)		
	Actual	Aim	At Construction	4 y after Construction	10 y after Construction
CCC Cl 80 bitumen	28.3	25.0	10.4	8.4	8.1
ARRB Gap-graded	28.9	25.0	7.1	5.3	4.8
CRB Type L	24.6	25.0	8.4	7.4	7.0
CCC Standard	27.3	25.0	11.1	10.3	9.1

Binder Hardening with Time

The change in viscosity of binder extracted from the cores is shown as a function of time in Figure 1. It can be seen that the three conventionally (densely) graded mixes have continued to harden since they were placed; the mix with the highest air void content hardened the fastest. The gap-graded mix did not harden further after it was tested in 1986.

Viscosity as a Function of Depth

Figure 2 shows the change in binder viscosity with depth from the surface for the 1991 cores. It is clear that the three conventionally graded mixes have hardened to a similar degree, whereas the gap-graded mix has hardened much less. There is a considerable decrease in viscosity from the top layer of a mix to the middle layer, but virtually no further decrease from the middle to the bottom layer.

Perhaps most surprising are the results for the gap-graded mix. The middle and bottom layers are at, or close to, the estimated laying viscosity of the binder, which is shown on the figure by a horizontal dashed line. Thus, the binder appears not to have hardened significantly during 10 years of service.

Relationship Between Binder Viscosity and Air Voids

The viscosity results for the middle and bottom layers of all cores are shown plotted against their air void content in Figure 3. There appears to be a trend for viscosity to increase sharply with air voids up to about 6 or 7 percent void content and then slowly thereafter. The bold line indicates this trend.

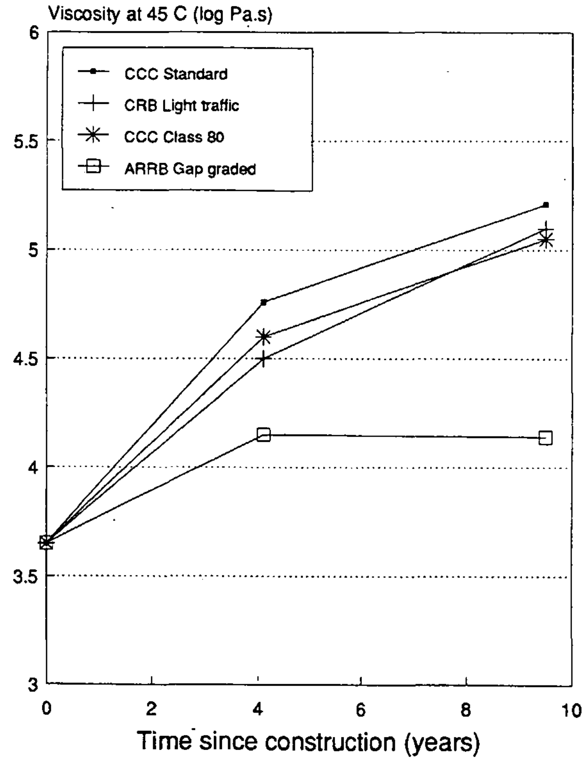

FIGURE 1 Change in binder viscosity of surfacings with time.

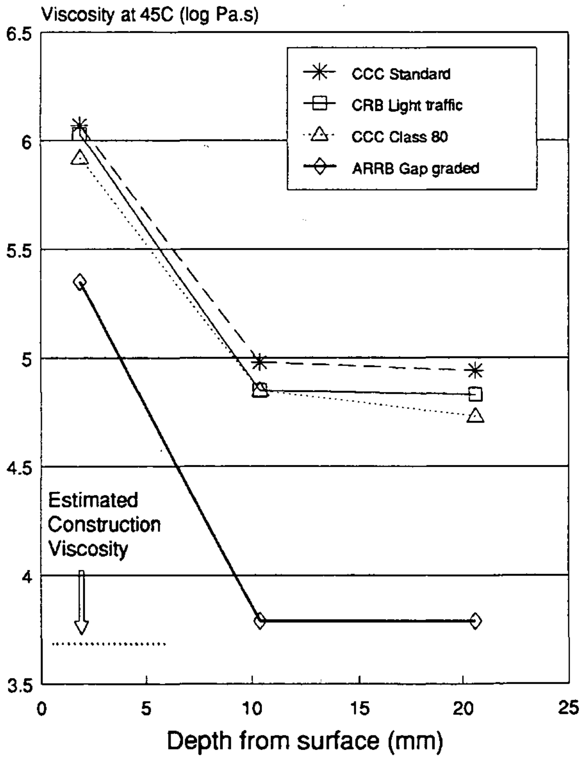

FIGURE 2 Plot of binder viscosity against depth beneath surface.

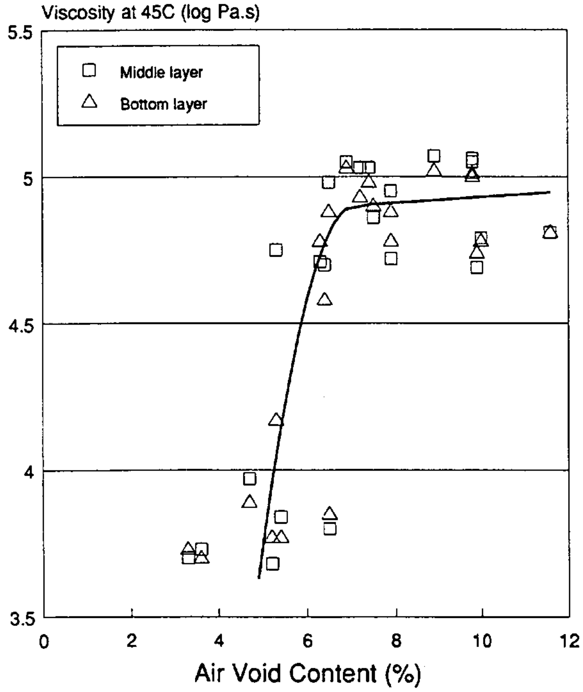

FIGURE 3 Plot of binder viscosity against air void content for middle and bottom layers of all mixes.

Results for the surface layer showed a wide scatter and are not displayed.

DISCUSSION OF RESULTS

After 10 years of service, the continuously graded mixes in the trial began to exhibit signs of stone loss and ravelling. It is likely that they will slowly abrade away during the next 5 to 10 years. Because the binder in the interior of the gap-graded mix is hardening extremely slowly, it is likely that it will provide a much longer service life, possibly on the order of twice that of the continuously graded mixes. Thus, a 30- to 40-year life may be achievable, provided that cracks are periodically treated so that water is excluded from the base.

The road trial has shown that the air void content achieved during construction of a mix is important in determining its future rate of binder hardening. This has been stated previously by others (*8*). Of interest is the finding that, for a mix with a sufficiently low air void content, significant hardening occurs only in the surface layer. At this void content the binder films are mainly continuous, and long diffusion paths to the interior of the mix are formed.

Densely graded Marshall mixes have traditionally been used in the United States, but workers have recently been investigating the use of other mix types, such as Split Mastic Asphalt. It may be worthwhile for U.S. authorities concerned with the design and construction of surfacings for lightly trafficked streets to consider the introduction of a gap-graded mix. These mixes are easier to compact than densely graded mixes and are considered to be less permeable at the same air void content than continuously graded mixes because fewer voids are interconnected (*9*).

REDUCTION IN BINDER HARDENING BY ADDITION OF ANTIOXIDANT

Background

Although a low air void content will reduce the rate of asphalt hardening in a surfacing mix, it is not always possible to achieve this condition. A more fundamental improvement, applicable to both asphalt mixes and chip seals, may be obtained by increasing the durability of the asphalt cement through selection of the source of crude petroleum, control of the refining process, or by addition of an antioxidant to the asphalt binder. The field evaluation of an antioxidant is described here.

The antioxidant lead diamyldithiocarbamate (LDADC) has been shown in laboratory testing to be effective in reducing the hardening rate of asphaltic cements (*10*). To determine whether such an improvement also occurs during the long-term hardening of pavement surfacings, two full-scale chip seal road trials were placed in Australia: the first was laid near Townsville in the tropical north, the second near Hopetoun in the more temperate south.

Control sections were constructed at both trials. These sections were identical in all respects to the experimental sections except that the binder contained no LDADC. The trials have been regularly sampled and tested to determine how fast the LDADC-modified binder sections were hardening compared with the control sections.

Both trials have been well documented, and a number of reports have been issued. These reports provide information on the construction operation (*11,12*), laboratory testing of the trial binders (*10*), and a procedure to determine the LDADC content of bituminous binders (*13*). Environmental and occupational health monitoring was undertaken at the Hopetoun trial (*14*), and results indicated no significant increase in lead in soil samples taken after the trial and no lead uptake by construction workers. The antioxidant is soluble in asphalt, and both it and its degradation product are insoluble in water.

Recent testing of the Townsville trial has shown that considerable binder hardening has occurred in the 6 years since it was placed. At the Hopetoun trial, the binder hardening rate has been slower because of the lower ambient temperature at the site. The results of the Townsville trial are discussed here.

Townsville Trial Layout

The Townsville trial sections were sprayed November 25–28, 1985. There are 12 experimental sections in the trial, each approximately 450 m long × 6 m wide, and the same base asphaltic cement was used throughout. Duplicate sections containing 0 percent (control) and approximately 1, 2, and 3 percent by mass LDADC in the binder were placed. In addition, there were single sections with approximately 4 and 5 percent LDADC and two extra control sections. No cutter or flux was added to the binder.

The layout of the sections is shown in Figure 4. Testing by infrared analysis (*13*) determined the concentration of active LDADC in the binder immediately after construction; this information is included in the figure.

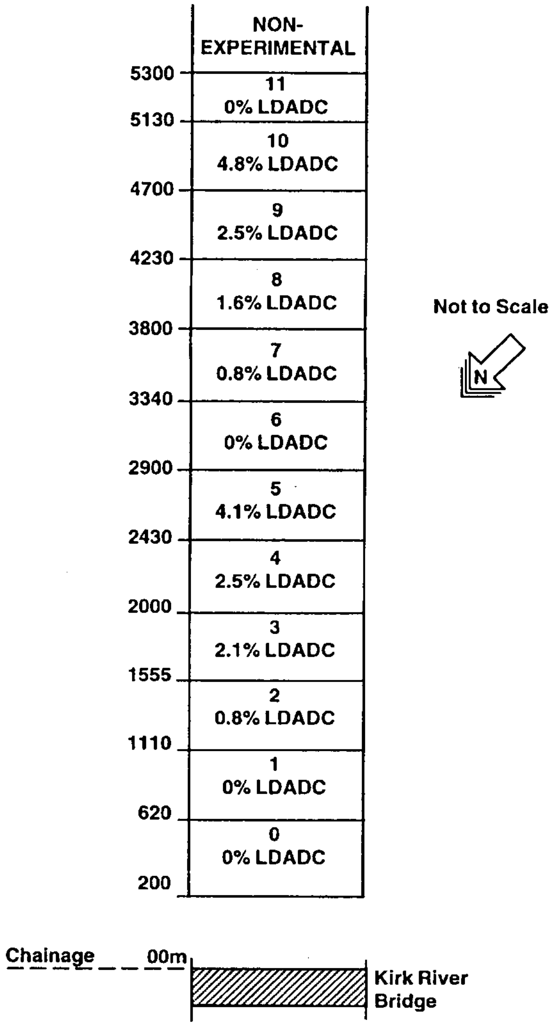

FIGURE 4 Layout of Townsville trial sections.

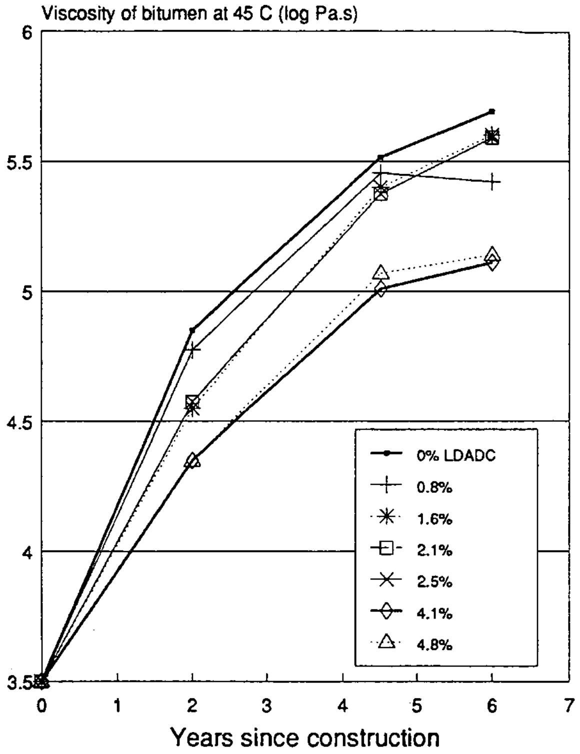

FIGURE 5 Increase in viscosity with time at Townsville.

1991 Sampling and Testing

Two different sample locations were identified in each trial section. At each location a motor-powered Carborundum cutting disc was used to cut a section of seal approximately 200 mm square. The seal sample, with any adhering material, was carefully removed from the surface and transported to the laboratory for testing.

The seal sample was warmed in an oven, and individual stones were plucked from the surface. The binder adhering to the undersides of these stones was recovered by solution in toluene, centrifuging and decanting the solution, and then removing the solvent by evaporation. The degree of hardening of the recovered binder was determined by measuring the apparent viscosity at 45°C and a shear rate of 5×10^{-3} s^{-1} using a Shell sliding plate microviscometer.

Viscosity of Recovered Binder

Figure 5 shows binder viscosity plotted as a function of time for different levels of initial antioxidant concentration. The graph indicates that the samples that had an initial LDADC concentration of 2.5 percent or less show only a small improvement in hardening rate over the control asphalt (0 percent LDADC). However, samples with initial LDADC concentrations of 4.1 and 4.8 percent demonstrate a substantial reduction in hardening rate.

The 0.8 percent LDADC curve appears anomalous because it suggests that the binder has softened between 1990 and 1991. This softening is unlikely, and the effect is probably due to experimental error.

Decomposition of LDADC

LDADC in an asphalt can degrade during high temperature storage and during long-term exposure on the road, where it is believed to act sacrificially to prevent oxidation of the binder. To determine the concentration of active LDADC remaining at any time, a measurement technique based on infrared spectroscopy was developed. This procedure detects the presence of the dithiocarbamate entity and is described by Huxtable and Oliver (*13*). Table 6 presents the concentration of LDADC in the trial sections measured by this method.

Examination of the results shows that rapid decomposition of LDADC occurred during the first 2 years. Only sections that originally contained more than 4 percent LDADC had any dithiocarbamate structure remaining after 2 years of pavement service. The concentration of dithiocarbamate in these sections was observed to have decreased further after 4.3 years of service, and no material was detected after 6 years.

TABLE 6 Change in LDADC Content

Section No.	%LDADC measured 0 years	% LDADC measured 2.0 years	%LDADC measured 4.3 years	%LDADC measured 6.0 years
1	0.0	-	-	-
2	0.8	0.0	-	-
3	2.1	0.0	-	-
4	2.5	0.0	-	
5	4.1	1.1	0.4	0.0
6	0.0	-	-	-
7	0.8	0.0	-	-
8	1.6	0.0	-	-
9	2.5	0.0	-	-
10	4.8	1.6	0.5	0.0

Discussion of Results

The results to date suggest that LDADC reduces binder hardening until all the antioxidant is consumed. A substantial reduction in asphalt hardening rate has been obtained for binders that contained more than 4 percent LDADC.

It is important to determine what happens after all the LDADC in a binder has decomposed. The possibilities are shown in Figure 6. The horizontal line indicates the estimated distress viscosity level at Townsville, which is 6.6 log Pa.s. This value is only a coarse estimate using a model based on a limited data set (*15*). The point at which a curve intercepts this line indicates the expected seal life. For the control binder (0 percent LDADC), this appears to be about 12 years.

The arrow shows the 1991 result for the section that originally contained approximately 4 percent LDADC. The dashed lines indicate three possible future hardening scenarios: (a) the LDADC-modified binder may now harden faster than the control bitumen until it catches up with it; (b) the reduction in viscosity achieved by the LDADC-modified binder, compared with the control bitumen, may be maintained at the same level; (c) the LDADC-modified binder may continue to harden more slowly than the control bitumen.

Possibilities b and c should result in a substantial increase in surfacing life. Further sampling and testing of the trial will be carried out to determine future behavior.

CONCLUSIONS

1. Testing of the SHRP core asphalts suggests that North American binders may be much less durable than Australian ones.
2. The service lives of thin asphalt surfacings could be extended by reducing the rate of oxidation hardening of the binder.
3. A gap-graded mix design for surfacing lightly trafficked streets was found, 10 years after placement, to have experienced much less binder hardening than conventional, densely graded mixes. The binder in the interior of the gap-graded mix had undergone virtually no hardening since construction.
4. The low hardening rate of the gap-graded mix is due to its low air void content at construction and also the lower degree of interconnection between voids in gap-graded mixes than in continuously graded mixes.
5. Gap-graded mixes may be able to achieve service lives of 30 to 40 years on lightly trafficked streets, provided that cracks are periodically treated.
6. Another means of reducing the rate of asphalt hardening in surfacings is by addition of an antioxidant. A field trial has shown that, after 6 years, sections in which the binder originally contained more than 4 percent LDADC have hardened much less than the control sections (same asphalt with no LDADC).
7. LDADC appears to act sacrificially to reduce asphalt oxidation, and all the antioxidant has now decomposed. Further testing is needed to determine whether the observed improvement continues to be maintained.

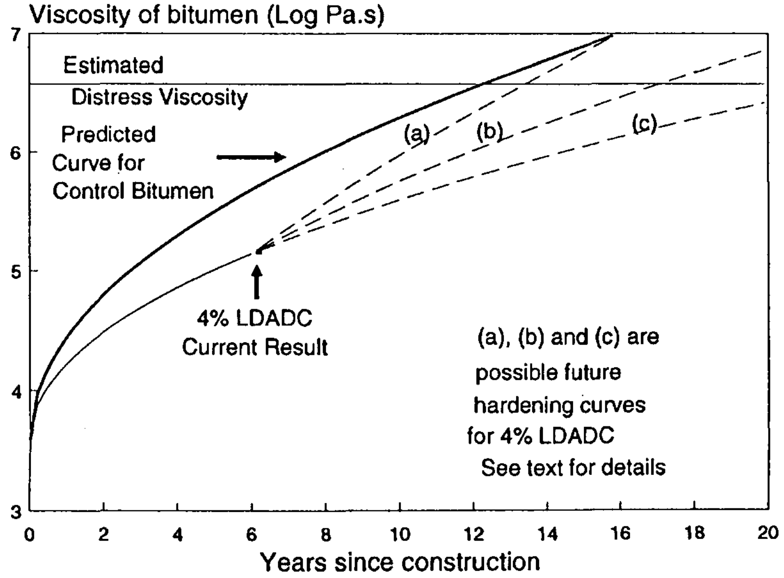

FIGURE 6 Predicted hardening curves for Townsville.

REFERENCES

1. Dickinson, E. J. The Diffusion Controlled Reaction of Oxygen with Paving Binders: The Effect of the Diurnal Temperature Variation in a Seal Binder. *Australian Road Research,* Vol. 14, No. 4, 1984, pp. 222–225.
2. Dickinson, E. J. *Pavement Temperature Regimes in Australia: Their Effect on the Performance of Bituminous Constructions and Their Relationship with Average Climate Indicators.* Special Report SR 23. Australian Road Research Board, Victoria, 1981
3. *Methods of Testing Bitumen and Related Products.* Australian Standard 2341.5, Determination of Apparent Viscosity by Shell Sliding Plate Microviscometer, 1986; Australian Standard 2341.10, Determination of the Effect of Heat and Air on a Moving Thin Film of Bitumen (RTFO test), 1982; Australian Standard 2341.13, Determination of the Durability of Bitumen, 1986. Standards Association of Australia.
4. Dickinson, E. J. The Performance of Thin Bituminous Pavement Surfacings in Australia. *Proc., 11th Australian Road Research Board Conference,* Vol. 11, No. 3, Victoria, 1982, pp. 35–51.
5. Oliver, J. W. H. Asphalt Hardening in Sprayed Seals. In *Transportation Research Record 1106*, TRB, National Research Council, Washington, D.C., 1987, pp. 196–201.
6. Oliver, J. W. H. Asphalt Durability: From Laboratory Test to Field Implementation. *Fuel Science and Technology International*, Vol. 10, Nos. 4–6, 1992, pp. 501–518.
7. Oliver, J. W. H. The Design of Bituminous Plant Mix for Specific Operational Conditions. *Proc., 10th Australian Road Research Board Conference,* Vol. 10, No. 3, Victoria, 1980, pp. 115–127.
8. Vallerga, B. A., and W. J. Halstead. Effects of Field Ageing on Fundamental Properties of Paving Asphalts. In *Highway Research Record 361*, HRB, National Research Council, Washington, D.C., 1971, pp. 71–92.
9. Marais, C. P. Surfacings for Asphalt Pavements: Asphaltic Concrete or Gap-Graded? *Proc., 7th Australian Road Research Board Conference,* Vol. 7, No. 6, Victoria, 1974, pp. 277–296.
10. Oliver, J. W. H. *Australian Lead Antioxidant Trials: Laboratory Testing of the Trial Binders.* Research Report ARR No. 165. Australian Road Research Board, Victoria.
11. Oliver, J. W. H., and W. P. Holtrop. Hopetoun Lead Antioxidant Trial: Construction Report. Internal Report AIR 410-2. Australian Road Research Board, Victoria, 1986.
12. Oliver, J. W. H. Townsville Lead Antioxidant Trial: Construction Report. Internal Report AIR 410-3. Australian Road Research Board, Victoria, 1987.
13. Huxtable, A. E., and J. W. H. Oliver. Determination of the LDADC Content of Oxidised Bitumens. Internal Report AIR 410-4. Australian Road Research Board, Victoria, 1989.
14. Oliver, J. W. H. Field Trials of a Lead Based Asphalt Antioxidant. In *Transportation Research Record 1228,* TRB, National Research Council, Washington, D.C., 1989, pp. 138–144.
15. Oliver, J. W. H. *Models To Predict Bitumen Hardening Rate and Distress Viscosity Level in Sprayed Seals.* Research Report ARR No. 182. Australian Road Research Board, Victoria, 1990.

Publication of this paper sponsored by Committee on Characteristics of Bituminous-Aggregate Combinations To Meet Surface Requirements.