CHIPSEAL BITUMEN HARDENING TRIALS IN NEW ZEALAND

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AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transfund New Zealand.

Transfund New Zealand is a Crown entity established under the Transit New Zealand Act 1989. Its principal objective is to allocate resources to achieve a safe and efficient roading system. Each year, Transfund New Zealand invests a portion of its funds on research that contributes to this objective.

The material contained in this report is the output of research and should not be construed in any way as policy adopted by Transfund New Zealand but may form the basis of future policy.

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Mr Philip Herrington of Opus Central Laboratories, Lower Hutt, developed the procedures for extracting bitumen from seals using dichloromethane and for estimating bitumen viscosity from measurement of the area of the infrared carbonyl peak. Also he has provided extensive assistance in interpreting results, especially with regard to the chemistry.

Dr Murray Forbes, also of Opus Central Laboratories, carried out the rheological testing on the Carri-Med rheometer.

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EXECUTIVE SUMMARY

Introduction

Trial pavement chipseals to measure the hardening of bitumens in New Zealand conditions were constructed at a number of sites throughout the country, and the bitumens from these chipseals were sampled and tested for 15 years, between 1984 and 1998. Supplementary information was obtained from seals at Gracefield (Lower Hutt) and near Chatto Creek north of Alexandra, Central Otago, as well as from artificial seals exposed on racks at Gracefield. The effects of a variety of bitumen types, seal types and chip grades were investigated.

Conclusions

Viscosity (45°C and 25°C) versus time plots of the bitumens gave an initially fast increase in viscosity for approximately four years, followed by stabilisation at a viscosity level that depended on the bitumen source and grade, and the seal chip size. No measurable relationship was found between the final viscosity level and climate, although it appears that the rate at which the final level was approached was greater for warmer climates.

The hardening of binder at the surface of a chipseal depends on the hardness of the binder in any underlying surface. Mixing of the bitumens occurs in the two surface layers.

Bitumen in seals constructed with small chips hardens faster than in seals with larger chips. The reason for this is unknown, but laboratory test evidence does support the possibility that the effect is probably related to the time that oxygen takes to diffuse through the bitumen to the bottom of the seal layer. Another cause associated with the field trials could have been mixing with different grade bitumens in the underlying road surfaces.

The observed viscosity–time plots did not match the predictions of the Australian Road Research Board (ARRB)-derived equation for bitumen hardening. In particular, the ARRB equation indicates that the viscosities will continue to increase with time, whereas the observed viscosity curves for the New Zealand trials levelled off.

The Australian durability oven results did not give a good indication of relative field performance. Safaniya and Venezuelan Boscan 180/200 penetration grade bitumens have very different laboratory durabilities, but seals constructed with them were indistinguishable in behaviour up to the time of the completion of the trials.

At all the trial sites, the ultimate reason for resealing was flushing. The trials were all in areas that are relatively highly trafficked for New Zealand. This suggests that cracking is likely to be a more of a problem for roads with relatively low traffic levels. Another implication is that there may be a conflict in using harder bitumens to delay flushing and softer bitumens to prevent cracking. However, this may not be so.

Based on binder hardness at different parts of the Kyeburn trial site, the evidence is that the condition of a seal can differ significantly on a scale of 20 m or less. Sampling at a few points may not therefore give a true indication of the overall state of a seal.

The presence of kerosene or diesel (AGO) in a chipseal does not affect the oxidation hardening of the bitumen itself.

Towards the end of the life of a seal, very little if any kerosene is left in the seal binder. Therefore, the use of kerosene cutback would not be expected to affect the long-term performance of a seal.

Rheological measurements of aged bitumens indicate that, although at higher road temperatures the bitumens (Safaniya 180/200 and 80/100 and Venezuelan Boscan 180/200) may differ significantly, at lower temperatures they may for practical purposes be indistinguishable. This cannot be assumed for other bitumens.

It may be possible to choose bitumens which are relatively hard at higher temperatures, to minimise the possibility of premature seal flushing, while avoiding the effects of greater susceptibility to cracking at low temperatures. It is not clear at this time (1999), however, whether the principal causes of cracking in New Zealand seals are relatively sudden failure of the bitumen at low temperatures, or accumulated fatigue from trafficking at typical daytime temperatures. Both types of crack development may occur, and the local climate might determine which is the most important.

Recommendations

Since in New Zealand, bitumens can now be obtained that are from a variety of oil fields and are produced by a variety of processes, a test method is needed for predicting the performance in seals constructed of bitumens which have not been used in this country before.

Development of such a test method requires information on the chemical processes of bitumen aging, and on the effects of bitumen rheological properties on different types of distress that occur in seals. Some work is already being carried out in these areas in New Zealand.

A field trial of seals is recommended to test the indication from rheological measurements that 80/100 bitumen may provide as good a resistance to seal cracking as 180/200 bitumen in low temperature regions, while reducing the rate of development of flushing at higher temperatures.

The effects of bitumen thickness on oxidative hardening and of the use of diesel to improve seal performance in low temperature climates would also be examined.

ABSTRACT

This report summarises the results of several road trials carried out in New Zealand, over 15 years between 1989 and 1998, to investigate the hardening of bitumen in chipseals. Such hardening is expected to limit the potential lifetimes of the chipseals. Suggestions are made for further research to develop ways to select bitumens to minimise types of seal distress associated with bitumen aging.

1. INTRODUCTION

This report summarises the results of several pavement trials carried out in New Zealand over 15 years, between 1984 and 1998, under the auspices of the National Roads Board and Transit New Zealand, and latterly of Transfund New Zealand, to investigate the hardening of bitumen in pavement chipseals. This hardening is expected to limit the potential lifetimes of the chipseals.

The studies have been important because most of the surfaced areas of roads in New Zealand consist of chipseals, and their failure is associated with two main types of distress. These are flushing (bitumen on the road surface) and alligator cracking (Ball & Owen 1998). The mechanisms of these two phenomena are currently (1999) being investigated (Transfund Research Project PR3-0309, "Flushing Processes in Chipseals"; Foundation of Research, Science and Technology Research (FRST) Contract OPS804, "Bituminous Surfacings").

All the mechanisms currently proposed for cracking would be expected to be affected by the hardening of the bituminous binder through oxidation. The mechanisms are:

- fatigue associated with repeated trafficking,
- thermal expansion and contraction of the road surface,
- brittle cracking at low temperatures under traffic loading.

Consequently, if bitumens can be chosen that harden more slowly, or can be modified to do so, chipseal life may be significantly increased.

This report describes and discusses the physical measurements obtained for the various weathering trials investigating hardening of bitumen. Other work which has been carried out on the chemical processes associated with bitumen oxidation has been reported elsewhere (Ball & Herrington 1996, Herrington 1998, Herrington & Wu 1998).

2. BACKGROUND

The first road trial study of seal bitumen hardening was established in New Zealand at Albany, just north of Auckland, in November 1984 (Somerville 1986). The design of the study sought to follow the pattern of the extensive trials carried out by the Australian Road Research Board (ARRB) in Australia since the 1970s, and the initial goal was to see whether or not New Zealand results fitted the Australian pattern.

The Australian research by ARRB staff (Dickinson 1976, 1980, 1982; Oliver 1984, 1985, 1987, 1989, 1990a, 1990b, 1993) led to a number of important developments, including:

- The Australian durability oven test for bitumens (SAA 1997). This test was adopted for the New Zealand roading bitumen standard in 1989, but was dropped in 1995 after the New Zealand trial work.

- The establishing of critical binder viscosity levels (Oliver 1990a, 1990b). If a binder hardens above the appropriate level, the seal is expected to deteriorate rapidly. The critical binder viscosity, $\eta_{distress}$, measured in Pascal seconds (Pa s) at 45°C and 0.005 s^{-1} shear rate, is given by:

$$\log \eta_{distress} = 0.105\ \mathrm{TMIN} + 4.78 \qquad (1)$$

- The development of an equation to predict the change in viscosity with time of an Australian Class 170 bitumen (approximately equivalent to a penetration grade 80/100 bitumen) for a chipseal (measured in the wheeltracks) (Oliver 1987):

$$\log \eta = \left[0.0476 \left(\frac{\mathrm{TMAX} + \mathrm{TMIN}}{2} \right) - 0.0227\ \mathrm{V} \right] \sqrt{\mathrm{Y}} + 3.59 \qquad (2)$$

where:

η = viscosity of the bitumen in Pa s units, measured at 45°C and a shear rate of 0.005 s^{-1}

V = durability in days of a bitumen, as measured by the Australian durability oven test (SAA 1997). Durability is defined as the time for the bitumen being tested in the Australian durability oven under the standard procedure to reach a viscosity of 5.67 (in log Pa s units)

Y = the time since the construction of a seal, in years

TMAX = the average of the daily maximum air temperature (°C) at a road site, measured over a year

TMIN = the average of the daily minimum air temperature (°C) at a road site, measured over a year

New Zealand sealing practice and environmental conditions differ in a number of important respects from Australian, so therefore it cannot be assumed that the Australian findings apply here:

- The variety of bitumens that is available in Australia but not in New Zealand. Until recently, practically all bitumen used in New Zealand since the late 1960s has been produced from the one source - Heavy Arabian (or Safaniya) crude oil - by the one refinery at Marsden Point near Whangarei.

- In Australia most sealing is done with Class 170 viscosity graded bitumen (roughly equivalent to New Zealand 80/100 penetration grade bitumen).

  In New Zealand two different penetration grades have generally been used: 180/200 for all first coat (new) seals and other seals in cooler climates, and 80/100 bitumen otherwise. In the 1980-90s trends have been to use a higher proportion of 180/200, and to use 130/150 bitumen around Napier and on the West Coast of the South Island.

- Australian bitumens are generally straight run or contain propane-precipitated asphalt (PPA) to increase laboratory measured durability levels. New Zealand 180/200 bitumen has been straight run, with all harder grades made by adding 45/55 or 40/50 bitumen produced by blowing. This produces a relatively low laboratory durability product. For example, the ARRB durability oven test typically gives a durability of 4.5 days for a New Zealand 80/100 bitumen, whereas a value of 7 days or more would be expected for the roughly equivalent Australian Class 170.

- Chip loss from old seals is not an important distress phenomenon on New Zealand roads. Thus the critical viscosity levels adopted in Australia from observation of stripping of old seals may be inappropriate for New Zealand.

- Standard New Zealand sealing procedures differ from Australian practices in a number of details, namely different chip sizes and application rates, use of washed rather than precoated chip, and the use of adhesion agents in the binder.

- With the generally cooler New Zealand climate, many New Zealand seals experience minimum winter temperatures well below anything encountered in the Australian seal trials.

3. NEW ZEALAND TRIAL DESIGN

Field trials were sprayed near Albany (approximately 15 km north of Auckland on State Highway (SH) 1N) in November 1984, near the Pahurehure Inlet Number 2 and the Papakura Interchange in South Auckland (also SH 1N) in November 1985, and at Kyeburn (SH 85) in Central Otago, in February 1986.

All trials contained a section sealed with a bitumen of Safaniya oil field origin for comparative purposes. Advantage was taken of a one-off shipment of Light Arabian bitumen from Singapore in 1984, and of Venezuelan Boscan bitumen imported during the 1985/86 Marsden Point refinery modification shutdown, to establish comparative seals near the Safaniya bitumen test strips. The essential details of the trials are listed in Tables A1.1 to A1.3 in the Appendix.

The data from the original trials was supplemented by sampling:

- From a site at Chatto Creek north of Alexandra, Central Otago, sealed with Boscan bitumen in 1985 and with Safaniyah in 1986. The two seals were adjacent to each other. The data obtained from this were used to supplement that from the Kyeburn site which had been sealed over prematurely. (Site details are listed in Table A1.4, Appendix.)

- From a trial site sealed in December 1988 on Gracefield Road in Lower Hutt. This trial was originally established by Lower Hutt City Council to study the rate of kerosene evaporation from seals. Safaniya bitumen data were obtained from it to compare with the other sites and to see if the presence of cutter alters the rate of oxidation of the bitumen. (Table A1.5, Appendix, has details.)

Some comparative tests with artificial chipseals were also carried out at Gracefield (Herrington 1989). The artificial chipseals were constructed in 1989 on galvanised steel trays and then weathered outdoors on racks. Single coat seals with different chip sizes and bitumen grades and a two coat seal were tested, using standard New Zealand binder application rates for sealing over smooth surfaces. Details are listed in Table A1.6 (Appendix). All binders were Safaniya bitumen with no adhesion agents, diluents or other additives. The binder was applied as hot bitumen in all cases, except for the Grade 5 chip on the two coat seal, for which a cationic emulsion was used.

4. EXPERIMENTAL METHODOLOGY

Sample recovery and analysis methods developed with the advent of new technology during the period of the trials.

Once a year, over the 15 years, square sections of approximately 150 x 150 mm size, were taken from outer wheeltracks (the outer side is the side furthest from the centre line of the road) at the field trial sites, using a portable masonry saw. The samples were heated to approximately 120°C and chips removed from the surface and immersed in a bitumen solvent.

Toluene was the solvent for the initial recoveries, but this proved to be unsuitable for the relatively volatile Boscan bitumens, and a recovery method using methylene chloride was later developed so that reliable results could be obtained.

After filtration the bitumen was recovered. A rotary evaporator was used for recovery from the toluene solutions. The methylene chloride solutions were poured as a film on to stainless steel plates, that were then mounted in sealed box, and the solvent was removed by a stream of dry nitrogen.

Samples from the artificial chipseals were obtained by scraping an area of seal off the exposed plate. The bitumens were then extracted from the scraped portion with solvents, as for the field trial site samples.

Following the approach of the Australian studies, bitumen viscosities of the road trials were measured at 45°C and a shear rate of 0.005 s^{-1}. Viscosities were initially measured with a Cannon cone plate viscometer using a procedure designed to give the same test conditions as those applied by the Shell sliding plate viscometer used in the Australian work (in particular, a progressively decreasing shear rate). The artificial seal sample viscosities, also obtained with the Cannon viscometer, were initially measured at 25°C, 0.1585 s^{-1} shear rate, with a progressively increasing shear rate mode. Later on, measurements at 45°C were carried out to compare the observed hardening with behaviour on the road. Towards the end of the trials the Cannon viscometer was replaced with a Carri-Med CSL^2 500 rheometer with a cone plate fitting.

Corrections of the viscosity results were required for those samples that had been recovered with toluene, as the residue turned out to routinely contain around 1% toluene (recovery from methylene chloride left no detectable solvent in the bitumen). The actual toluene content was determined by weighing the quantity of toluene evaporated from a small recovered sample in a thermogravimeter. The viscosity correction was then calculated using viscosity data from a number of bitumen samples containing known amounts of toluene.

In some cases viscosities were also estimated by measuring the area of the infrared carbonyl peak of the recovered bitumens. The viscosities were evaluated from carbonyl peak area versus viscosity relationships for standard bitumen samples. These standards were produced by aging fresh bitumens, of the same types as used in the trials, to varying degrees in a pressure bomb at 60°C and 2.068 MPa (300 psi) oxygen pressure. The results complemented and confirmed 45°C viscosity measurements (using a Carri-Med rheometer with cone plate fitting), performed on the samples from Chatto Creek and on some samples retained from the last sampling of the Kyeburn trial.

When the trials were completed a rheological study of a number of samples was carried out over a range of temperatures and frequencies using the Carri-Med rheometer with parallel plate fittings.

5. VISCOSITY–TIME BEHAVIOUR

Figures 5.1 to 5.5 show the increase in viscosity (45°C, 0.005 s^{-1} shear rate) with time for the trial locations. Curves, where indicated, are the hardening predicted by the ARRB relationship (equation (2)). The viscosity measurements for the Gracefield test plates are shown in Figures 5.6 to 5.9 (at 25°C with a shear rate of 0.1585 s^{-1}) and Figures 5.10 and 5.11 (at 45°C).

5.1 Albany and Pahurehure Inlet No. 2 / Papakura Interchange Trials

Sampling and testing for these trials were first carried out 3 or 4 years after sealing. The subsequent results up to the time of resealing (Figures 5.1 to 5.3) reveal that the viscosities of the 80/100 bitumens do not appear to be increasing or are increasing only very slowly. The viscosities appear to be plateauing at around 4.5 log Pa s.

The Auckland field trial data generally show a poor fit to the ARRB viscosity–time relationship (Equation (2)). All site temperature parameters were within ranges for which Equation (2) and critical viscosity levels (Equation (1)) are considered valid. Equations (1) and (2) combined predict lifetimes for the Albany seals of 19.6 years (Light Arabian 80/100) and 14.5 years (Safaniya 80/100), and for the Pahurehure seals of 12.6 years (Boscan 80/100) and 15.0 years (Safaniya 80/100). Clearly, on the basis of the trends observed, the bitumens were unlikely to reach the critical viscosity levels even after 13-15 years which, in New Zealand experience, is the upper limit of the expected lifetime for these seals.

Figure 5.1 Increase in 45°C viscosity shown in the Albany trial using Light Arabian 80/100 bitumen.

.... ARRB predictive curve

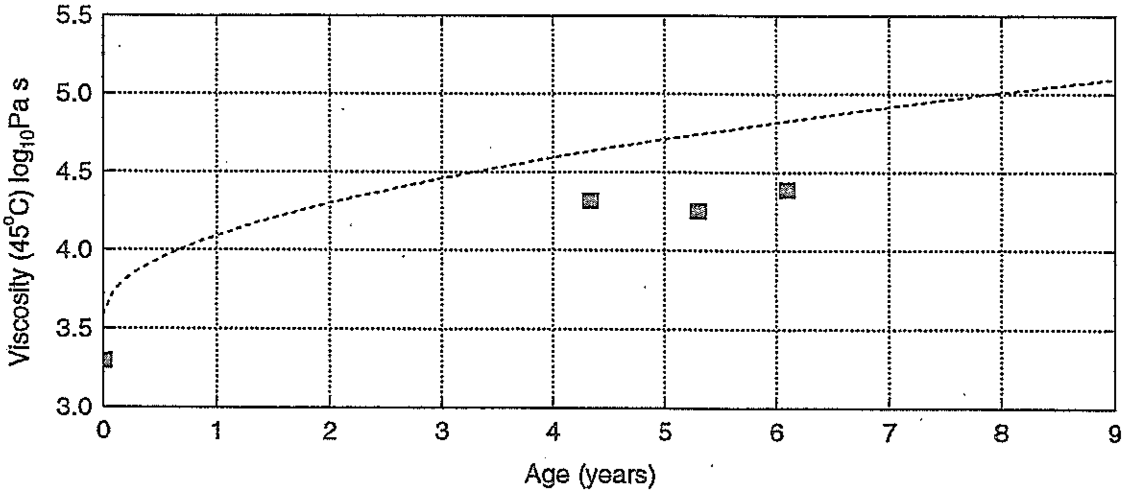


Figure 5.2 Increase in 45°C viscosity shown in the Albany trial using Safaniya 80/100 bitumen.

.... ARRB predictive curve

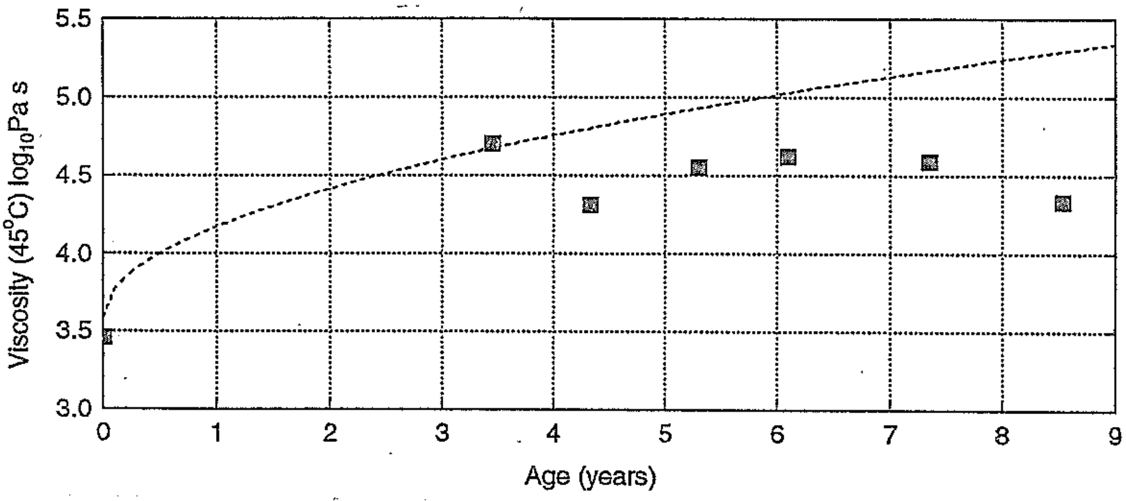


Figure 5.3 Increase in 45°C viscosity shown in the Pahurehure Inlet No. 2 / Papakura Interchange trial using Safaniya 80/100 bitumen.

.... ARRB predictive curve

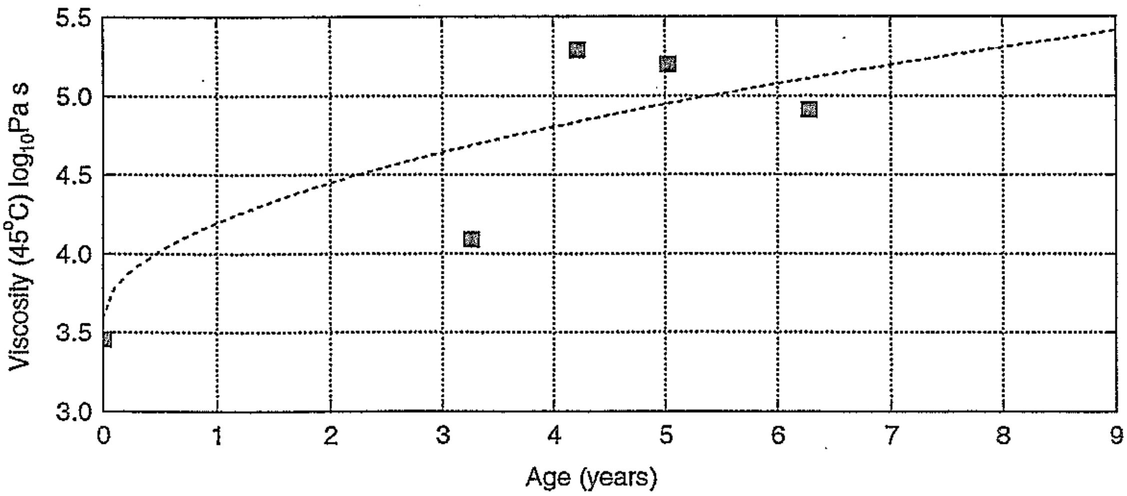


Figure 5.4 Increase in 45 °C viscosity shown in the Kyeburn and Chatto Creek trials using 180/200 Safaniya and Boscan bitumens.

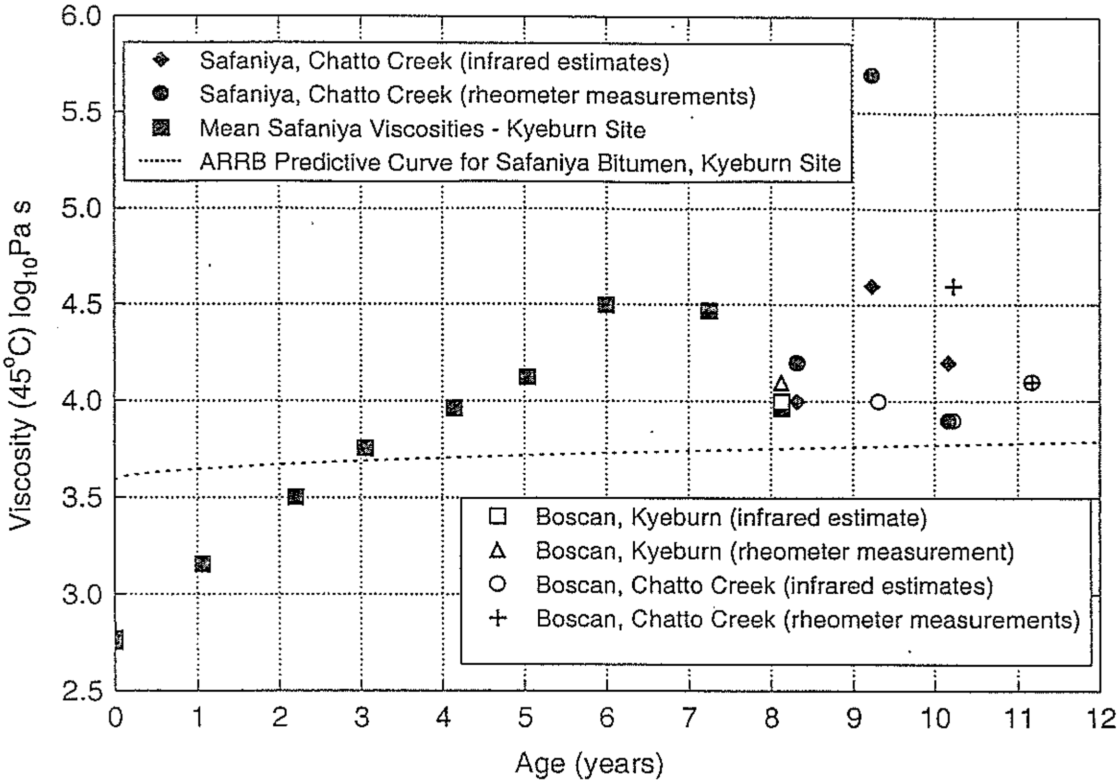


Figure 5.5 Increase in 45 °C viscosity shown in the Gracefield Road trial using Safaniya 180/200 bitumen.

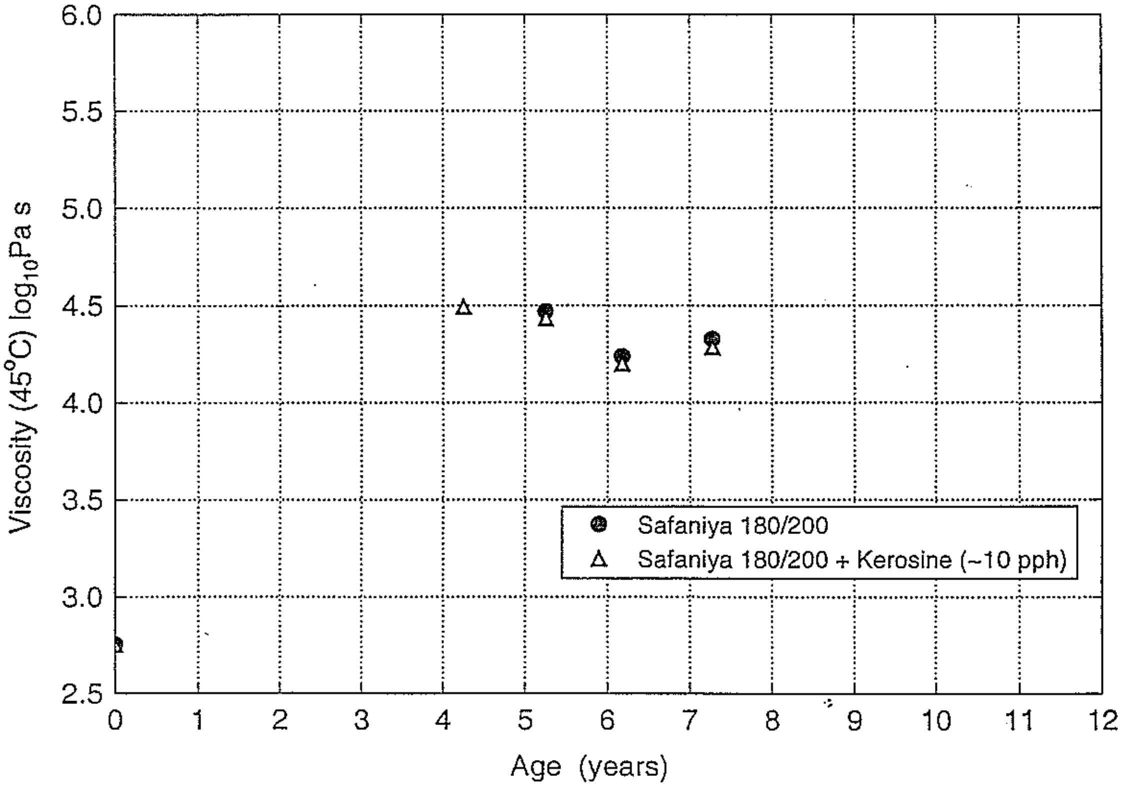


Figure 5.6 Changes in 25°C viscosity for artificial seals using Safaniya 180/200 bitumen.

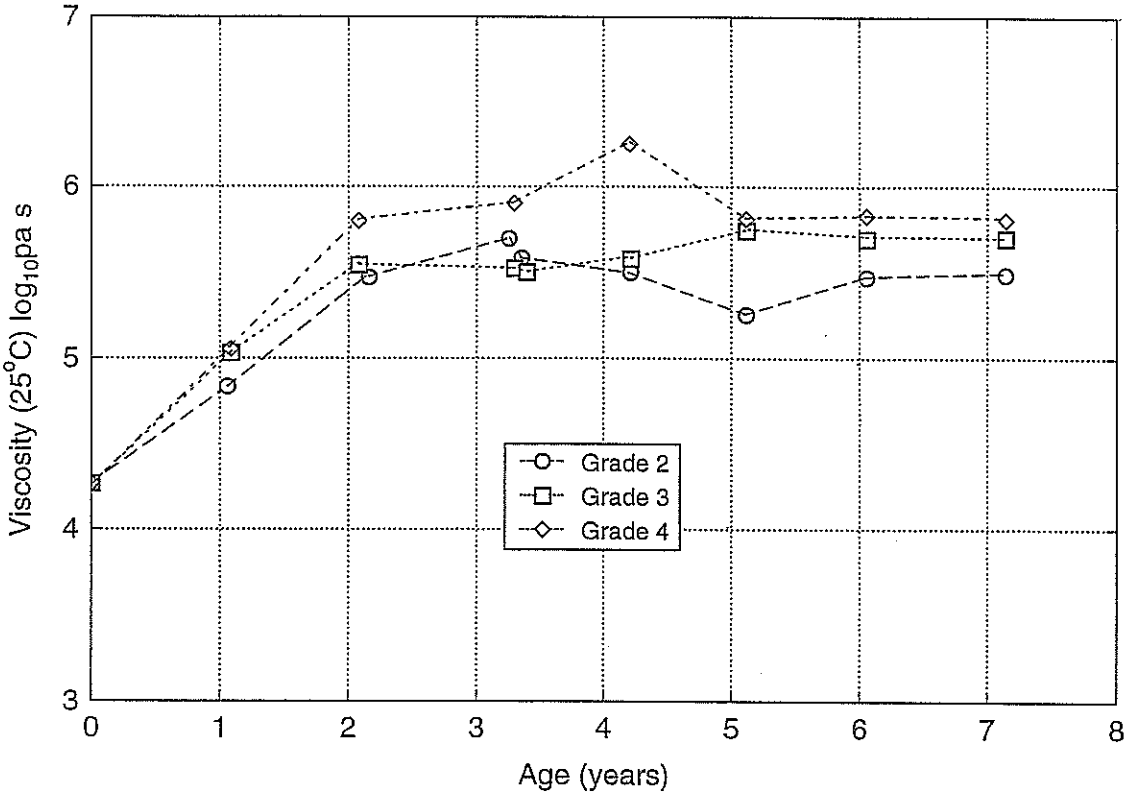


Figure 5.7 Changes in 25°C viscosity for artificial seals using fluxed and unfluxed Safaniya 180/200 bitumen with Grade 3 Chip.

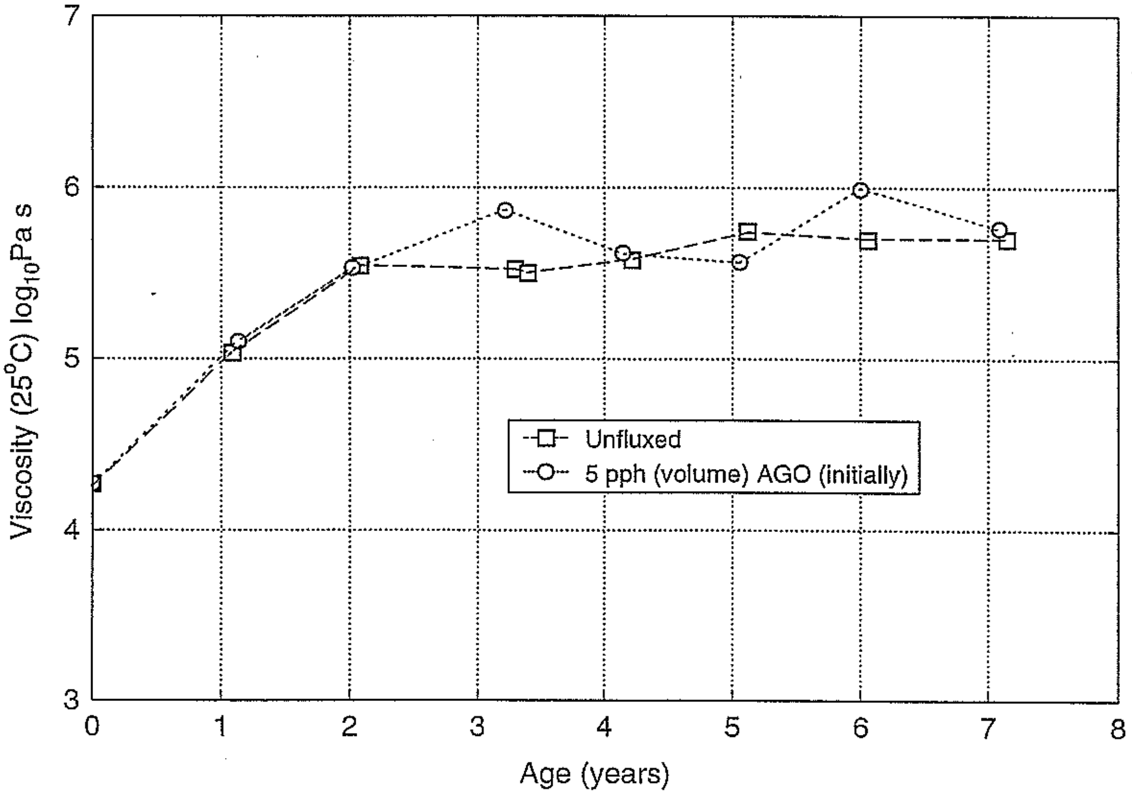


Figure 5.8 Changes in 25 °C viscosity for artificial seals using single and two-coat seals (with Safaniya 180/200 bitumen).

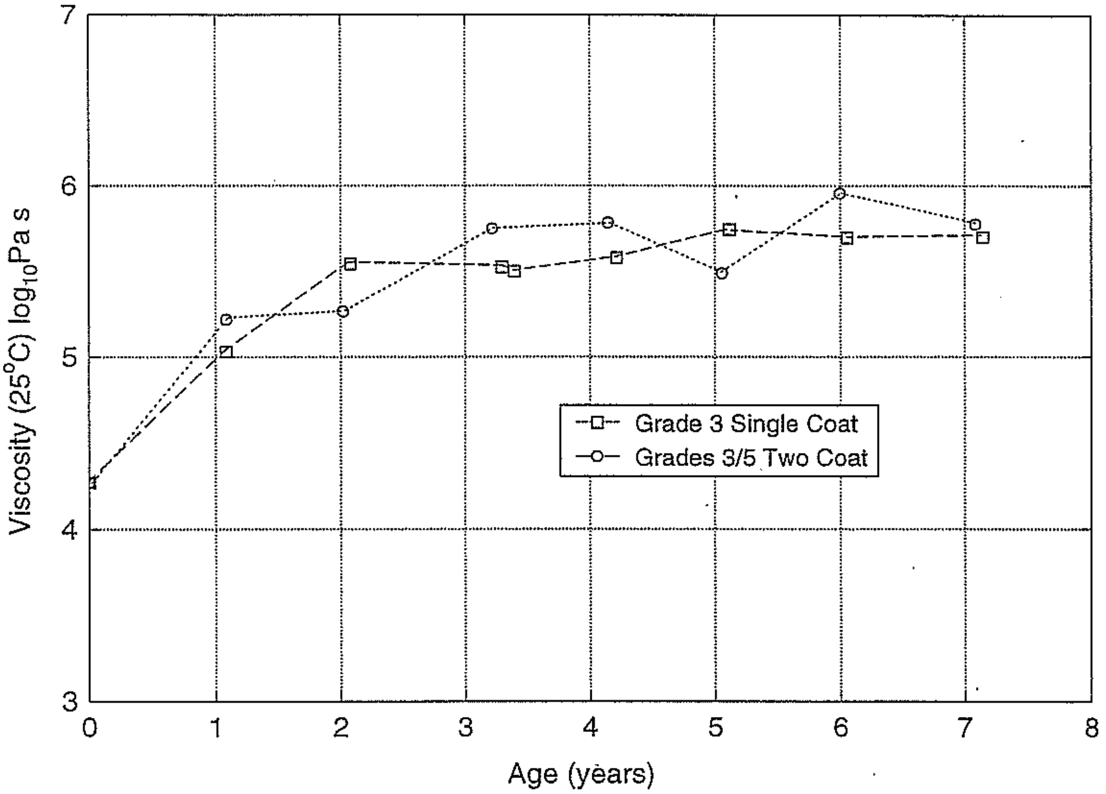


Figure 5.9 Changes in 25 °C viscosity for artificial seals using Safaniya 80/100 bitumen.

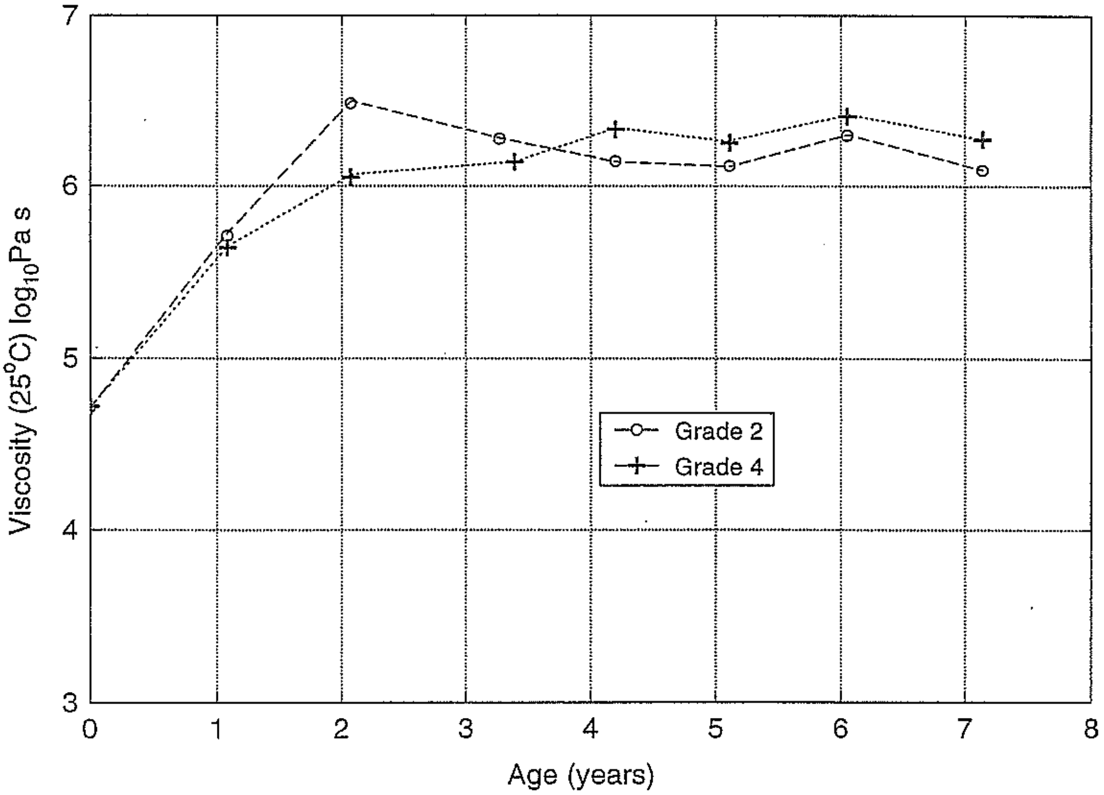


Figure 5.10 Changes in 45°C viscosities for all 180/200 artificial seals.

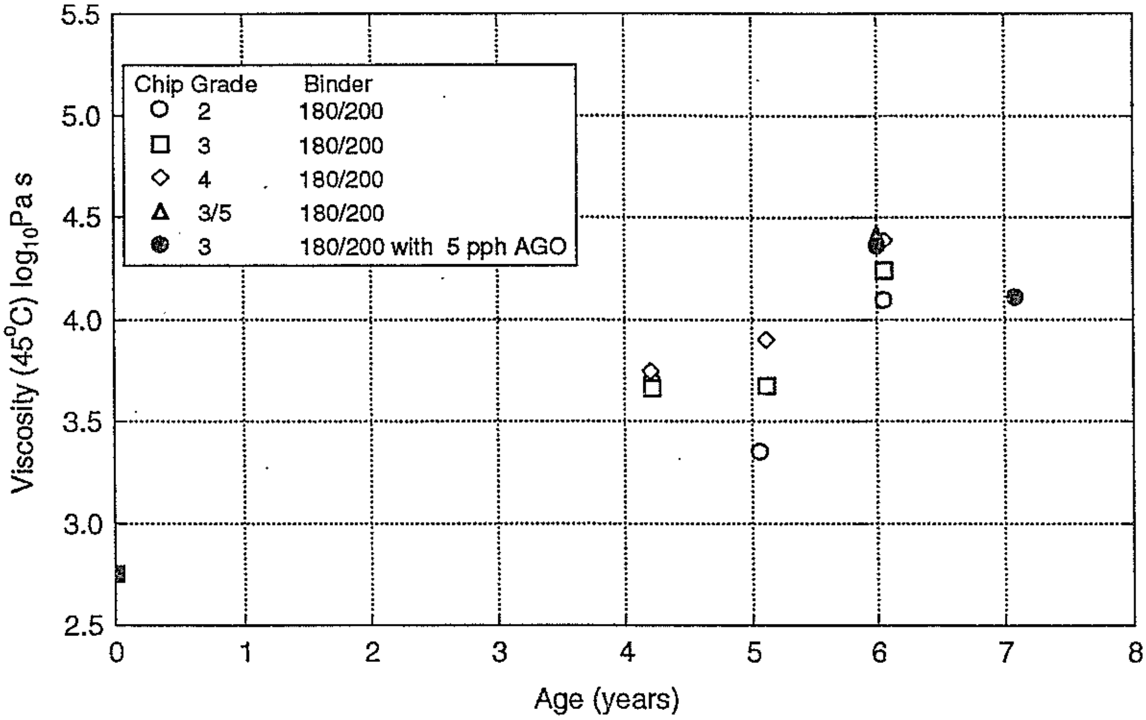
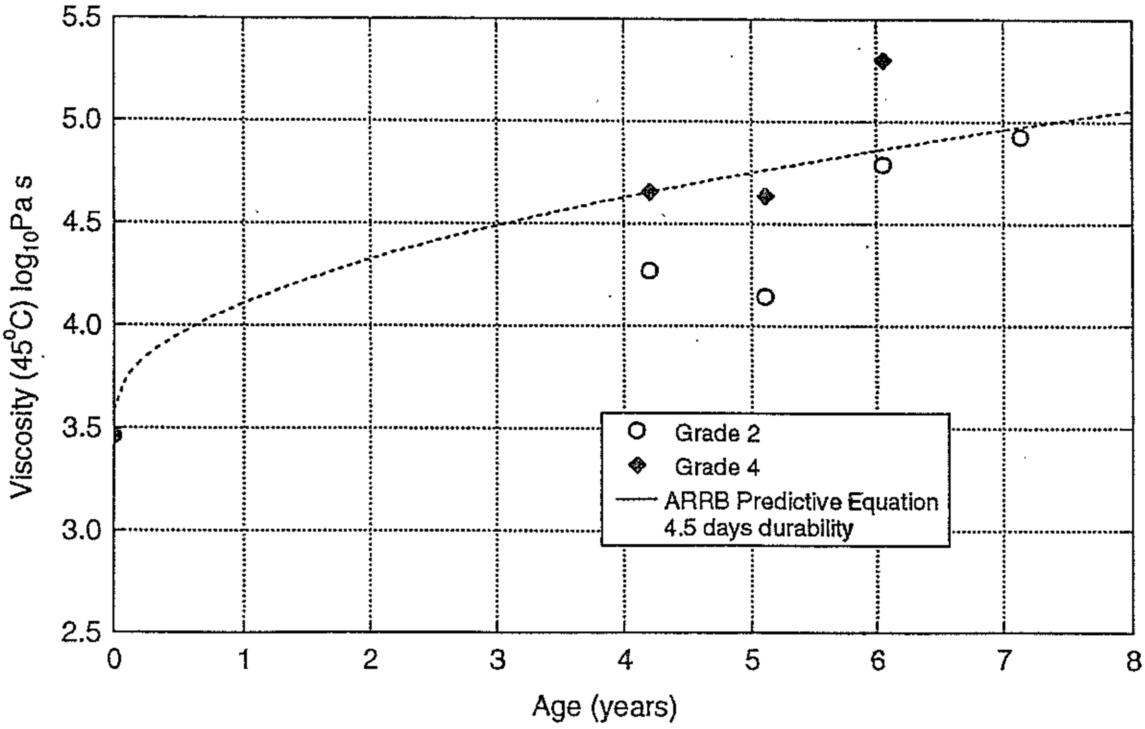


Figure 5.11 Changes in 45°C viscosities for all 80/100 artificial seals.



5.5 Comments on Viscosity Values

5.5.1 End-of-trial Viscosities

Table 5.1 Comparison of hardening for different Safaniya bitumen trials.

Source	**TMAX (°C)**	**TMEAN(°C)**	**180/200 log-viscosity**	**80/100 log-viscosity**
Fresh Bitumen	–	–	2.8	3.5
Kyeburn (Grade 3)	14.8	8.7	4.3	–
Chatto Creek (Grade 3)	16.2	10.2	4.3	–
Gracefield Road (Grade 3)	16.6	13.1	4.3	–
Artificial Seals				
Grade 2 chip, ALD = 11.2 mm	16.6	13.1	4.1	4.9
Grade 3 chip, ALD = 9.2 mm			4.3	–
Grade 4 chip, ALD = 7.0 mm			4.4	5.3
Pahurehure #2 (Grade 3)	18.7	14.9	–	5.0
Albany (Grade 2)	18.9	14.4	–	4.6

- Approximate values for end-of-trial viscosities (log Pa s units, at 45°C and 0.005 s^{-1} shear rate) of Safaniya bitumens are listed in Table 5.1. Unless otherwise indicated, the seals were constructed with Grade 3 sealing chip (average least dimension (ALD) approximately 9.2 mm).

- The final viscosities do not appear to be very sensitive to the range of climates experienced by the trials.

- The difference of the log-viscosity values of 80/100 and 180/200 Safaniya bitumens remains approximately constant throughout the aging process.

- At Gracefield the results for the artificial chipseal with 180/200 bitumen and Grade 3 chip matches those on the nearby Gracefield Road.

- There is an apparent tendency for seals with large chip to harden to a lesser degree than those with smaller chip. Compare, for example, the result for Albany, where Grade 2 chip was used, with that for the Grade 3 seals at Pahurehure Inlet No 2. The tendency is clear for the artificial seals exposed at Gracefield.

5.5.2 Log-viscosity Time Curves

The log-viscosity time curves for the field trials can be made to fit closely to hyperbolic relationships of the form:

$$\Delta \log \eta = \frac{t}{a + bt} \qquad (3)$$

where t = time
η_t = viscosity at time t
η_0 = initial viscosity
$\Delta\log \eta$ = $\log \eta_t - \log \eta_0$
a = constant ($t/(\Delta\log\eta)$ as $t \to 0$)
b = constant

Herrington (Ball & Herrington 1996) has compared the field results with those found by aging bitumens in a pressure bomb at 60°C and 2.068 MPa (300 psi) oxygen pressure. He found that the bitumen hardening curves in general are best approximated in terms of a combination of an initial curved hyperbolic region followed by a linear increase in log (viscosity) with time. For some bitumens - Safaniya 180/200 bitumen is a notable example - the extent of the initial hyperbolic curve region is greater than for others.

Herrington concludes that the initial rapid increase in viscosity on aging is caused by the rapid depletion of relatively low concentrations of very reactive chemical species (probably sulphides); following this there is a more gradual viscosity rise associated with the slower formation of carbonyl groups (in ketones, carboxylic acids, anhydrides). In addition, at atmospheric pressure, the rate at which oxygen can diffuse into the bitumen is affected by the bitumen viscosity, and will affect the shape of the log viscosity–time curve. Thus curves observed at atmospheric pressure have an effectively hyperbolic shape over the entire life of the chipseal.

5.5.3 Comparison with Hardening of Australian Seals

The behaviour of seals observed in the field trials is markedly different to that reported by Oliver and co-workers (Oliver 1990a, 1990b). The Australian field trial log-viscosity versus time relationships show a continuous rise throughout the trials, contrasting with the trend for New Zealand viscosities to level out.

The discrepancy between the ARRB viscosity prediction Equation (2) and the behaviour of bitumens in the field in New Zealand may be in part associated with the different maximum surface temperatures experienced in New Zealand (up to 60°C) and those in the durability oven (163°C preconditioning followed by 100°C thin film exposure). Laboratory tests have demonstrated that relative rates and degrees of hardening of two different bitumens will depend upon the temperature at which they are aged (Ball & Herrington 1996). Thus, any single-temperature laboratory test for bitumen durability, such as the Australian durability test, can rank bitumens incorrectly for oxidative field hardening.

The current report concerns details of the field trial results and its scope does not extend to the chemical studies which led to the above conclusions. The chemical studies were carried out under a Foundation for Research, Science and Technology programme, and the interested reader is referred to Ball & Herrington (1996), Herrington (1998) and Herrington & Wu (1998).

5.6 Additional Studies from Viscosity Seal Trial Data

5.6.1 Effect of Kerosene Cutter Loss in Seals

The change in kerosene content of seals with time at the Gracefield Road trial site was measured using thermogravimetry to determine the volatiles content of small bitumen samples taken from the seal surfaces.

Approximately 14% of kerosene was lost during spraying. At the end of 20 minutes after chip spreading, approximately 75% of the original kerosene remained, and at two hours the content was 70%. Thereafter the rate of loss dropped off markedly, with percentages of kerosene remaining being of the order of 15% and 10% at three and five years (the end of the study) respectively. Amounts of kerosene retained at different times are closely proportional to the original dosages. At an absolute level, this amounts to 0.5 pph residual kerosene, presumably of heavy ends, for a typical seal originally containing 5 pph of kerosene. The long-term retention of kerosene ends will therefore counter the effect of bitumen hardening to some extent, but the effect will be small.

As noted before, the presence of kerosene cutter has no effect on the eventual degree of hardening of the residual bitumen.

5.6.2 Variability of Bitumen Hardness over the Road Surface

Concurrently with the 1993 (year 7) sampling at Kyeburn, a study was carried out to examine the repeatability of viscosity results.

Five sets of Safaniya seal samples were taken at 20-m intervals along one side of the trial area. Each set contained five samples from positions at:

- the shoulder of the road (second coat seal),
- the outer wheeltrack (resealed area),
- between wheeltracks,
- the inner wheeltrack, and
- the centreline.

The road had been widened with a first coat chipseal in 1985, so that after spraying of the trial seal over the full road in 1986 the shoulders were effectively second coat seals, whereas the central part of the road was a reseal.

Figures 5.12 and 5.13 show the mean viscosities across the road and along the road.

Figure 5.12 Mean residual bitumen viscosity across the road at the Kyeburn trial, for Safaniya seals sampled 1993.

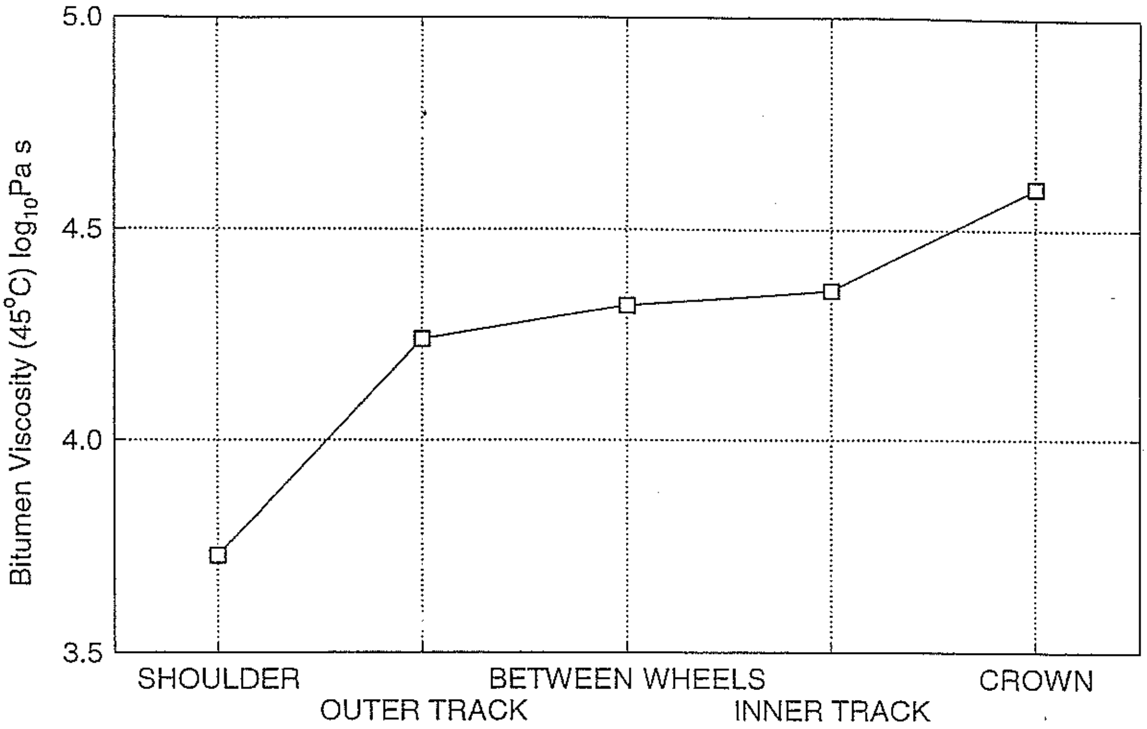
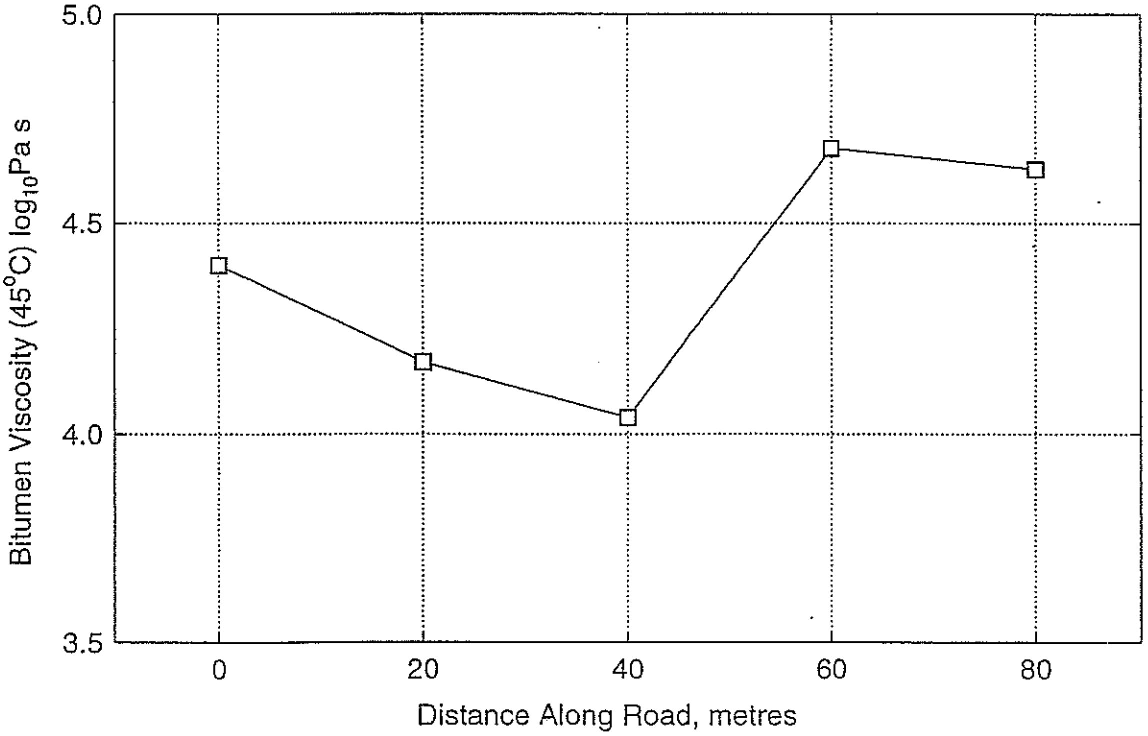


Figure 5.13 Mean residual bitumen viscosity along the road at the Kyeburn trial, for Safaniya seals sampled 1993.



Analyses of variance (ANOVA) studies on the data indicated that the observed variation of residual binder viscosities both across and along the road was significant. The second coat seal on the road shoulder was of consistently and significantly lower viscosity than the rest of the road, while on the central resealed area there was first a decrease in viscosity in samples taken along the road, and then an increase. Samples across the resealed portion showed a trend to a higher viscosity at the centreline compared to the outer wheeltrack, statistically significant at the 90% level. Baker (1968) had observed a lower viscosity in the wheeltracks than at the less trafficked centreline, and also relatively high viscosity material between the wheeltracks. The between-wheeltrack effect is not apparent here, but could have been disguised by oil dripping from passing vehicles.

The procedure of bitumen sampling by plucking chips from the seal samples after heating to 120°C (see Section 4 of this report) was designed to ensure that only the bitumen in the immediate vicinity of the chip surfaces was recovered for testing. The low viscosity values for the second coat seals suggest the likelihood that some mixing of the top seal bitumen with the bitumen in the lower, older seals takes place, and that this mixing continues almost right to the chip–bitumen interface.

The observation of viscosity variability over the Kyeburn seal means that samples taken in different years at seal trials need to be taken as close to each other as possible to make comparisons valid. The variability over the surface means that a very accurate predictive equation for seal binder hardening cannot be expected. Oliver (1987) came to this conclusion for a different reason on the basis of his analysis of all the available ARRB sealing trial data. He recommended using the derived equation for binder hardening (Equation (2), Section 2) only for estimating mean hardening in a given climatic region.

5.6.3 Causes of Variation of Hardening with Sealing Chip Size

The observed variation in the hardening of seal bitumen with change of chip grade from Grade 2 to Grade 4 was approximately half that of the difference between 180/200 and 80/100 bitumens (Table 5.1). If this variation is typical of road behaviour, it would imply that use of higher penetration bitumen may be desirable with seals constructed with small chip (and consequently relatively low spray rates and bitumen film thicknesses) to counter the hardening effect associated with seals constructed with small chip.

The reason for the differences observed is not known. One possibility suggested was that seals constructed with small chip might absorb solar radiation more efficiently than large-chip seals, and so reach higher temperatures. To check this possibility, thermistors were placed on the backs of two artificial seals, and the temperature was measured throughout a sunny November day.

A plate holding the Grade 2 seal was found to be consistently at a higher temperature than that with a Grade 4 seal. For example, the Grade 2 seal reached a maximum temperature of 38°C while the Grade 4 maximum was 35°C. The higher temperature of the Grade 2 seal was confirmed with an infrared emission temperature probe. Thus temperature difference does not explain the greater hardening of the seals with the smaller chip.

Another possibility is that the difference between seals is related to the time that oxygen takes to diffuse through to the bottom of a seal. This means that the bitumen at the base of a seal would not harden as quickly as that at the surface, and the result would be that the overall hardness of the thick binder layer would take a longer time than a thin layer to reach its final level. The hardness of thin and thick binder layers would gradually converge, but not within the typical lifetimes of New Zealand seals. Some work by Button et al. (1993) on oxidising bitumen films of various thicknesses in the laboratory (71°C, 300 psi air pressure) supports this possibility.

The lesser hardening of the Safaniya 80/100 bitumen at the Albany test site (Figures 5.2, 5.3) compared to that at Pahurehure Inlet No. 2 site may also show this affect. However, the results may also be affected by mixing of bitumens from the underlying road surfaces, as was clearly the case at Kyeburn. At Albany the trials were laid over first coat seals constructed with 180/200 bitumen, while at Pahurehure Inlet the original surface was a thin surfacing asphaltic concrete mix containing 80/100 bitumen and laid in 1971.

6. DYNAMIC SHEAR RHEOMETER MEASUREMENTS

6.1 Introduction

Because of technical limitations, binder hardening has been examined by viscosity measurements at a limited number of temperatures, following the approach developed by the ARRB for their seal bitumen hardening trials. If binder hardening significantly affects the liability of a seal to crack, the cracking is likely to be induced principally in the mid to low temperature range. Accordingly, measurements were carried out on fresh and field-aged Safaniya and Boscan bitumens with a recently acquired Carri-Med CSL^2 500 rheometer. The dynamic shear moduli of the bitumens were measured over a range of temperatures and frequencies with the bitumen samples held between oscillating parallel plates.

The quantities measured were:

- The amplitude of the dynamic modulus, $|G^*|$, the ratio of the maximum shear stress to maximum shear strain during an oscillation. The size of the oscillation is kept within the linear range. Thus halving the oscillation amplitude would, to a close approximation, halve both shear stress and shear strain values, giving effectively the same value for $|G^*|$.

- The phase shift, δ, a measure of the amount the maximum strain follows the maximum shear stress during oscillation. This figure can range from 0° for a perfectly elastic sample (maximum strain and maximum stress occur at the same time) to 90° for a completely fluid material. In the temperature range of the experiments (0°C to 60°C) the bitumens are viscoelastic, so that δ lies between these extreme values.

The values of $|G^*|$ increase as frequency increases, and decrease as the temperature increases. For each measurement temperature, a separate plot of $|G^*|$ versus the logarithm of frequency (ω, in radians/second) is obtained. For any test temperature, T_r say, we can extend the effective frequency range over which the value of $|G^*|$ is known by moving the $|G^*|$ versus log ω curves for different temperatures along the log ω axis until they merge smoothly, while keeping the curve measured at T_r fixed. The resultant curve is termed the "master curve", and is usually a good approximation to the $|G^*|$ versus log ω curve at T_r over a much increased frequency range. The shift in the log ω value for the curve measured at temperature T is written "log α_T"; thus the frequency values ω for the values of $|G^*|$ measured at temperature T are changed to $\alpha_T\omega$. The quantity α_T is called the "shift factor".

In the results to be described, master curves of $|G^*|$ for the various bitumens have been plotted for 5°C and 55°C, i.e. at or close to the maximum and minimum temperatures at which measurements were taken.

Dobson (1969) found that a Williams-Landel-Ferry (WLF) relationship (Williams et al. 1955) shown in Equation (4) closely describes log α_T for bitumens:

$$\log \alpha_T = \frac{A(T_r - T_S)}{B + (T_r - T_S)} - \frac{A(T - T_S)}{B + (T - T_S)} \tag{4}$$

A, B and T_S are constants. T_S is called the "characteristic temperature" of the bitumen. The values of A and B are 8.86 and 101.6 respectively for T (or T_r) $\geq T_S$, and 12.5 and 142.5 for T (or T_r)$\leq T_S$. Dickinson (1984) notes that the glass point of a bitumen is approximately 50°C below T_S. (As temperature drops through the glass point the mechanical response of the bitumen changes from that of a viscoelastic material to that of a glass.) Thus if, upon field aging of a sealing bitumen, the value of T_S increased until (T_S – 50) was above the minimum temperature experienced by the seal, the bitumen could shatter under traffic stress and seal failure follow.

6.2 Test Results

Values of the characteristic temperatures of the various bitumens tested were obtained by carrying out non-linear regression fits of values obtained for α_T to Equation (4). These values are shown in Table 6.1. Master curves of |G*| at 5°C and 55°C for the same bitumens are shown in Figures 6.1, 6.2 and 6.3.

Table 6.1 Characteristic temperatures, T_S, for tested bitumens.

	Age (years)	Chip Grade	T_S (°C)	T_S - 50
Safaniya 180/200				
Fresh	0	-	38.7	-11.3
Exposure Rack	8	2	43.6	-6.4
Exposure Rack	8	4	47.1	-2.9
Chatto Creek	10	3	46.2	-5.8
Boscan 180/200				
Fresh	0	-	34.4	-15.6
Chatto Creek	11	3	44.4	-5.6
Safaniya 80/100				
Fresh	0	-	43.7	-6.3
Exposure Rack	8	4	44.8	-5.2

6.3 Discussion of Results

1. The greater hardening of Grade 4 180/200 artificial seals than Grade 2 seals is confirmed, both by the higher T_S value for the grade 4 at 8 years and by the greater $|G^*|$ values (Figure 6.1).

2. The values of $(T_S - 50)$ of aged bitumens, of the order of -5°C (Table 6.1), are achieved during the winter in many parts of New Zealand, particularly in the Central Otago area. Thus, for bitumens used currently (1998) in New Zealand, a possibility is that seals will be particularly susceptible to cracking at low winter temperatures.

3. While the spread of characteristic temperatures of fresh bitumens is 9.3°C, that for the aged bitumens tested is 3.5°C (Table 6.1). The apparent advantage against low-temperature cracking that the higher penetration bitumens give when fresh is not nearly as great when they have aged.

4. Figure 6.2 illustrates this fact also. At 55°C, 80/100 Safaniya bitumen is harder (higher values of $|G^*|$) than the 180/200, both for fresh and aged bitumens. However, at 5°C, while there is a significant difference for the different penetration grade fresh bitumens, the master curves for aged 180/200 and 80/100 Safaniya bitumens are practically coincident.

5. Figure 6.3 compares Safaniya and Boscan bitumens. Here the limitations of carrying out durability test measurements at just one temperature are apparent. At 55°C the Boscan bitumen is slightly harder than the Safaniya bitumen, both for fresh bitumen and for that aged in the field. However, at 5°C the situation is reversed for the fresh bitumens, with the Safaniya bitumen being the harder, while for the aged bitumens the master curves cannot be distinguished. Below 5°C the Boscan bitumen would be expected to be more resistant to cracking than the Safaniya, as suggested by the Boscan's lower value of T_S (44.4°C as against 46.2°C). This is in strong contrast to the early prediction of a short lifetime for Boscan bitumen seals based on the low Australian durability oven result.

   The Australian durability evaluation procedure, using a single test temperature, was designed for comparing similar bitumens derived from Middle East crude oils. That it is an inappropriate procedure for Venezuelan Boscan bitumen, which contains a higher proportion of relatively volatile material and is more temperature sensitive, was not unexpected.

6. The observed rheological data indicate that, for the bitumens examined, no significant improvement in resistance to low temperature cracking is likely to be gained either by using a lower penetration binder or by choosing one bitumen source over the other. Bitumens from other sources may not perform as well.

Figure 6.1 **Master curves (for 5°C and 55°C viscosities) for aged 180/200 Safaniya bitumens in seals with Grades 2 and 4 chip, for Chatto Creek and artificial trial samples.**

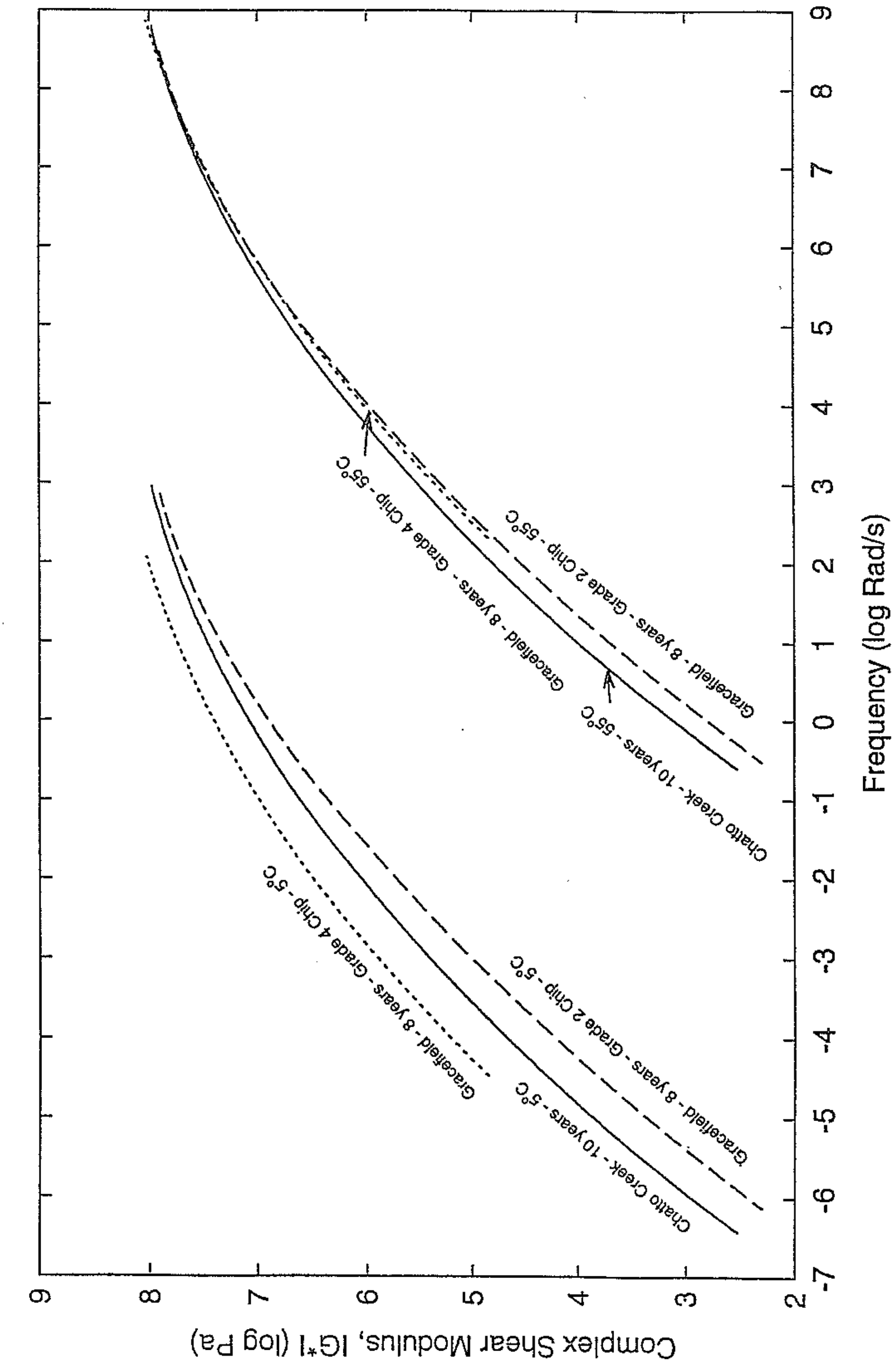


Figure 6.2 Master curves (for 5°C and 55°C viscosities) for fresh and 8-year old 80/100 and 180/200 Safaniya bitumens.

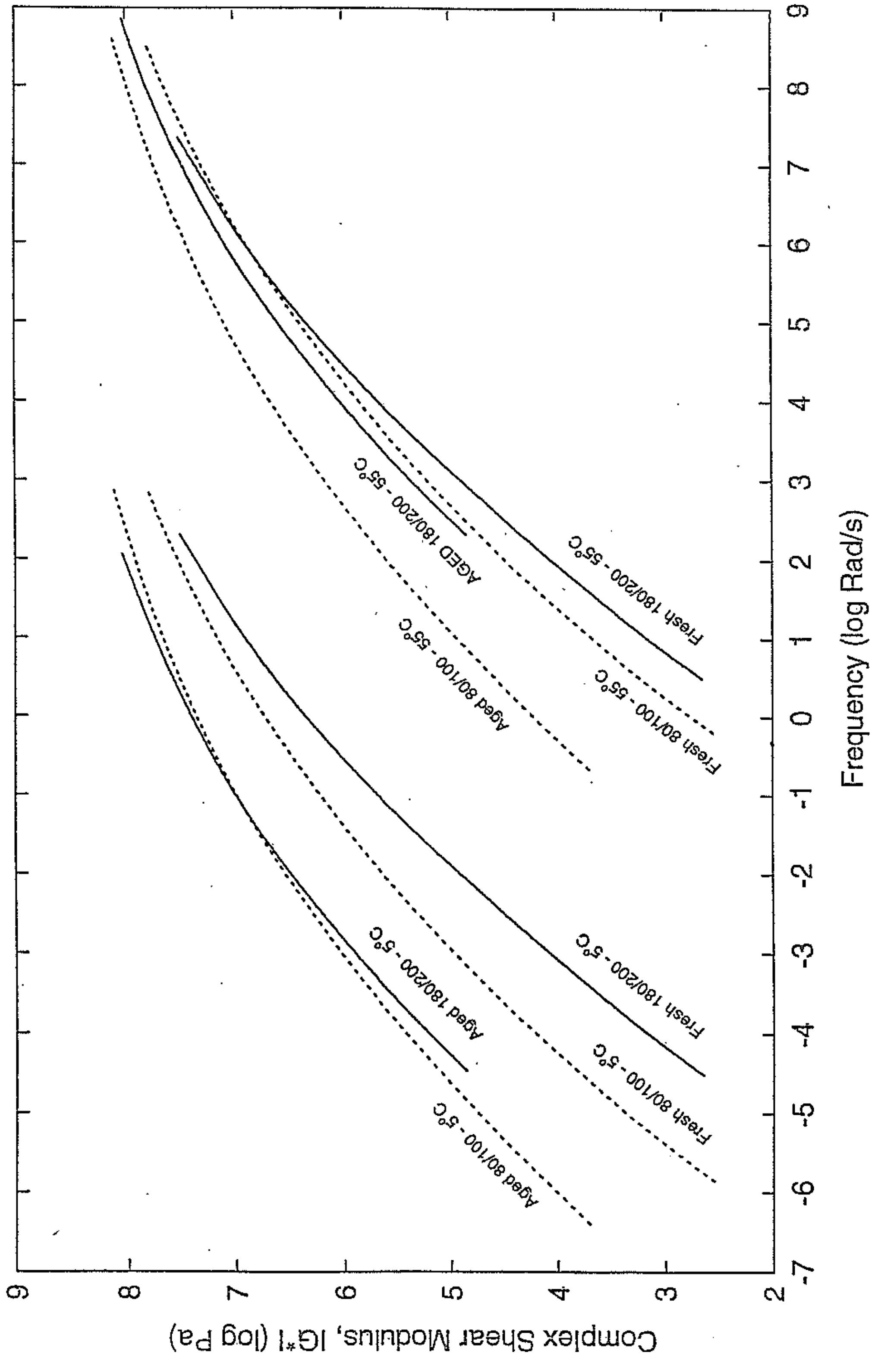
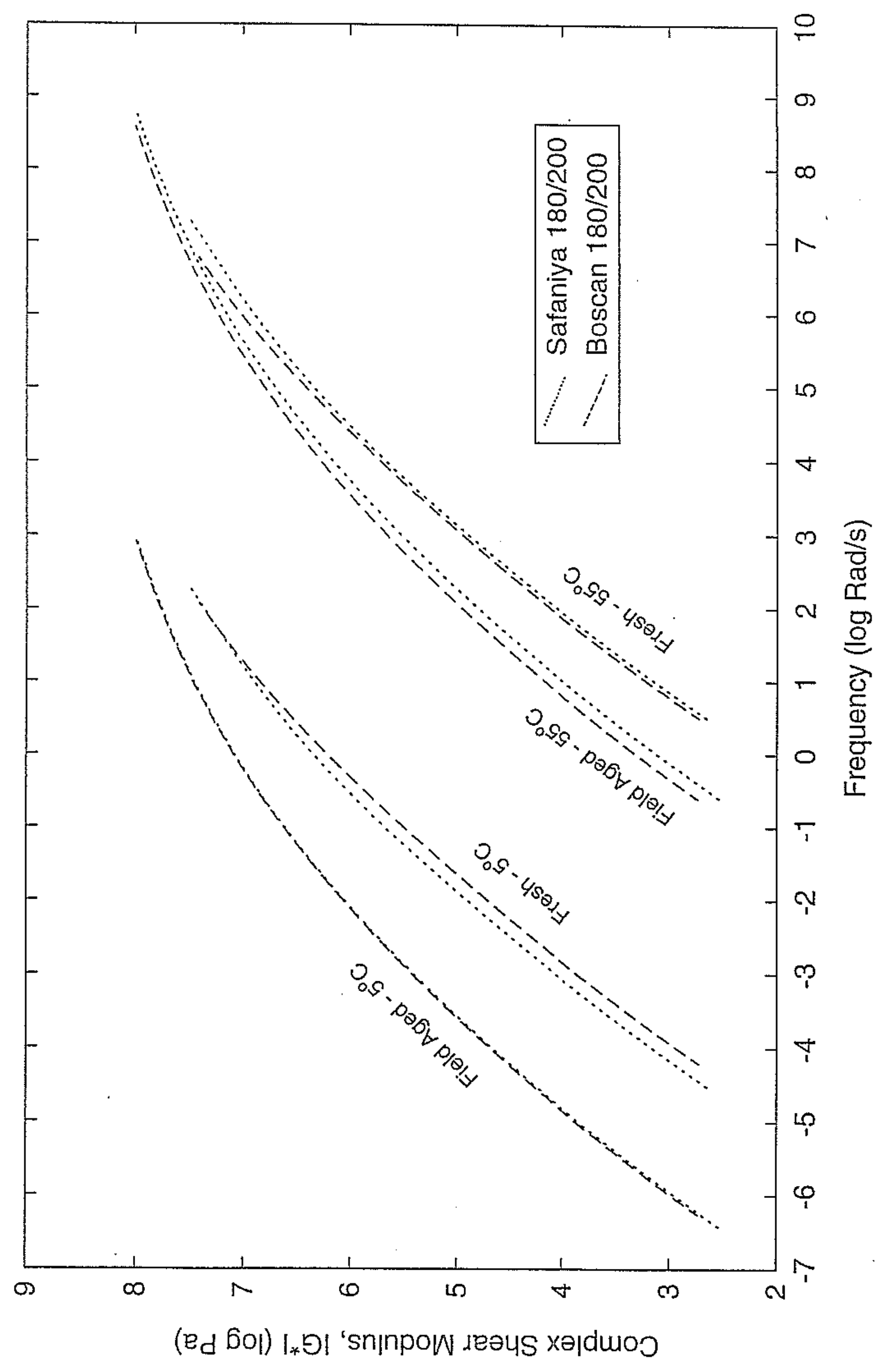


Figure 6.3 Master curves (for 5°C and 55°C viscosities) for fresh and field-aged 180/200 bitumens at Chatto Creek trial.



7. CONCLUSIONS

- Viscosity (45°C and 25°C) versus time plots of the trial and artificial chipseal bitumens gave an initially fast increase in viscosity for approximately four years, followed by stabilisation at a viscosity level that depended on the bitumen source and grade, and the seal chip size. No measurable relationship was found between the final viscosity level and climate, although, based on the differences in seal hardening at Kyeburn and Gracefield, it appears that the rate at which the final level was approached was greater for the warmer climates.

- The degree to which binder at the surface of a chipseal hardens depends on the hardness of the binder in any underlying surface. Mixing of the bitumens occurs in the two surface layers (Section 5.6.2 of this report).

- Bitumen in seals constructed with small chips hardens faster than in seals with larger chips. The reason for this is unknown, but laboratory test evidence does support the possibility that the effect is probably related to the time that oxygen takes to diffuse through the bitumen to the bottom of the seal layer. Another cause associated with the field trials could have been mixing with different grade bitumens in the underlying road surfaces.

- The observed viscosity–time plots did not match the predictions of the ARRB-derived equation (Equation (2)). In particular, the ARRB equation indicates that the viscosities will continue to increase with time, whereas the observed viscosity curves for the New Zealand trials levelled off.

- The Australian durability oven results did not give a good indication of relative field performance. Safaniya and Venezuelan Boscan 180/200 penetration grade bitumens have very different laboratory durabilities, but seals constructed with them were indistinguishable in behaviour up to the time of the completion of the trials.

- At all the trial sites, the ultimate reason for resealing was flushing. The trials were all in areas that are relatively highly trafficked for New Zealand. This suggests that cracking is likely to be a more of a problem for roads with relatively low traffic levels. Another implication is that there may be a conflict in using harder bitumens to delay flushing and softer bitumens to prevent cracking. However, this may not be so (see last item in these Conclusions).

- Based on binder hardness at different parts of the Kyeburn trial site, the evidence is that the condition of a seal can differ significantly on a scale of 20 m or less. Sampling at a few points may not therefore give a true indication of the overall state of a seal.

- The presence of kerosene or diesel (AGO) in a chipseal does not affect the oxidation hardening of the bitumen itself.

- Towards the end of the life of a seal, very little if any kerosene is left in the seal binder. Therefore, in view of the above item in these Conclusions, the use of kerosene cutback would not be expected to affect the long-term performance of a seal.

- Rheological measurements of aged bitumens indicate that, although at higher road temperatures the bitumens (Safaniya 180/200 and 80/100 and Venezuelan Boscan 180/200) may differ significantly, at lower temperatures they may for practical purposes be indistinguishable. This cannot be assumed for other bitumens.

- It may be possible therefore to choose bitumens which are relatively hard at higher temperatures, to minimise the possibility of premature seal flushing, while avoiding the effects of greater susceptibility to cracking at low temperatures. It is not clear at this time, however, whether the principal causes of cracking in seals used in New Zealand are relatively sudden failure of the bitumen at low temperatures or accumulated fatigue from trafficking at typical daytime temperatures. Both types of crack development may occur, and the local climate might determine which is the most important.

8. RECOMMENDATIONS

- Since in New Zealand bitumen can now be obtained from a variety of oil fields and produced by a variety of processes, a test method is needed for predicting the performance in seals constructed of bitumens which have not been used in this country before.

- The test will have to include a method for relatively rapid laboratory hardening of a newly proposed bitumen to give a product similar to that which would be obtained on the field.

- To develop such a test method the following information is needed:
  - Information on the chemical processes of bitumen aging. This is needed to give an indication on the way in which the bitumen oxidation and hardening depends on the temperature of the bitumen (a determinant for the choice of laboratory aging temperatures), and on possible ways of reducing the susceptibility of bitumen to aging. Work in this area is currently being carried out under a FRST programme ("Bituminous Surfacings Programme", Contract 804).

- Information on the effects of bitumen rheological properties on different types of distress that occur in seals, and the desirable limits for these properties. This information will determine the tests that should be carried out on laboratory-aged bitumen to best enable predictions of field performance to be made.

The required information may be obtained in two ways:

- From studying how the development of various types of seal distress for seals changes with bitumen source and grade. In particular, comparison of typical degrees of cracking at sites with different extreme winter temperatures may indicate whether or not cooling below the glass point temperature is likely to be a significant cause of crack initiation (see Section 6.3 of this report).

  Some work in this area, based on the Transit New Zealand Road Assessment and Management (RAMM) database, has been carried out under Transit New Zealand Research project PR3-0126, "End-of-Life Chipseal Conditions", and further study is in progress under the FRST "Bituminous Surfacings Programme".

- From inducing seal failure in the laboratory and studying the mechanisms involved, and how the rheological properties of the bitumens affect these mechanisms. Study of this sort is currently being carried out under Transfund Research Project 0309 ("Flushing Processes in Chipseals") and, for cracking, under the FRST "Bituminous Surfacings Programme".

- A field trial of seals is recommended to resolve issues raised in the work reported here. The trial would be constructed on a uniform section of road in a region with a similar climate to the Kyeburn trial, i.e. low winter surface temperatures and reasonably high summer temperatures. It should preferably be in an area where seal cracking is a common mode of failure.

  180/200 and 80/100 Safaniya bitumens would be used for construction of the seals. The rheometer testing indicated that, after oxidative hardening in the field, the low temperature rheological properties of the two grades are practically indistinguishable. Therefore it is possible that 80/100 bitumen might be no more susceptible to cracking at low temperatures than 180/200, while at higher temperatures it might provide the greater resistance to flushing.

The following seal sections are proposed:

(i) Single coat, Grade 2 chip, seal with 180/200 Safaniya bitumen .
(ii) Single coat, Grade 2 chip, seal with 80/100 Safaniya bitumen.
(iii) Single coat, Grade 3 or Grade 4 chip, seal with 180/200 Safaniya bitumen.
(iv) Single coat, Grade 2 chip, seal with 180/200 Safaniya bitumen and two parts per hundred diesel (automotive gas oil, AGO).

This trial would also address two questions:

- Does the suspected dependence of the degree of bitumen hardening on the thickness of the binder film, occur in the field (this entails comparison of seals (i) and (iii)).

- Does the use of AGO in seals in colder climates actually reduce susceptibility to cracking (this entails comparison of seals (i) and (iv)). The artificial seal results for Gracefield indicated that diesel does not affect the hardening of the bitumen itself. Laboratory testing of fluxed binders (Herrington et al. 1996) indicated that most of the diesel is lost from a fluxed binder during the seal lifetime. This was discovered to be the case for kerosene in the work described in this report.

  If diesel does not increase a seal's lifetime, a case to reduce its use is strengthened based on:
  - lower cost, as contractors will not need to maintain facilities for adding diesel as well as kerosene;
  - environmental concerns, as use of volatile hydrocarbons will be reduced.

Recovered binder could be analysed using the Carri-Med CSL^2 500 rheometer. This analysis would give a far more complete picture of the effects of the bitumen aging process than was possible during the trials reported here, when only viscometers were available for testing. In addition, developments in testing make it possible to test binder material without removing any residual diesel, to obtain closer correspondence to behaviour on the road.

Other low temperature testing of recovered binder, e.g. bending beam rheometer and extensometer readings, could be used to provide further insight on the effects of aging. They could also provide useful background information to address the possibility of adopting a performance graded specification for bitumens.

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APPENDIX
SITE DATA FOR BITUMEN HARDENING TRIALS

Table A1.1 Albany/Rosedale Road trial data.

Sealing Dates:	1-2 November 1984	
Trial Location:	State Highway 1, 36°44′ S, 174°42′ E	
Route Positions:	RP 312/4.00-4.05	RP 312/5.20-5.75
Test Bitumens:	80/100 Safaniya	80/100 Light Arabian (Singapore)
Bitumen Durabilities:	4.4 days	8 days
Initial Viscosities (45°C, 0.005 s^{-1})	2890 Pa s	2000 Pa s
Additives:	6 pph lighting kerosene, 0.7 pph Duomeen T adhesion agent	
Sealing Details:	Grade 2 basalt chip, 2.2 ℓ/m^2 Binder Application Rate (170°C), 1.9 ℓ/m^2 Residual Bitumen Application Rate (15°C)	
Initial Benkelman Beam Deflections:		0.1-0.8 mm
Meteorological Conditions:	TMIN = 9.8°C, TMAX = 18.9°C, Average = 14.35°C	
Predicted Viscosities (ARRB equation) (equation (2)):		
	Safaniya 80/100	$\log \eta = 0.5832 \sqrt{Y} + 3.59$
	Light Arabian 80/100	$\log \eta = 0.5015 \sqrt{Y} + 3.59$
Predicted ARRB Distress Viscosity (Equation (1)):	644000 Pa s [5.81 log Pa s]	

TMAX, TMIN, η and Y are as defined for Equation (2)

Table A1.2 Pahurehure Inlet No. 2/Papakura Interchange trial data.

Sealing Date:	28 November 1985	
Trial Location:	State Highway 1, 37°04' S, 174°55' E	
Route Positions:	RP 355/8.43-8.48	RP 355/8.00-8.05
Test Bitumens:	80/100 Safaniya	80/100 Venezuelan Boscan
Bitumen Durabilities:	4.4 days	2 days
Initial Viscosities (45°C, 0.005 s^{-1})	2890 Pa s	–
Additives:	8 pph lighting kerosene, 0.7 pph Duomeen T adhesion agent	
Sealing Details:	Grade 3 greywacke chip, 1.6 ℓL/m^2 Binder Application Rate (165°C), 1.3 ℓ/m^2 Residual Bitumen Application Rate (15°C)	
Initial Benkelman Beam Deflections:	0-0.2 mm	
Meteorological Conditions:	TMIN = 11.0°C, TMAX = 18.7°C, Average = 14.85°C	
Predicted Viscosities (ARRB equation) (Equation (2)):	Safaniya 80/100	$\log \eta = 0.6070 \sqrt{Y} + 3.59$
	Venezuelan Boscan 80/100	$\log \eta = 0.6615 \sqrt{Y} + 3.59$
Predicted ARRB Distress Viscosity (Equation (1)):	861000 Pa s [5.94 log Pa s]	

Table A1.3 Kyeburn road trial data.

Sealing Date: 24 February 1986

Trial Location: State Highway 85, 45°09' S, 170°18' E

Route Positions: RP 49/10.48-10.58 RP 49/10.58-10.68

Test Bitumens: 180/200 Safaniya 180/200 Venezuelan Boscan

Bitumen Durabilities:
15.5 days 3.7 days

Initial Viscosities (45°C, 0.005 s^{-1}):
570 Pa s 650 Pa s

Additives: 0.7 pph Redicote N561 (Safaniya seals) and 1.2 pph Redicote N561 (Boscan seals) adhesion agent, 4 pph kerosene, 2 pph diesel (AGO)

Sealing Details: Grade 3 greywacke/quartz with some schist and a little sandstone, 2.2 ℓ/m^2 Binder Application Rate (150°C), 1.8 ℓ/m^2 Residual Bitumen Application Rate (15°C)

Initial Benkelman Beam Deflections: 0.5-2.0 mm

Meteorological Conditions: TMIN = 2.5°C, TMAX = 14.8°C, Average = 8.65°C

Predicted Viscosities (ARRB equation) (Equation (2)):
Safaniya 180/200 $\log \eta = 0.0599 \sqrt{Y} + 3.59$
Venezuelan Boscan 180/200 $\log \eta = 0.3278 \sqrt{Y} + 3.59$

Predicted ARRB Distress Viscosity (Equation (1)): 110300 Pa s [5.04 log Pa s]

Table A1.4 Chatto Creek road trial data.

Sealing Dates: (approximate) 25 December 1985 (Boscan), 25 December 1986 (Safaniya)

Trial Location: State Highway 85, 45°11' S, 169°28' E

Route Positions: RP 148/5.54 RP 148/5.50

Test Bitumens: 180/200 Safaniya 180/200 Venezuelan Boscan

Bitumen Durabilities (presumed the same as for the Kyeburn trial):
15.5 days 3.7 days

Initial Viscosities (45°C, 0.005 s^{-1}):
570 Pa s 650 Pa s

Additives: 1.0 pph Diamin OLB (Safaniya seal) and 1.2 pph Redicote N561 (Boscan seal) adhesion agents, 4 pph kerosene, AGO content unknown (0-2 pph)

Sealing Details: Aggregate similar in appearance to Kyeburn site; Residual Bitumen Application Rates(15°C) 2.08 ℓ/m^2 (Safaniya), 1.93 ℓ/m^2 (Boscan)

Meteorological Conditions: TMIN = 3.9°C, TMAX = 16.2°C, Average = 10.1°C

Predicted Viscosities (ARRB equation) (Equation (2)):
Safaniya 180/200 $\log \eta = 0.1289 \sqrt{Y} + 3.59$
Venezuelan Boscan 180/200 $\log \eta = 0.3968 \sqrt{Y} + 3.59$

Predicted ARRB Distress Viscosity (Equation (1)): 154700 Pa s [5.19 log Pa s]

Table A1.5 Gracefield Road trial data.

Sealing Dates: 16 December 1988

Trial Location: Gracefield Road, Lower Hutt, 41°14' S, 174°55' E

Test Bitumen:		
	180/200 Safaniya 0 pph kerosene	180/200 Safaniya 10 pph kerosene

Bitumen Durability (typical for 1988): 14.5 days

Initial Bitumen Viscosity (45°C, 0.005 s^{-1}): 570 Pa s

Additives: 1.0 pph Diamin HBG; kerosene as indicated above

Sealing Details: Single coat seals, Grade 3 aggregate, sealed over 8 year old asphaltic concrete

Meteorological Conditions: TMIN = 9.7°C, TMAX = 16.6°C, Average = 13.1°C

Predicted Viscosity (ARRB equation) (Equation (2)):

$$\log \eta = 0.2944 \sqrt{Y} + 3.59$$

Predicted ARRB Distress Viscosity (Equation (1)): 628800 Pa s [5.80 log Pa s]

Table A1.6 Gracefield exposure rack trials constructed February-March 1989.

Seal Type	Chip Type	Bitumen Grade	Application Rate (ℓm^{-2})
Single coat	Grade 2	180/200	1.50
	Grade 2	80/100	1.50
	Grade 3	180/200	1.23
	Grade 3	80/100	1.23
	Grade 4	180/200	0.94
	Grade 4	80/100	0.94
Two coat	Grade 5 on Grade 3	180/200	0.51 for Grade 3 0.69 for Grade 5

Chip average least dimensions (mm):

Grade 2	11.2
Grade 3	9.2
Grade 4	7.0
Grade 5	4.6

All bitumens were applied as hot binder, except for the second coat of the two-coat seal which was applied as an emulsion