Effect of Binder Hardness on Rate of Texture Change in Chipseals

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Abbreviations and Acronyms

ALD	average least dimension (of sealing chip)
evl	equivalent vehicles per lane
pph	parts per hundred
SBS	styrene-butadiene-styrene

Contents

Appendices

Executive summary

A laboratory test was developed at Opus Central Laboratories, Lower Hutt, to assess the setting up of the bond between binder and sealing chip for roads in New Zealand. A reciprocating tyred wheel was passed over loose chip on binder on a plate and the amount of chip that had bonded was assessed at intervals. The test was sensitive to the different performance of standard bitumen grades, but had to be carried out at 20°C and below, as bonding to 180/200 bitumen is too fast to observe at higher temperatures. The rate of bonding was strongly related to the binder viscosity at the test temperature.

Five road trials were set up, near Pukepapa on State Highway (SH) 3, north of Bulls, Otakiri on SH34 near Tauranga, Kaiwhatiwhati on SH38 near Rotorua all in the North Island, and in the South Island at The Wilderness on SH94 near Te Anau and Kingston Crossing on SH94 both in Southland. The trials were set up with a range of binder grades and types to compare the effects of binder properties on the rates of sealing chip compaction and chipseal texture reduction.

The rheological (flow) properties of several of the binders used in the trials were characterised. Adding SBS (styrene-butadiene-styrene) polymer to a bitumen produced a product which was less temperature sensitive than the original 130/150 bitumen, and so was softer than 130/150 bitumen at low temperatures.

The site located near Pukepapa suffered drastic chip loss on three of its four test sections on the occurrence of the first autumn frost, approximately three months after sealing. The fourth test section, unlike the others, had been sealed with a mix of SBS polymer and kerosene with the bitumen, which probably prevented binder fracture as chip moved under traffic at low temperatures, thus preventing stripping. As a result of the stripping the Pukepapa trial was discontinued.

Both kerosene and SBS polymer additives have the potential to minimise the chance of first winter chip loss in seals. Textures were measured periodically on the four surviving sites. Considerable differences in rates of texture loss were noted.

The principal factor affecting rates of texture loss with trafficking was the site itself. Variations in the hardness of the underlying surface and/or surface geometry (which affect the impact of traffic) are suggested as possibly being important in determining amounts of texture loss. Binder properties had no measurable effect.

Since the penetration grade of the binder had no measurable effect on the rate of texture reduction in seals, use of harder binders than is current practice is not recommended. The softer the original bitumen, the less it will harden under oxidation, and long-term pavement performance is likely to be better.

However, it is not recommended that there be a general movement towards use of softer bitumens for sealing work as this could increase the occurrence of high temperature induced bleeding. In some parts of New Zealand, the occurrence of bleeding was reduced by changing from soft 180/200 to harder 130/150 bitumens for sealing.

In situations where frost will occur, some kind of additive may be needed to prevent early stripping. Both kerosene and elastomeric products such as SBS polymer can do this job. Yet in situations where the climate ranges between very low winter and very high summer temperatures, or for sealing late in the season, SBS (with some kerosene to ensure initial adhesion to chip) may be recommended rather than high kerosene content, in order to stop bleeding in the first spring after sealing.

Abstract

This report describes a New Zealand study of the effect of different binders on the rate of chipseal texture loss under traffic. Work to measure the adhesive and rheological (flow) properties of different binders is described. Several chipseal trials were constructed and seal texture depth development over time was observed. Conclusions are drawn on the choice of sealing binders.

1. Introduction

1.1 Background

This report describes an investigation of the use of hard bituminous binders in chipseals for New Zealand roads.

Standard chipseals in New Zealand are constructed using 80/100, 130/150 and 80/100 penetration grade bitumens. Polymers are sometimes added where high traffic stresses are anticipated. It has been suggested that sealing with harder bitumens may offer the following advantages:

- It may reduce sealing chip loss (caused by binder softening in hot weather) and consequent binder pickup. This would be a clear advantage in built-up areas, where it is essential to avoid the tracking of binder and chip indoors.
- It may reduce binder pickup and tracking on open roads in hot weather, thus maintaining a safe surface to drive on in subsequent wet weather.
- It may reduce the rate of texture loss under traffic, thus extending the seal lifetime. The suggestion of this possibility arose as a result of wheelpath testing of seal samples at controlled laboratory temperatures (Ball & Patrick 1998), where the rate of compaction increased with increased temperature (and consequently with reduced binder viscosity), up to a limiting temperature where it stabilised. In addition, a field trial study of very heavily trafficked forestry roads (Arnold & Pidwerbesky 1996) showed that premature flushing can be delayed by use of harder binders. The size of the effect on the road under different climates and traffic conditions and its dependence on binder physical properties remain to be determined.

On the other hand, the rate of setup of the bond between a hard binder and sealing chip will be slower than for standard binders. Consequently, such seals may be more subject to early chip loss.

In view of these matters, the project described in this report was set up with the following objectives:

- To compare the requirements of several hard binder types for satisfactory bonding to aggregate in chipseals.
- To ascertain the effect of hard binder properties of the rate of chipseal texture reduction and hence on the potential chipseal lifetime.

1.2 Experimental approach

This project addressed the following problems:

1. The harder the binder, the greater the difficulty in achieving a good bond between binder and sealing chip.
2. The definition of a 'hard' binder depends on the particular test method used for assessing the binder. It is important that a test method gives a good indication of the rate of seal texture reduction.
3. The degree of improvement in potential seal lifetime cannot at present be predicted.

Item 1 was addressed by comparative laboratory roller tests of the bonding of chip in artificial chipseals constructed with binders of a range of hardnesses under controlled conditions.

For Item 2, binder hardness was determined by measurement of both the softening point and the dynamic modulus. These two standard measurements do not rank all binders in the same order. In particular, binders containing SBS rubbers can have high softening points but relatively low dynamic moduli at typical high pavement temperatures.

For Item 3, binders assessed in the laboratory tests were used in field trials, in which the rates of seal texture change were compared with each other and with the predictive equation of Transit New Zealand Specification P/17:

$$\text{Texture Depth (mm)} = k(\text{constant}) - 0.07 \times ALD \times \log_{10}(\text{total traffic in equivalent light vehicles}) \qquad \text{Equation 1.1}$$

where:

ALD is the sealing chip average least dimension (in mm)

The trials were conducted at a number of sites with significantly different climate conditions and traffic levels and vehicle profiles to allow for the possibility that the temperature regime and types of vehicles might affect rates of texture change.

2. Laboratory testing

2.1 Adhesion testing of binders

2.1.1 Development of test apparatus

The aim of the work to be described here has been to develop a laboratory test to assess the effect of rolling and traffic on the initial bonding of chip to various binders.

The apparatus used was developed from a reciprocating weighted pneumatic-tyred roller developed for an earlier Transfund project (Ball et al. 1999). The roller was contained in a temperature-controlled cabinet. The wheel tracked back and forth, over a metal plate on which a one millimetre layer of binder had been placed and covered with sealing chip. Grade 3 chip was used for all testing. The chips were placed sufficiently far apart to ensure that they did not touch each other during rolling and thus obscure any differences in binder performance. The weight on the wheel was reduced to a minimum to maximise the differences in performance of the different binder types.

Chips and plate were brought to the test temperature before rolling and the chips were placed on the binder surface immediately before rolling commenced. After a selected number of rolls, the chips were checked by touch for adhesion to the binder, the proportion adhering noted (as the measure of adhesion), and rolling then recommenced.

Unrolled control plates with the same binder and chip were also checked for bonding for some of the tests during the rolling process. The rates of adhesion observed on these unrolled plates were of the order of half that of the corresponding rolled plates. The rolling effect could be made more significant by increasing the weight on the wheel. However, this would probably make the adhesion process too rapid to observe for some softer binders.

The combination of roller speed and tyre track length meant that the binder experienced an impulse of an approximate duration of 156 ms, three times or so longer than would be caused by typical moving traffic on a road. This would mean that the test binder would consequently appear slightly softer to the chip than it would on the road. The effect could be compensated for by testing at slightly lower than normal road temperatures. However, this refinement was not investigated given:

- the variability of road traffic and weather conditions,
- that bonding to chip will depend on rates of chemical reaction (decreasing as temperature falls) as well as the rheological properties of the binder.

2.1.2 Test results

At temperatures above 25°C, bonding of the softer grades of bitumen to aggregate was too rapid to be observed. Consequently, comparative testing to evaluate the method was carried out at binder surface temperatures of approximately 20°C and 10°C. Three grades of bitumen (180/200, 130/150 and 40/50) were tested using a standard chip.

Subsequently limited quantities of two binders from the sealing trial site south of Pukepapa (see Table 3.1) and chip from that trial were received and tested at 20°C. The results are shown in Figures 2.1 and 2.2. The trial binders were a 130/150 bitumen containing 0.5 parts per hundred (pph) adhesion agent, and a polymer modified binder based on 130/150 and containing 2% polymer, 2 pph kerosene, and 0.5 pph adhesion agent.

2.1.3 Discussion

As set up at present, the test provides useful information at temperatures of 20°C and below. At higher temperatures the bonding process is too rapid to observe with softer grades of bitumen. A new rolling apparatus with reduced weight on the wheel would be needed to make the test practicable at higher temperatures.

The test method is sensitive to differences in initial bonding. The amount of rolling required to obtain equivalent bonding varies over several orders of magnitude through the bitumen grades. The general rule is that the harder the binder (by penetration), the longer the rolling process required to achieve a given bonding level.

Adhesion performance measured by this method turns out to depend on the chip source as well as the bitumen grade. It is notable that the 130/150 laboratory bitumen shows a significantly greater adhesive power than the 130/150 binder used on the Pukepapa trial, even though the latter contains 0.5 pph of adhesion agent. The different Grade 3 chip used in testing the trial material is presumably responsible for this difference in adhesion performance.

The 130/150 polymer blend contains 2 pph kerosene. This would be expected to make it approximately rheologically equivalent to a 180/200 bitumen without polymer. At 20°C the blend has an initial bond significantly better than the trial 130/150, but not as strong as the 180/200. Again, since standard laboratory sealing chip was used for testing the 180/200 while the Pukepapa binders were tested with different chip from the Pukepapa trial site, this result must be viewed with care.

Figure 2.1 Results of adhesion tests, at 20°C, on three grades of bitumen and two binders.

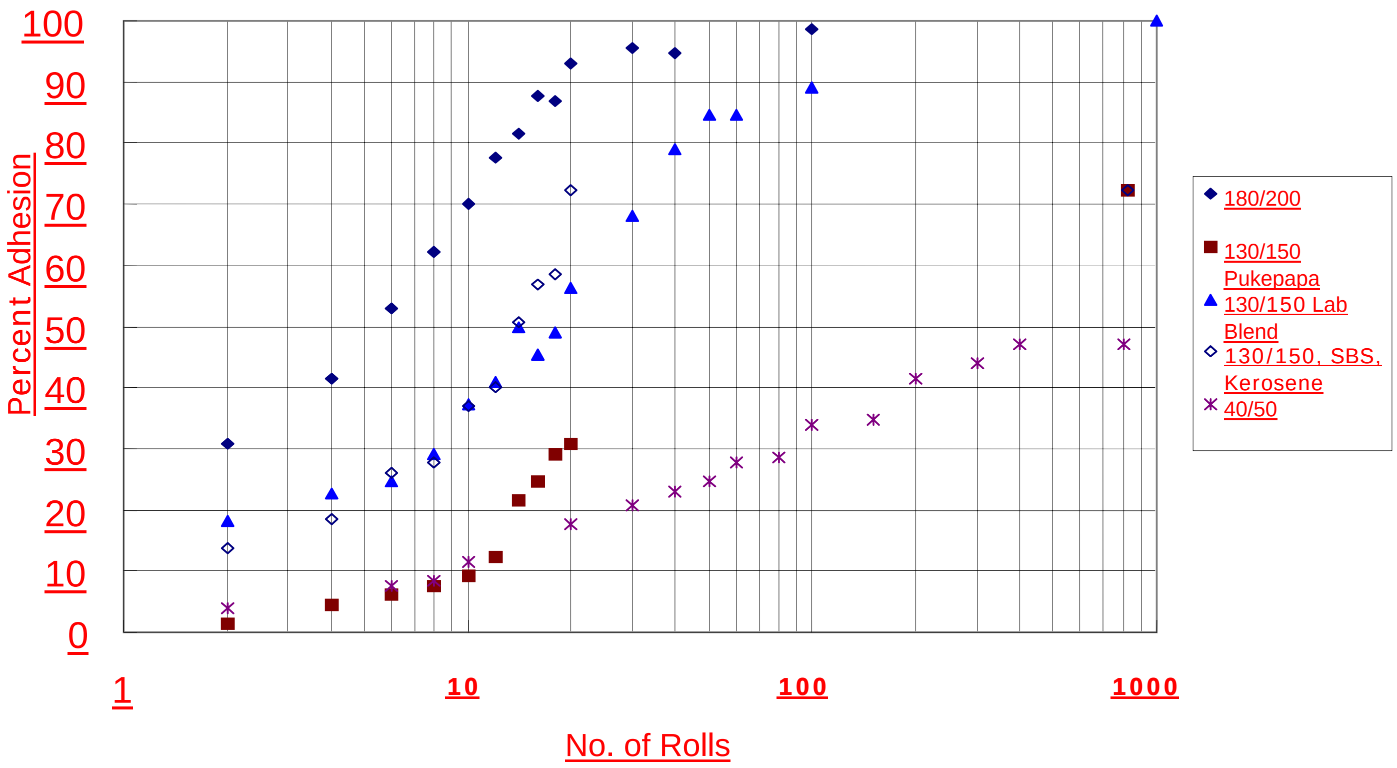
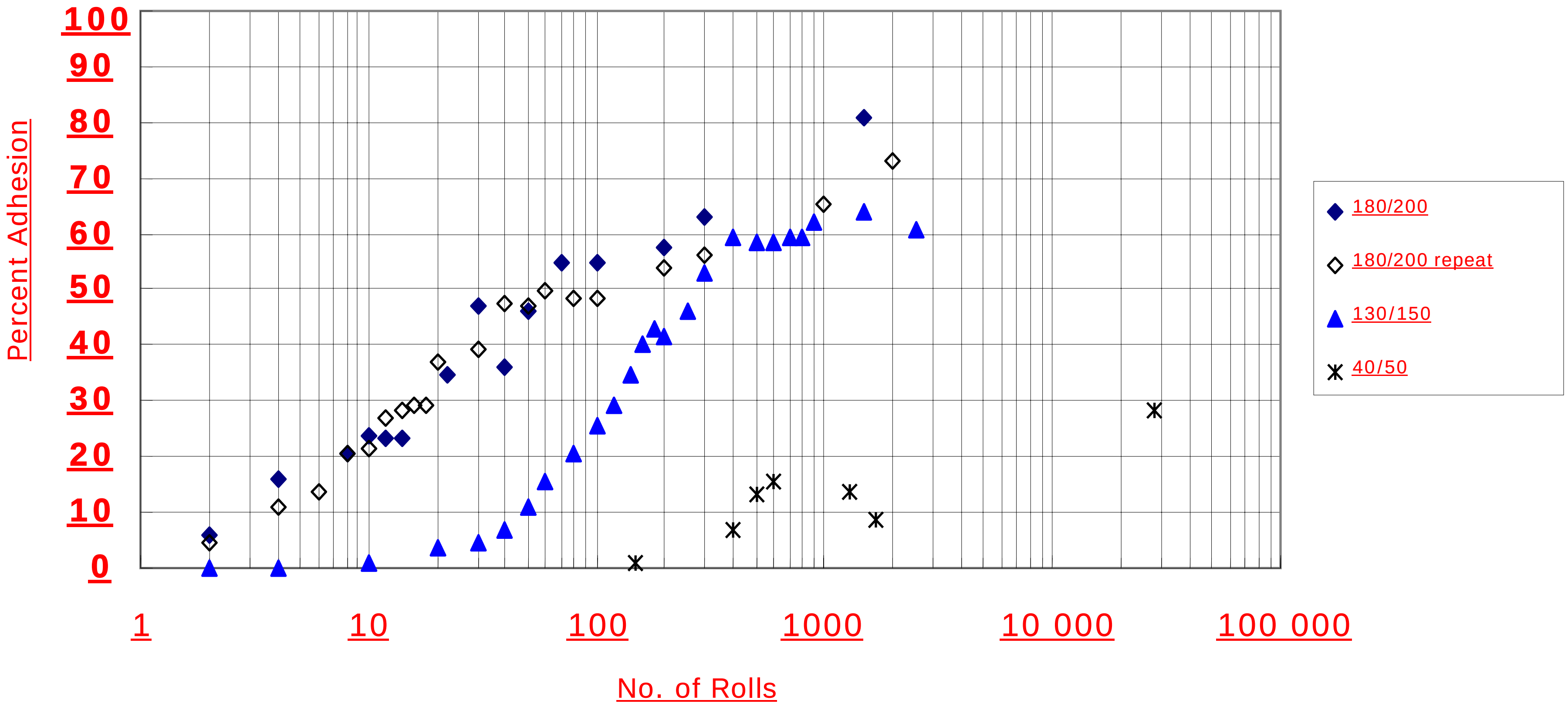


Figure 2.2 **Results of adhesion tests, at 10°C, on three grades of bitumen.**



2.2 Rheological testing of binders

Binders used in the laboratory adhesion tests and field trials were characterised in the laboratory, using a Carri-Med CSL² 500 rheometer when available. Values of the dynamic shear modulus |G*| (the ratio of maximum shear stress to maximum shear strain during a sample film oscillation) were measured over a range of temperatures and frequencies, and the data combined to produce ‘master curves’ at 25°C covering a span of approximately eight decades of frequency. In addition an estimate was made of:

- the limiting viscosity of the binders, i.e. the viscosity estimate, $\eta_0(25)$, of each binder for zero frequency at 25°C,
- the way |G*| varies with temperature,
- the way η_0 varies with temperature.

For details of the procedure, including calculation of the master curves and limiting viscosities at temperatures other than 25°C, see Appendix A.

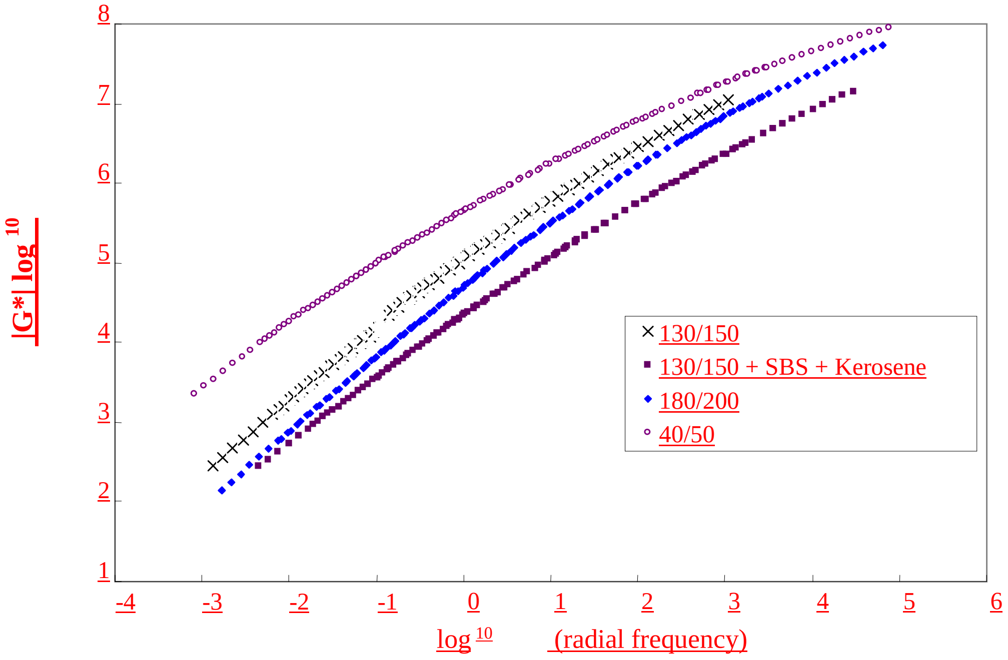


Figure 2.3 Master curves for four test binders at 25°C.

Plots of the 25°C master curve points are shown in Figure 2.3. These curves can be closely fitted, using nonlinear regression techniques, to equations of the form:

$$|G^*(\omega,25)| = \frac{G_\infty(25)}{[1+(\frac{\omega_c}{\omega})^v]^{\frac{w}{v}}}$$

Equation 2.1

where:

$\lvert G^*(\omega, 25)\rvert$	is the dynamic shear modulus of the material at 25 °C and frequency ω rad/s
$G_\infty(25)$	represents the fitted value of the 25 °C shear modulus at the high frequency limit
ω_c, v and w	are fitting constants of no particular physical significance

(Marastaneau & Anderson 1999, 2000)

Values of the constants for Equation 2.1 are shown in Table 2.1. The 130/150 binder with SBS polymer additive has been assigned a value of G_∞ equal to that of the undoped 130/150, as the software used could not fit the data to Equation 2.1 with four unknowns. The curve obtained fitted the data closely, but the success of this fairly arbitrary value of G_∞ in getting a good fit indicates that extrapolation to obtain dynamic moduli at very high frequencies will not always give accurate results.

Table 2.1 Rheological parameters of four test binders.

Binder	**G_∞ Pa**	**ω_c rad/s**	**v**	**w**	**$\eta_{0(25)}$ Pa.s**	**T_s °C**
180/200	8.89×10^8	1332.4	0.15512	1.10815	7.03×10^4	41.4
130/150	1.96×10^9	272.5	0.12783	1.14709	2.11×10^5	40.1
40/50	4.86×10^9	0.10438	0.087062	1.38611	2.35×10^6	36.5
130/150 +2% SBS +2 pph kerosene	1.96×10^9	107515	0.13547	0.90408	4.61×10^4	30.1

The quantity T_S, called the ‘characteristic temperature’, is a measurement of how quickly binder rheological properties change with temperature. T_S can be used to transform the master curve for 25°C into one for another temperature (see Appendix A for details). The larger T_S is, the more sensitive the binder is to temperature change.

The effect of adding polymer to 130/150 has been to produce a product which is considerably less temperature sensitive than the straight 130/150. Although the 130/150 is generally harder than 180/200, its lower temperature sensitivity means that the properties of the two bitumen grades converge at lower temperatures.

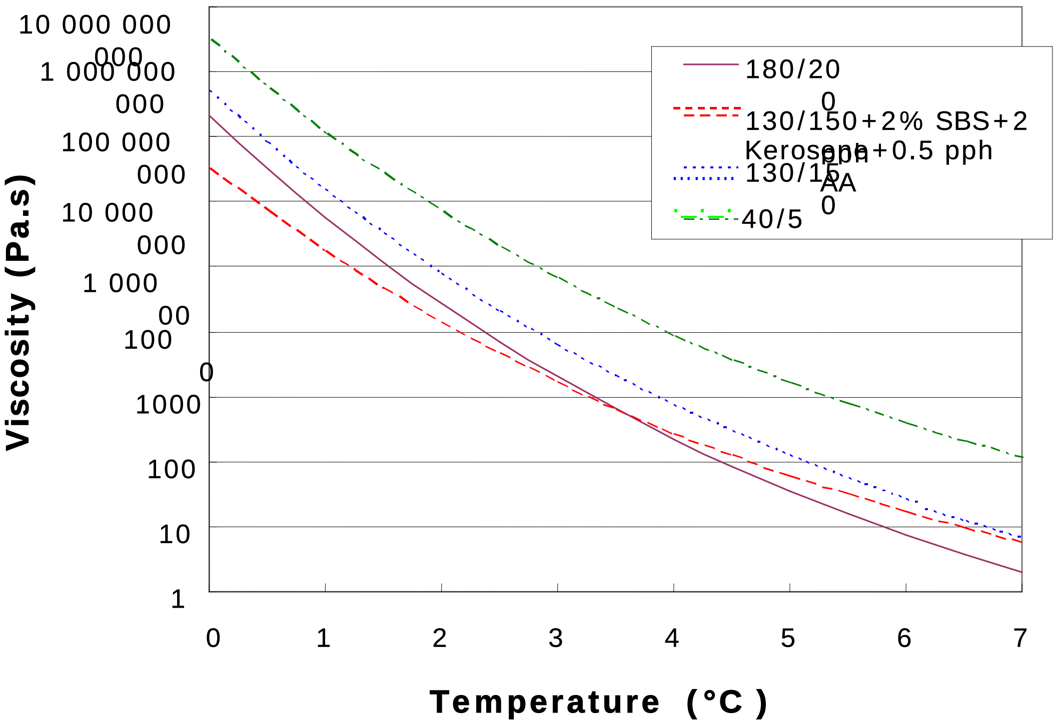


Figure 2.4 Temperature dependence of limiting low shear rate viscosities for test binders.

2.3 Relationship of adhesion results and rheological properties

A cursory inspection of Figures 2.1 and 2.2 suggests that, for a single type of chip, the higher the viscosity the lower the expected degree of adhesion as a general rule. This would also be expected on basis of the investigation of adhesion carried out by Forbes et al. (2000). To quantify this observation, we considered the number of rolls needed to reach 40% adhesion with the standard chip and compared these with various rheological parameters, listed as follows:

- The limiting low shear rate viscosities (η_0) for different binders (see Figure 2.4).
- The viscosity estimates from the rheological data of the different binders at a shear rate of 48.63 rad/s. This shear rate corresponds to the pulse of approximately 156 ms imparted by the tyre of the test roller (see Section 2.1.1).

The viscosity at temperature T, $\eta(48.63, T)$, is given by:

$$\eta(48.63,T) = \frac{G''(48.63,T)}{48.63} \qquad \text{Equation 2.2}$$

where:

the loss modulus $G''(48.63, T)$ is as defined by Equation A.2 in Appendix A.

The viscosity was extrapolated by the approach of Heukelom (1973), which enables viscosities to be estimated by extrapolation using typical ring and ball softening points and the 25°C penetrations of the bitumen. Table 2.2 lists the viscosities estimated for different bitumen grades and temperatures.

Table 2.2 Estimated bitumen viscosities (Pascal-seconds) for 3 grades of bitumen at 20°C and 10°C.

Bitumen Grade	Temperature °C	N_{40}	η_0	$\eta(48.63, T)$	$\eta_{Heukelom}$
180/200	20	4	267 878	33 320	45 325
130/150	20	12	773 933	50 799	102 048
40/50	20	200	8 012 906	82 643	1 575 262
180/200	10	30	5 605 295	158 700	455 394
130/150	10	95	14 843 839	202 613	1 284 002
40/50	10	120000	128 777 748	236 488	27 640 186

Log-log fits of the number of rolls required to reach 40% adhesion (N_{40}) give the following equations:

$$\log_{10}N_{40} = -8.1141 + 1.5205 \log_{10}\eta_0 \qquad r^2 = 0.837$$

Equation 2.3

$$\log_{10}N_{40} = -14.3145 + 3.2772 \log_{10}\eta(48.63,T) \qquad r^2 = 0.508$$

Equation 2.4

$$\log_{10}N_{40} = -6.9341 + 1.5432 \log_{10}\eta_{Heukelom} \qquad r^2 = 0.933$$

Equation 2.5

Viscosities η_0 and $\eta_{Heukelom}$ were found to be closely correlated for the bitumens used in this work:

$$\log_{10}\eta_0 = 1.1755+ 0.9466 \log_{10}\eta_{Heukelom} \qquad r^2 = 0.967$$

Equation 2.6

i.e.

$$\eta_0 = 14.9788\ \eta_{Heukelom}^{0.9466} \qquad \text{Equation 2.7}$$

The extrapolated Heukelom viscosity is the best predictor of adhesion for the wheeltracking method described here. Assuming that Equation 2.5 can be extended to higher temperatures, we can estimate $\eta_{Heukelom}$ at different temperatures, and examine the expected variation of adhesion levels.

This also allowed us to extend the results to 80/100 bitumens. If we normalised the calculated values of N_{40} by dividing them by the value of N_{40} for 180/200 at 55°C (approximately the maximum seal temperature experienced in New Zealand), we obtained the results listed in Table 2.3, which gave an indication of the relative resistance to initial adhesion.

Table 2.3 Relative resistance to bitumen–chip initial adhesion extrapolated from rolling study data.

Temperature °C	Bitumen Grade			
	180/200	**130/150**	**80/100**	**40/50**
10	191 205	946 702	4 648 072	107 959 566
20	5434	19 014	79 558	1 297 866
30	279	756	2774	34 098
40	23	50	166	1618
50	3	5	15	121
55	1	2	5	38

The results here have been extrapolated a relatively long distance beyond the 20°C upper limit of the experimental data, and so can be regarded only as very approximate indicators of bonding behaviour. It is evident, though, that temperature is the principal factor affecting bonding behaviour. Bitumen viscosities are very sensitive to temperature, while the figures in Table 2.3, being approximately proportional to viscosities raised to the power of 1.5, are even more sensitive. Differences in grade, within the range of bitumens used for sealing work, are less critical. Thus a hard 80/100 bitumen at any given temperature bonds more effectively than a 180/200 bitumen at 10°C below that temperature. Success in chip retention after sealing will be critically dependent on the surface temperature at which the work is carried out.

3. Chipseal trials

3.1 Trial sites

The project brief required five sites. Four consultants supervising Transit New Zealand contracts agreed to provide the sites as listed in Table 3.1, and Figure 3.1 shows the locations of the sites.

Table 3.1 Hard binder chipseal trial sites and their climatic conditions.

Trial site	SH	MRP	AADT	HCV %	Northing	Easting	Alt. m	TMAX °C	TMIN °C
The Wilderness	94	115/4.5	1050	12.1	5507987	2105543	293	14.1	4.4
Kingston Crossing	94	16/3.6	650	9.1	5462556	2184452	100	15.0	4.9
Pukepapa South	3	432/5.7	6110	18	6100874	2722697	39	17.3	8.2
Otakiri	34	0/6.1	1070	21	6348839	2841845	15	19.6	8.7
Kaiwhatiwhati	38	0/16.3	1456	19.6	6307553	2813730	497	16.7	5.0

Notes to Table 3.1:

(a) SH – State Highway number; MRP – Mean Route Position; Alt. – altitude (m).

(b) Northing, easting, and altitude of sites were estimated by linear interpolation on the known positions of the two adjacent route stations.

(c) TMAX = Estimated mean of the daily maximum temperatures over a year.

TMIN = Estimated mean of the daily minimum temperatures over a year.

These values are calculated by a linear interpolation of the known values for the four nearest meteorological stations (New Zealand Meteorological Service 1983), weighted according to the distance of the station and making allowance for the different altitudes of the stations.

3.2 Chipsealing programme

Details of the sealing work are listed in Table 3.2. The five trial sites were divided into test sections, each sealed with different binder grades and types so that the effects of binder properties on the rates of sealing chip compaction and seal texture reduction could be compared. The two South Island sites were divided into three test sections and the three North Island sites into four.

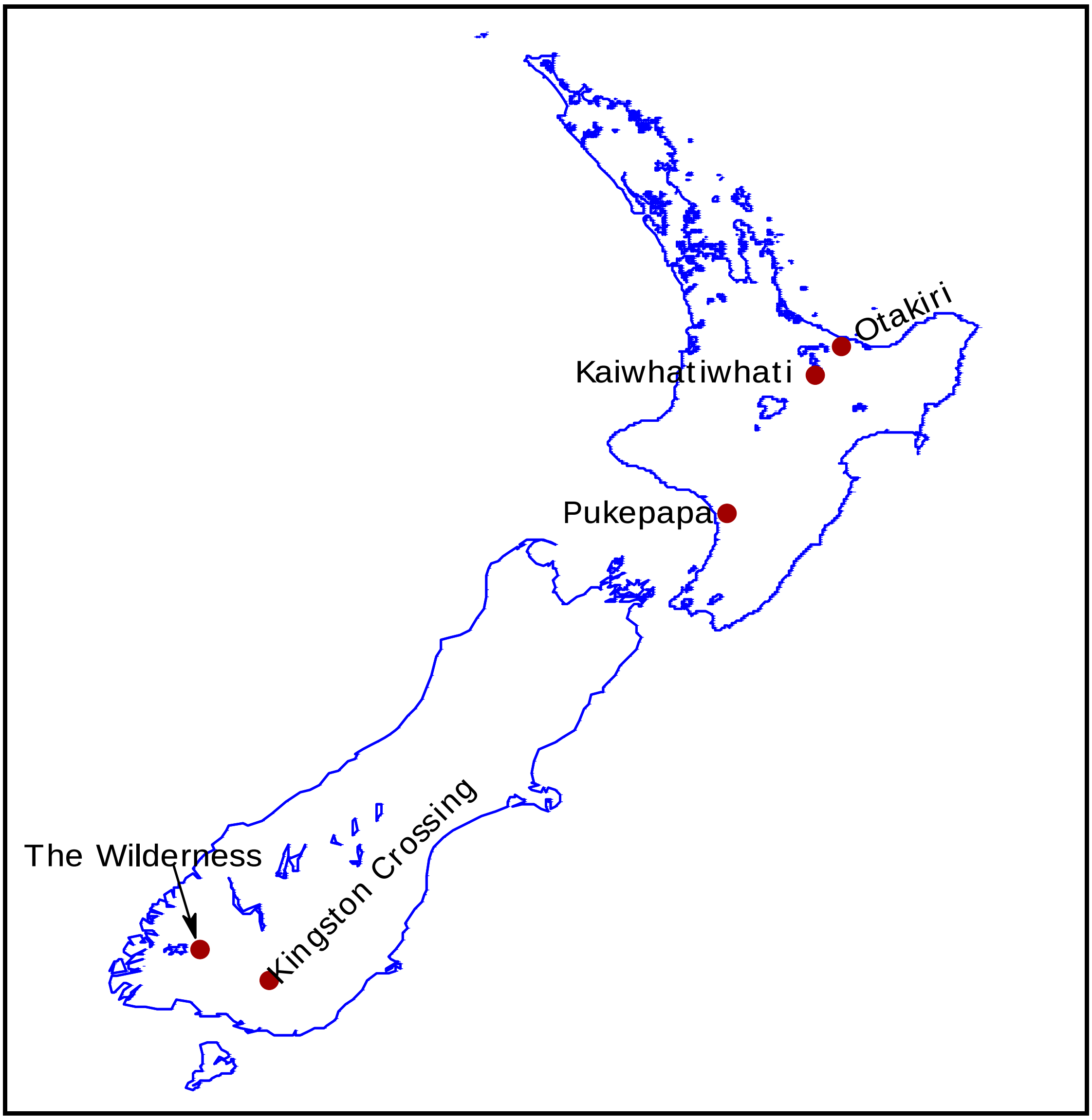


Figure 3.1 Locations of chipseal trial sites.

Otakiri, SH34, near Tauranga
Kaiwhatiwhati, SH38, near Rotorua
Pukepapa South, SH3, north of Bulls
The Wilderness, SH94, near Te Anau, Southland
Kingston Crossing, SH94, in Southland

Trial Site	Test section route position	Sealing Date	Binder	Cutter* pph	Antistrip pph	Chip grade/s	ALD/s mm	Residual application/s L/m^2
The Wilderness	SH 94 RP 115/4.34 – 4.57	14-Mar-01	180/200	3	0.8	3	9.4	1.68
	SH 94 RP 115/4.95 – 5.34	13-Feb-01	130/150	3	0.8	3	9.4	1.75
	SH 94 RP 115/4.57 – 4.95	13-Feb-01	80/100	3	0.8	3	9.4	1.71
Kingston Crossing	SH 94 RP 16/3.91 – 4.02	14-Mar-01	180/200	3	0.8	3	8.5	1.64
	SH 94 RP 16/3.28 – 3.68	13-Feb-01	130/150	3	0.8	3	8.5	1.62
	SH 94 RP 16/3.09 – 3.28	13-Feb-01	80/100	3	0.8	3	8.5	1.62
Pukepapa	SH 3 RP 432/5.714 – 6.008	16-Feb-01	180/200	0	0.5	3	9.87	1.66
	SH 3 RP 432/5.424 – 5.714	14-Feb-01	130/150	0	0.6	3	9.87	1.68
	SH 3 RP 432/6.008 – 6.297	16-Feb-01	80/100	0	0.5	3	9.87	1.66
	SH 3 RP 432/5.220 – 5.424	2-Feb-01	130/150+2%SBS	2	0.5	3	9.87	1.63
Otakiri	SH 34 RP 0/4.129 – 5.13	19-Mar-01	180/200	1	0.7	2/4	11.81/7.48	0.92/0.92 [1.84]
	SH 34 RP 0/5.13 – 6.13	19-Mar-01	130/150	3	0.7	2/4	11.81/7.48	0.92/0.92 [1.84]
	SH 34 RP 0/6.13 – 7.13	20-Mar-01	80/100	5	0.7	2/4	11.81/7.48	0.92/0.92 [1.84]
	SH 34 RP 0/7.13 – 8.031	20-Mar-01	80/100	3	0.7	2/4	11.81/7.48	0.92/0.92 [1.84]
Kaiwhatiwhati	SH 38 RP 0/15.549 – 15.932	15-Mar-01	130/150+2%SBS	2	1.0	2/4	9.99/6.60	0.954/0.959[1.913]
	SH 38 RP 0/15.932 – 16.312	15-Mar-01	130/150	2	1.0	2/4	9.99/6.60	0.976/0.982[1.958]
	SH 38 RP 0/16.312 – 16.695	15-Mar-01	80/100	4	1.0	2/4	9.99/6.60	0.950/0.949[1.899]
	SH 38 RP 0/16.695 – 17.145	15-Mar-01	CRS2 70% 130/150	2	0	2/4	9.99/6.60	0.742/0.677[1.419]

* Cutter is kerosene in all cases, except for the emulsion on SH38 (Kaiwhatiwhati) where low aromatic white spirits were used.

Table 3.1 Chipsealing trial details of sealing work at the five trial sites.

Notes to Table 3.2:

(a) The project brief specified that the different binders for a given site should have equal dosages of cutter. The contractors' reservations did not always allow this and extra cutter was used for harder bitumens on occasion. Since approximately 70% of cutter is ultimately lost through evaporation (Ball 1999), we considered that the harder bitumens might still delay flushing, and observation of these sites was continued.

(b) Most of the chipsealing trials were conducted towards the end of the sealing season, since carrying out programmed work generally took priority for consultants and contractors.

(c) A multigrade bitumen from Australia (C600/170 grade) was donated to the sealing programme. A trial seal was placed at the Kingston Crossing site, with the donor and contractor choosing to add 3 pph automotive gas oil (diesel) and 0.8 pph antistrip. This seal stripped on the day of sealing. In terms of typical current New Zealand penetration grade bitumens, the bitumen was similar to a 60/70 at ambient temperatures and to a (softer) 80/100 at spraying temperatures (C600/170 bitumen is the softer of the two multigrade products used in Australia). These 60/70 bitumens are not used for sealing in New Zealand. In view of the experience of this trial, a softer multigrade product than is produced in Australia is probably needed to suit the local conditions. The (undesirable) alternative would be to add a large amount of cutter to assist initial chip bonding.

3.3 Site inspection programme

We planned to inspect the sites in May and June 2001, then in the following (2002) spring and autumn, and annually thereafter until 2004.

However, the Pukepapa site experienced severe early chip loss. Only a small amount of loss had been noticed up to 28 May 2001. On the night of 28-29 May a heavy frost occurred and extensive chip loss occurred on three test sections but not on the fourth polymer modified binder section which remained in good condition. Repairs were carried out with a C60 emulsion and Grade 5 sealing chip and the trial was abandoned. Appendix B contains a review of possible causes of seal failure.

For the other sites, the programme for inspection included a general assessment of the state of the surface, assessment of chip retention, and sand circle texture measurements at two fixed route positions for each binder surface. The texture measurements were performed in each wheelpath and between wheelpaths on both sides of the road, and on the crown of the road. The route positions for the sand circle measurements are listed in Table 3.3.

Table 3.3 Sites used for texture measurements and binders.

Trial site*	SH	Binder	Test section route position	
The Wilderness	94	180/200	115/4.405	115/4.460
		130/150	115/5.162	115/5.261
		80/100	115/4.660	115/4.761
Kingston Crossing	94	180/200	16/3.906	16/3.993
		130/150	16/3.393	16/3.494
		80/100	16/3.140	16/3.194
Otakiri	34	180/200	0/4.900	0/4.950
		130/150	0/5.230	0/5.280
		80/100	0/6.700	0/6.750
		80/100	0/7.930	0/7.980
Kaiwhatiwhati	38	130/150+SBS	0/15.600	0/15.700
		130/150	0/16.140	0/16.200
		80/100	0/16.400	0/16.430
		CRS2 70%	0/16.850	0/16.960

* Pukepapa trial site was discontinued.

3.4 Texture trend evaluation

During the development of the Transit New Zealand performance-based chipseal specification TNZ P/17, it was found that texture depths on chipseals vary approximately according to the equation:

$$\frac{V_V}{ALD} = A - 0.07 \log_{10} T \qquad \text{Equation 3.1}$$

where:

V_v	is the total volume of voids per unit area in the seal
A	is a constant which may vary from site to site
ALD	is the average least dimension of the sealing chip (for a two-coat seal it is the average least dimension of the larger chip)
T	is a measure of the total equivalent vehicles per lane (evl) to date, with a car taken as equivalent to one vehicle and a truck as equivalent to ten (Patrick 1999)

Patrick (1999) showed that we can write to a close approximation:

$$V_v = T_d + V_b \qquad \text{Equation 3.2}$$

where:

V_b	is the volume of bitumen sprayed per unit area (V_B) less any required to fill the existing surface texture in litres/m^2
T_d	(texture depth measured in mm) is a measure of the volume of air voids in the chipseal

It follows from Equations 3.1 and 3.2 that for a given seal

$$T_d = k - 0.07 \times ALD \times \log_{10} T \qquad \text{Equation 3.3}$$

with k a constant ($= A \times ALD - V_b$) for that seal

The proposition to be tested is that different sealing binder types will result in different rates of texture change, i.e. divergence from the constant 0.07. To test this we have the option of trying to fit the data to Equation 3.1 or to Equation 3.3. For consistency with work published by others the results will be fitted to Equation 3.1, with the proviso that the total residual binder spray rate, V_B (without adjustment for original surface texture), has been used instead of V_b. The only result of this will be to change the constant A in Equation 3.1 slightly.

3.5 Results

To summarise the large number of texture results, averages across the road have been taken, following the procedure given in Transit New Zealand performance-based resealing specification P/17:2002. In this specification the mean sand circle texture, *T(mean),* is taken as:

$$T(mean) = \frac{[T(OWPa) + T(BWPa) = T\ (CL) = T(IWPb) = T\ (OWPb)]}{5}$$

Equation 3.4

where:

suffixes *a* and *b* indicate opposite lanes on the road

T(OWPa)	is the measured outer (near the road edge) wheelpath texture in lane *a*
T(BWPa)	is the measured texture depth between wheelpaths in lane *a*
T(CL)	is the measured texture depth at the centreline of the road
T(IWPb)	is the measured inner wheelpath texture in lane *b*
T(OWPb)	is the measured outer wheelpath texture in lane *b*

It is equally valid to calculate this mean starting on the other side of the road:

$$T(mean) = \frac{[T(OWPb) + T(BWPb) + T(CL) + T(IWPa) + T(OWPa)]}{5}$$

Equation 3.5

and since all texture values across the road were measured in the current work, the mean values of Equations 3.4 and 3.5 were taken as the estimates of T(mean).

All texture depths used in the calculations were the means for the two route positions at each trial site, except in a few instances where seal stripping had occurred at one position.

Estimates of T(mean) have been plotted against the logarithms of the total equivalent vehicles per lane (evl) to date in Appendix C for all seal trial sites (points joined by solid lines).

In one instance (Kingston Crossing, 130/150 bitumen seal), early stripping on the centreline meant that an alternative estimate of the texture had to be used:

$$T_1(mean) = \frac{[T(OWPa) + T(BWPa) + T(IWPa) + T(IWPb) + T(BWPb) + T(OWPb)]}{6}$$

Equation 3.6

This quantity was calculated for all test sites and is also plotted in Appendix C (points joined by dotted lines). T_1(mean) is generally smaller than T(mean). However, the *slopes* of the plots of the two quantities on the graphs are closely similar, so that either quantity may be used to estimate the *rate* of texture change.

To obtain meaningful comparisons of different sites, we needed to allow for the different chip sizes. Quantities $(T_d + V_B)/ALD$ were calculated and regressed against $\log_{10}T$ to find the constants for equations of the form of Equation 3.1:

$$\frac{T_d + V_B}{ALD} = A - B \log_{10} T$$

Equation 3.7

The larger the value of the constant B the greater the rate of texture decrease, i.e. the more susceptible the surface is to texture loss. Values of B are listed in Table 3.4.

To assist in the discussion the values are also plotted along with their uncertainties (± two standard deviations) in Figures 3.2 and 3.3.

3.6 Discussion

The major differences in chipseal performance, as measured by rate of seal texture change, were between sites rather than between binders. In general, the seals at the Kaiwhatiwhati site lost texture slightly more slowly than those at the Otakiri site, and much more slowly than those at the two Southland sites.

The chipseals in the three North Island trials were two-coat seals, as opposed to the single coat seals of the Southland trials. This does not account for the different rates of texture change, since the studies done in the development of the Transit New Zealand specification P/17 did not find a significant difference between the texture variation properties of two-coat and single coat seals.

The binder type had negligible effect on texture rate of change between test sections within a site compared to other factors.

At Otakiri there was no detectable difference in the rates of texture change for the test sections containing 80/100 bitumen and 3 or 5 pph of kerosene respectively (sites 7 and 8).

Trial Site		Site No.	Binder	Initial evl	Final evl	B for T(mean) values	B for T_1(mean) values
Kaiwhatiwhati SH38 RS 0	RP 0/15.549 – 15.932	1	130/150+ 2% SBS + 2 pph kero	181 097	2 193 289	0.027±0.014	0.029±0.021
	RP 0/15.932 – 16.312	2	130/150 + 2 pph kero	181 097	2 193 289	0.003±0.026	0.015±0.015
	RP 0/16.312 – 16.695	3	80/100 + 4 pph kero	181 097	2 193 289	0.007±0.034	0.006±0.023
	RP 0/16.695 – 17.145	4	CRS2 70% 130/150 + 2%cutter	181 097	2 193 289	0.018±0.019	0.003±0.016
Otakiri SH34 RS 0	RP 0/4.129 – 5.130	5	180/200 + 1 pph kero	132 969	1 679 119	0.051±0.029	0.043±0.031
	RP 0/5.130 – 6.130	6	130/150 + 3 pph kero	132 969	1 679 119	0.071±0.021	0.063±0.030
	RP 0/6.130 – 7.130	7	80/100 + 5 pph kero	132 969	1 679 119	0.031±0.029	0.037±0.026
	RP 0/7.130 – 8.031	8	80/100 + 3 pph kero	132 969	1 679 119	0.037±0.040	0.038±0.040
The Wilderness SH94 RS 115	RP 115/4.34 – 4.57	9	180/200 + 3 pph kero	78 709	1 302848	0.152±0.010	0.151±0.007
	RP 115/4.95 – 5.34	10	130/150 + 3 pph kero	78 709	1 302 848	0.114±0.020	0.114±0.014
	RP 115/4.57 – 4.95	11	80/100 + 3 pph kero	78 709	1 302 848	0.136±0.009	0.147±0.030
Kingston Crossing SH 94 RS 16	RP 16/3.91 – 4.02	12	180/200 + 3 pph kero	68 780	1 110 435	0.116±0.008	0.107±0.010
	RP 16/3.28 – 3.68	13	130/150 + 3pph kero	68 780	1 110 435	–	0.160±0.031
	RP 16/3.09 – 3.28	14	80/100 + 3 pph kero	68 780	1 110 435	0.156±0.014	0.160±0.018

Table 3.4 Rate of change of (volume of voids/ALD) (B) (Equation 3.7) for the four sites.

Site no. are of the test sections at each site (see Figures 3.2 and 3.3).

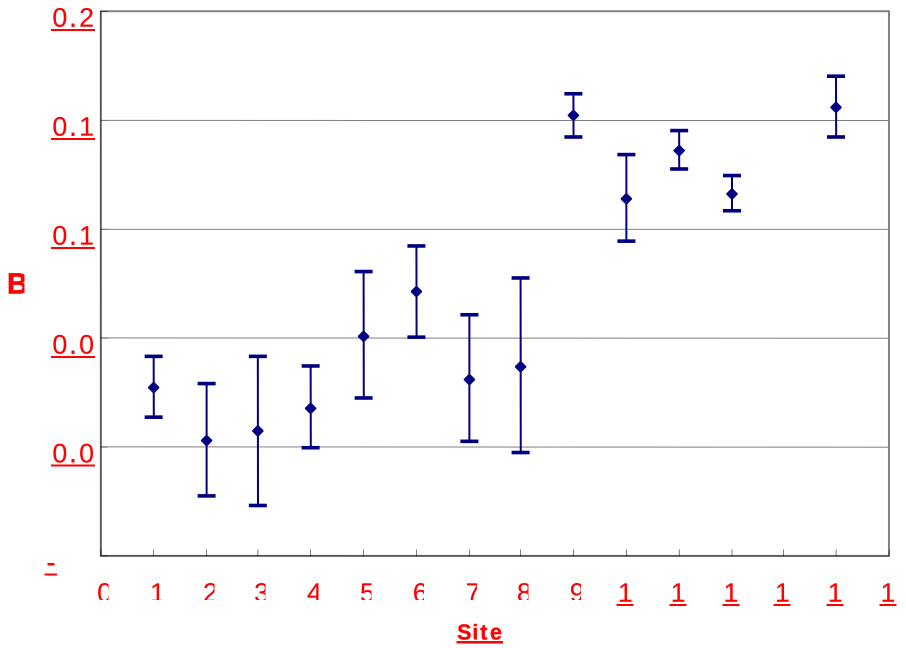


Figure 3.2 **Rate factor B for T(mean) texture values.**

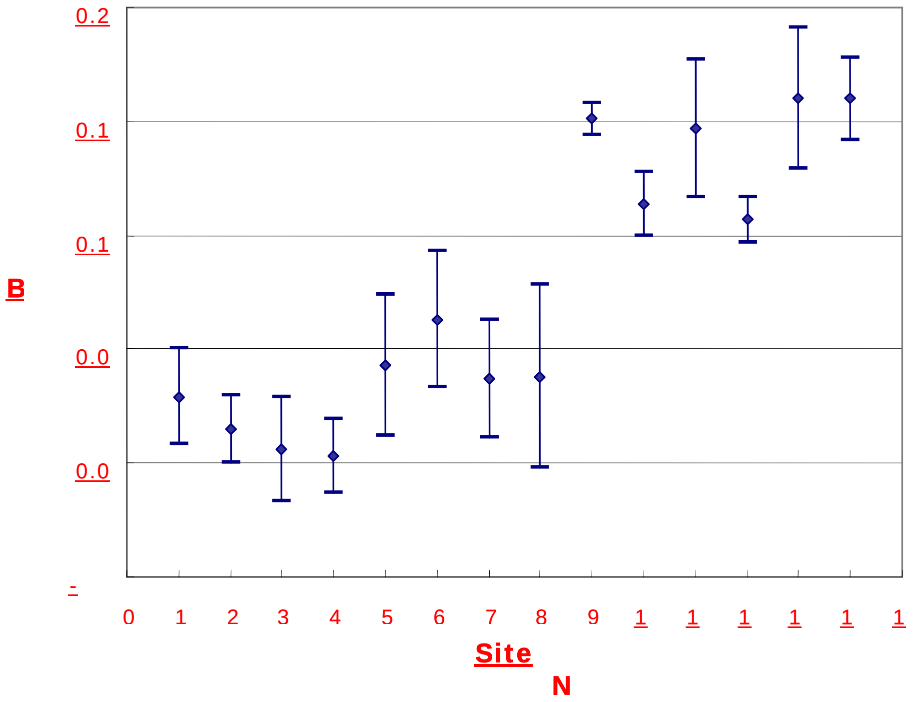


Figure 3.3 **Rate factor B for T1(mean) texture values.**

Site numbers for the test sections are as listed in Table 3.4.

Since the Southland test sections all had 3 pph kerosene, the hypothesis that softer binders meant higher rates of texture loss predicted that the rate of texture loss would decrease from 180/200 binder to 130/150 to 80/100. In fact, at the Kingston Crossing site, the 80/100 and 130/150 test sections lost texture significantly faster than the 180/200 section. In the site at The Wilderness, the 80/100 section appeared to have lost texture faster than the 130/150 site, although this trend was not as clear cut as at Kingston Crossing. Variations in the hardness of the underlying surface and/or surface geometry (affecting the impact of traffic) were suggested as possible reasons for these unexpected results.

4. Summary and Conclusions

A laboratory test was developed to assess the setting up of the bond between binder and sealing chip. A reciprocating tyred wheel was rolled over loose chip on binder on a plate and the proportion of chip adhering was assessed at intervals. The test was sensitive to the different performance of standard bitumen grades, but at present must be carried out at 20°C and below as bonding to 180/200 bitumen was too fast to observe at higher temperatures. The rate of bonding, as measured by increase in the proportion of chip adhering to the binder with increased number of wheel rolls, was extremely sensitive to the test temperature, being strongly related to the binder viscosity at that temperature.

The road trials set up at the five sites on North and South Island state highways were divided into three or four test sections. Each had been sealed with different binder grades and types so that the effects of binder properties on the rates of sealing chip compaction and seal texture reduction could be compared.

Several of the binders used in trials were characterised rheologically. Adding SBS polymer to a bitumen produced a product which was less temperature sensitive than the original 130/150 bitumen, and so would be softer than 130/150 bitumen at low temperatures.

One of the five sites, Pukepapa, experienced drastic chip loss on three of its four test sections on the occurrence of the first autumn frost, approximately three months after sealing. The seal on the fourth test section, unlike the others, had been sealed with a mix of SBS polymer and kerosene with the bitumen. This mix probably prevented binder fracture as chip moved under traffic at low temperatures, thus preventing stripping. As a result of the stripping the Pukepapa trial was discontinued.

Both kerosene and SBS polymer additives have the potential to minimise the chance of first winter chip loss in seals. Textures were measured periodically on the four surviving trial sites, and considerable differences in rates of texture loss were noted.

The principal factor affecting rates of texture loss with trafficking was the site itself. Variations in the hardness of the underlying surface and/or surface geometry (affecting the impact of traffic) were suggested as possibly being important in determining amounts of texture loss. Binder properties had no measurable effect.

5. Recommendations

Since the penetration grade of the binder had no measurable effect on the rate of texture reduction in chipseals, and laboratory testing indicated that the initial binder-to-aggregate bonding was significantly better the softer the bitumen grade, use of harder binders than is current practice is not recommended. The softer the original bitumen, the less it will harden under oxidation, and long-term pavement performance is likely to be better.

However, it is not recommended that there be a general movement towards use of softer bitumens for sealing work as this could increase the occurrence of high temperature induced bleeding. In some parts of New Zealand, the occurrence of bleeding was reduced by changing from soft 180/200 to harder 130/150 bitumens for sealing.

In situations where frost will occur, some kind of additive may be needed to prevent early stripping. Both kerosene and elastomeric products such as SBS polymer can do this job. Yet in situations where the climate ranges between very low winter and very high summer temperatures, or for sealing late in the season, SBS (with some kerosene to ensure initial adhesion to chip) may be recommended rather than high kerosene content, in order to stop bleeding in the first spring after sealing.

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Appendix A Derivation of master curves and limiting viscosities for bituminous binders

A1. Derivation of 25°C master curves and limiting viscosities

In the discussion that follows, $|G^*(\omega, T)|$ represents the dynamic shear modulus of a material at angular frequency ω /s (= $2\pi \times$ frequency in Hz) and temperature T°C. The phase angle in degrees, representing the amount by which the shear strain lags behind the shear stress during oscillatory testing, is indicated by δ, and the storage modulus and loss modulus are defined respectively as:

$$\text{Storage modulus} = G'(\omega, T) = |G^*(\omega, T)| \cos \delta \qquad \text{Equation A.1}$$

$$\text{Loss modulus} = G''(\omega, T) = |G^*(\omega, T)| \sin \delta \qquad \text{Equation A.2}$$

To obtain an accurate master curve at 25°C, measured values of $|G^*(\omega, T)|$ must be multiplied by a factor:

$$F(T,25) = \frac{298.15 \ \rho_{25}}{(T + 273.15)\ \rho_T} \qquad \text{Equation A.3}$$

where:

ρ_{25} and ρ_T are the densities of the material at 25°C and T°C respectively (Ferry 1980).

The ASTM specification for expansion of bituminous materials (ASTM D4311-04) provides formulae that can be used to calculate bitumen density at any temperature given the density at 15°C. New Zealand bitumens fall into the class for which the density at 15°C is greater than 965 kg/m³, and accordingly the appropriate formula is:

$$\rho_T = \rho_{15}\,(1.0094684142 - 6.33413410744 \times 10^{-4}\,T + 1.45710416212 \times 10^{-7}\,T^2) \qquad \text{Equation A.4}$$

Thus:

$$\rho_{25} = \rho_{15} \times 0.993724 \qquad \text{Equation A.5}$$

Inserting expressions from Equations A.4 and A.5 into Equation A.3 provides an expression for F(T,25) that does not require density measurements for the particular bitumen. Table A.1 lists values of F(T,25) at 5°C intervals for the temperatures at which measurements are usually carried out.

Table A.1 Values of Modulus Temperature Adjustment Factor F(T, 25).

T(°C)	F(T,25)	T(°C)	F(T,25)
0	1.074501	40	0.961152
5	1.058503	45	0.949040
10	1.043083	50	0.937315
15	1.028210	55	0.925959
20	1.013858	60	0.914955
25	1.000000	65	0.904288
30	0.986611	70	0.893943
35	0.973669	75	0.883906

To obtain the master curve at 25°C, the values of $\log_{10}|G^*(\omega, 25)|$ are held steady and the adjusted values $\log_{10}|G^*(\omega, T)|$ are shifted along the $\log_{10}\omega$ axis by amounts $\log_{10} a_T$ to form a smooth curve[1]. This curve can be closely fitted, using nonlinear regression techniques, to an equation of the form:

$$|G^*(\omega, 25)| = \frac{G_\infty(25)}{\left[1 + \left(\frac{\omega_c}{\omega}\right)^v\right]^{\frac{w}{v}}} \qquad \text{Equation A.6}$$

where:

$G_\infty(25)$, the fitted value	represents the limiting value of the 25°C shear modulus at the high frequency limits
ω_c , v and w	are fitting constants of no particular physical significance

(Marastaneau & Anderson 1999, 2000)

The relationship of $\log_{10} a_T$ to temperature T can be described closely by a Williams Landel Ferry (WLF) equation of the form:

$$\log_{10} a_T = \frac{A_{25}(25 - T_S)}{B_{25} + (25 - T_S)} - \frac{A_T(T - T_S)}{B_T + (T - T_S)} \qquad \text{Equation A.7}$$

where:

T_S = a constant (the 'characteristic temperature' of the binder)
A_T = 8.86 for $T_S < T$, and 12.5 otherwise (similarly for A_{25}, with T = 25)
B_T = 101.6 for $T_S < T$, and 142.5 otherwise (similarly for B_{25}, with T = 25)

(Dobson 1969)

The larger the value of T_S, the more sensitive the binder is to temperature change.

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[1] Strictly speaking, the standard approach is to prepare master curves for the storage (G') and loss (G") moduli separately and to compare the shift factors a_T for the two curves. If the shift factors are essentially equal, the method for preparing the master curves is validated. In this work, the results were validated by plotting G' and G" using the shift factors obtained for |G*| (log – log scale), and essentially smooth curves were obtained.

The limiting viscosity at very low shear rates, $\eta_0(25)$, is defined as:

$$\eta_0(25) = \lim_{\omega \to 0} \frac{G''(\omega, 25)}{\omega} \qquad \text{Equation A.8}$$

and is estimated from the data as:

$$\eta_0(25) \cong \frac{G''(\breve{\omega}, 25)}{\breve{\omega}} \qquad \text{Equation A.9}$$

where:

$\breve{\omega}$ is the lowest angular frequency in the 25°C master curve data.

A2. Master curve and limiting viscosity at temperature T°C

Conversion equations from values at 25 °C are:

$$\log_{10} |G^*(T, \omega)| = \log_{10}|G^*(25, \omega a_T)| - \log_{10} F(T,25) \qquad \text{Equation A.10}$$

(similarly for G'(T, ω) and G"(T, ω)) and

$$\eta_0(T) = \frac{a_T}{F(T)} \eta_0(25) \qquad \text{Equation A.11}$$

Appendix B Examination of the Pukepapa chipsealing trial

Since three of the four trial sections at this Pukepapa site stripped at the beginning of the first winter, a review of all information available about the trial was conducted to see if any explanation for the stripping could be developed.

B1. Trial details

Details of the trial sections are indicated in Table B.1.
All sections were sealed with Grade 3 sealing chip, ALD = 9.87 mm.

Table B.1 Pukepapa sealing trial test sections.

Binder	Route Position	Sealing Date	Spray Rate L/m^2
130/150, 3% SBS, 2 pph kerosene, 0.5 pph antistrip	5.220 – 5.424	2/2/01	1.63
130/150, 0.6 pph antistrip	5.424 – 5.714	14/2/01	1.68
180/200, 0.5 pph antistrip	5.714 – 6.008	16/2/01	1.66
80/100, 0.5 pph antistrip	6.008 – 6.297	16/2/01	1.66

The spray rate for the binder containing SBS polymer was slightly less than for the other seals. This binder was sprayed approximately a fortnight before the others, and the high speed survey (21 February 2001) indicated that the surface texture was, at the time of the survey, slightly less on the average than those of the other seals.

Three of the four trial sections were extensively stripped with the first severe frost in late May 2001. The section containing SBS polymer was unaffected.

The youngest seal was approximately 3½ months old at this time. Accordingly, the difference in sealing dates is not great enough to account for the observed differences in chip retention.

B2. Binder adhesion test results

The 130/150 trial polymer blend contained 2 pph kerosene. This would be expected to make it approximately physically equivalent to a 180/200 bitumen without polymer. At 20°C the blend has an initial laboratory-determined bond that is significantly better than the Pukepapa trial 130/150, but not as strong as the 180/200 (see Figure 2.1 in Chapter 2). The laboratory-produced 130/150 adhered significantly faster than the 130/150 used in the road trial. This may be because chip used for testing the laboratory sample adhered better than the chip used at Pukepapa.

Thus the difference in performance of the trial 130/150 polymer blend and the tested 180/200 may be largely due to the different chip used.

B3. Binder shear properties

Dynamic shear rheometer data are listed in Table 2.1 (main report). The master curves at 25°C are shown in Figure 2.3.

The quantity T_S in Table 2.1, called the 'characteristic temperature', is a measurement of how quickly binder rheological properties change with temperature. T_S can be used to transform the master curve for 25°C into one for another temperature. The larger T_S is, the more sensitive the binder is to temperature change.

From Figure 2.3 we can see that the effect of adding polymer plus kerosene to 130/150 has been to produce a product which is quite similar to a standard 180/200 at lower frequencies but which is softer than the 180/200 at higher frequencies. The limiting viscosity of the 130/150 polymer blend is higher than that of a 180/200 at high temperatures, but lower at lower temperatures (Figure 2.4).

At lower temperatures the curves will move to the left (increased $|G^*|$ values at lower frequencies) with the 180/200 curve moving further than the 130/150 curve which will move further than the 130/150 + SBS curve. Thus, although all binders will have higher moduli at low temperatures the *relative* hardnesses will change. The SBS binder will be softer than the 130/150 and 180/200 bitumens at lower temperatures. This may have made it less susceptible to cracking than the other binders when the first frost came.

B4. Textures after first frost

For purposes of comparison, the best trial site is the site at The Wilderness, which also has a single coat seal with a similar chip ALD (9.4 mm, cf. 9.9 mm for Pukepapa). Mean wheelpath textures for the two sites in May 2001 are similar. The textures for the Pukepapa site were measured prior to seal repair at positions where stripping had not occurred. Unfortunately, the texture of the Pukepapa site with polymer binder was not available for direct comparison.

Table B.2 Comparison of seal textures at Pukepapa and The Wilderness sites.

Trial site	Texture Depth mm	V_v/ALD	% Voids Filled
The Wilderness ALD = 9.4 mm			
180/200, 3 pph kerosene	3.52	0.0544	32.3
130/150, 3 pph kerosene	3.06	0.0490	36.4
80/100, 3 pph kerosene	3.22	0.0474	34.7
Pukepapa ALD = 9.9 mm			
180/200	3.31	0.0510	33.4
130/150	3.57	0.0531	32.0
80/100	3.59	0.0538	31.6

There is no evidence of unduly large textures. Sites at The Wilderness would have suffered the lower temperatures more consistently through the winter, and possibly residual kerosene contributed to their chip retention.

B5. Original site condition

Inspection of the high speed data survey textures for 24 February 2000, approximately a year before the commencement of the trial, shows good uniformity on most of the site, with MPD (mean profile depth) values of the order of 2.3 mm in wheelpaths and 2.5 mm between wheelpaths. There was a lower texture section with MPD ~ 1.8 mm on the 180/200 trial section, covering approximately one half of the section length on the decreasing right wheelpath, and with a shorter length (about 1/6 of the section) extending completely across the increasing side of the road. This low texture patch would have had no effect on the stripping that occurred, as all three unmodified bitumen sites stripped with the frost.

B6. Discussion

The sealing was conducted under a P/17 contract, which allows the contractor flexibility in determining seal spray rates. The rates used are not untypical. In any case, the retention of chip on the polymer seal, which had the lowest spray rate, indicated that a low spray rate was not the primary cause of chip loss.

Textures at the time of stripping did not seem to be unduly large compared to similar seals of similar age. No data are available to compare polymer seal texture with other seal textures at the time of seal failure.

The sealing took place in February and normally this would be expected to give adequate time for the seals to bed down before winter.

Given its lower modulus than the other binders at low temperatures, the polymer seal would be expected to be less brittle, and this may account for the chip retention on this seal. It will also have a degree of elasticity which the other seals will lack.

Binder properties may have little effect on how far a chip in a seal moves under heavy traffic stresses, so that the important property of a binder in preventing stripping should be its ability to accommodate a given strain, rather than ability to resist displacement as measured by the binder modulus.

Given the seal performance at the Wilderness trial, it is possible that the presence of retained kerosene in the binder may assist in chip retention in this way, rather than, or even beyond, the accepted mechanism of ensuring good compaction before winter.

Appendix C Field results for texture depth versus equivalent vehicles per lane

C1. Presentation of results

The averaged texture depths T(mean) (including the centreline measurements) and T_1(mean) (wheelpaths and between wheelpaths only) are plotted against the total equivalent vehicles per lane (evl) for each trial section. See Section 3.5 (main report) for formal definitions of *T(mean)* and *T_1(mean)*.

Figures C.1 to C.14 show *T(mean)* points, joined by solid lines, and *T_1(mean)* points, joined by dotted lines, for the four trial sites that were continued.

C2. Kaiwhatiwhati trial site

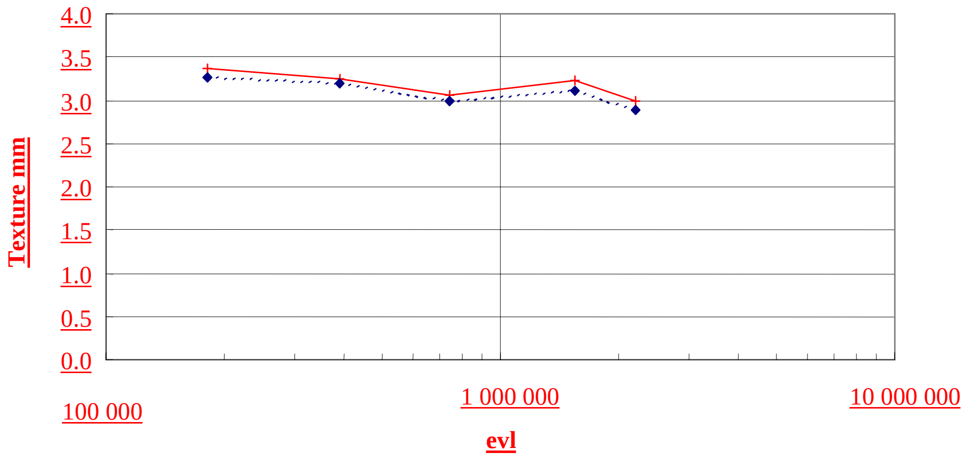

Figure C.1 Kaiwhatiwhati SH38 130/150+2% SBS+2 pph kerosene.

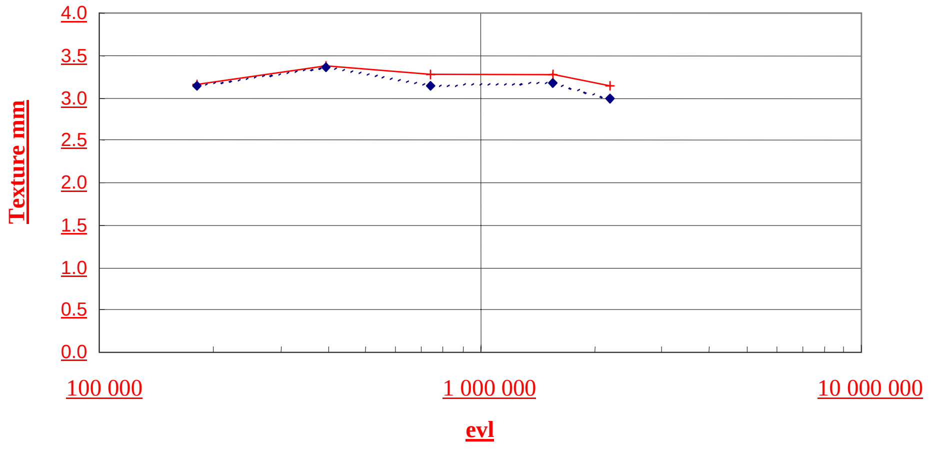

Figure C.2 Kaiwhatiwhati SH38 130/150 + 2 pph kerosene.

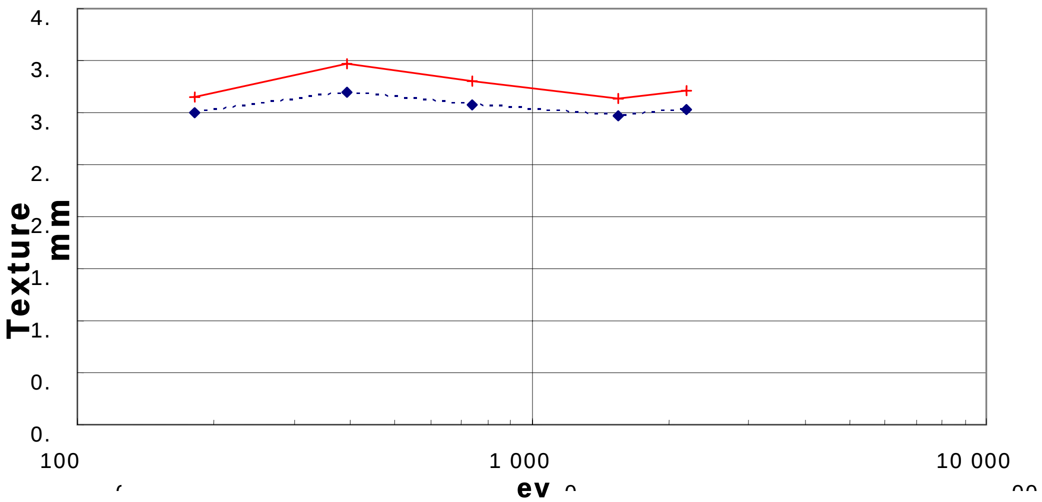

Figure C.3 Kaiwhatiwhati SH38 80/100+4 pph kerosene.

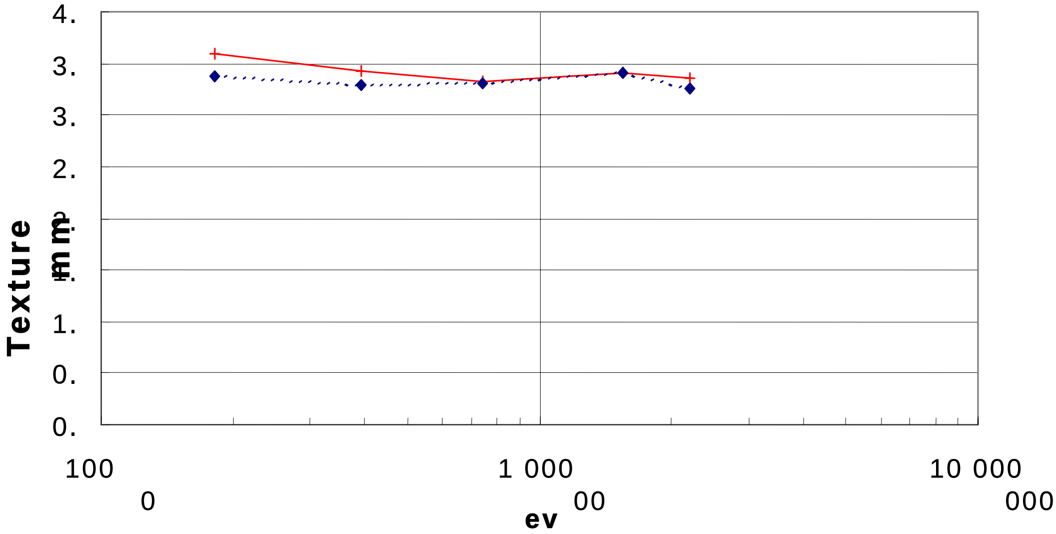

Figure C.4 Kaiwhatiwhati SH38 CRS2(130/150)+2% cutter.

C3. Otakiri trial site

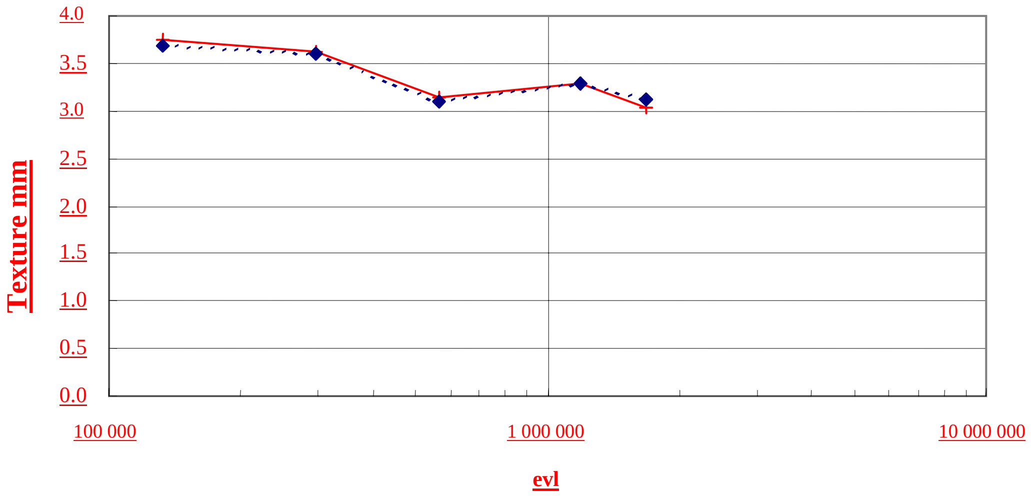

Figure C.5 Otakiri SH34 180/200+1 pph kerosene.

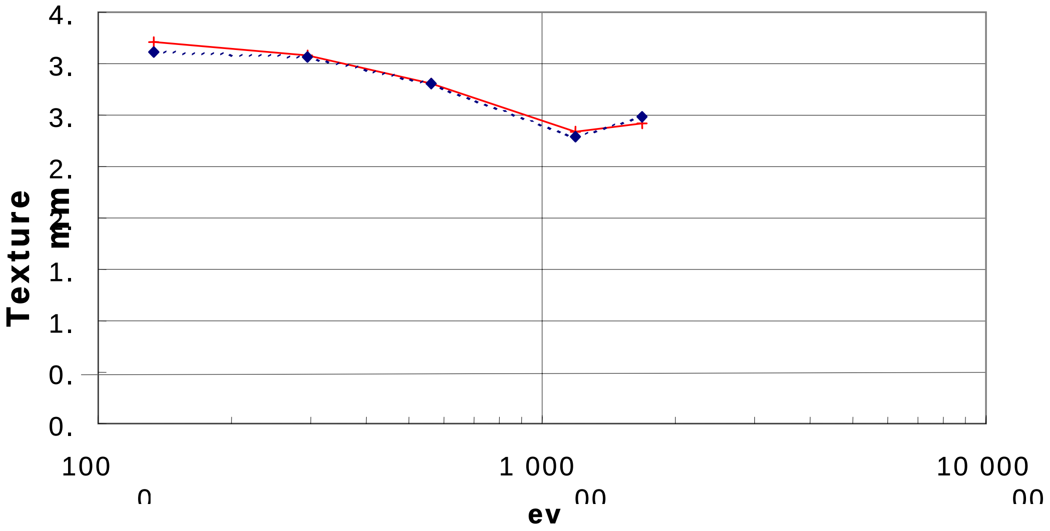

Figure C.6 Otakiri SH34 130/150+3 pph kerosene.

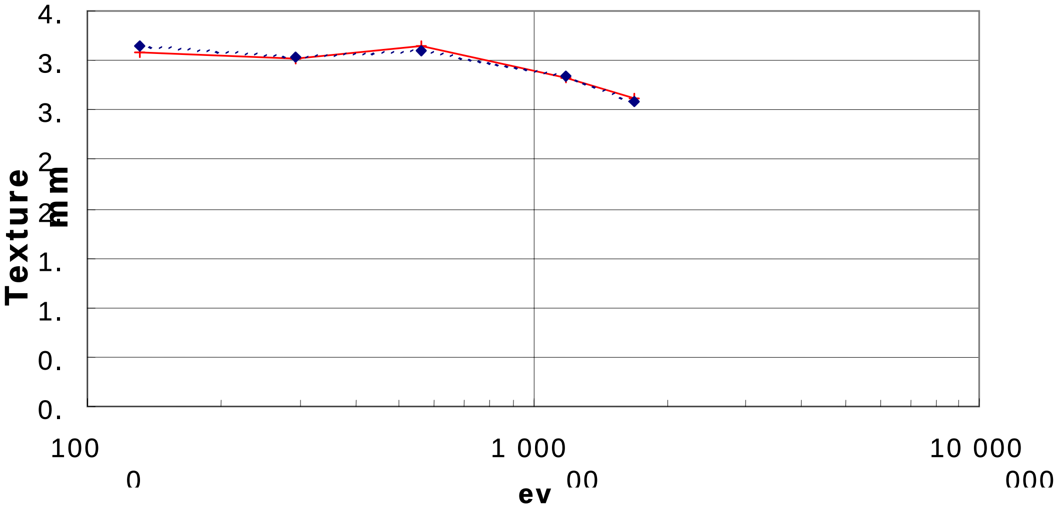

Figure C.7 Otakiri SH34 80/100+5 pph kerosene.

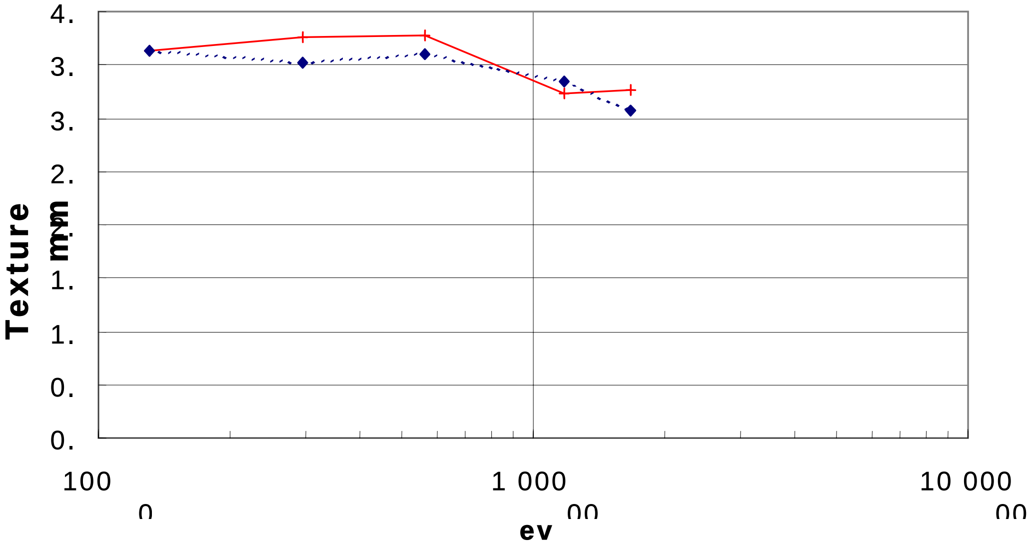

Figure C.8 Otakiri SH34 80/100+3 pph kerosene.

C4. The Wilderness trial site

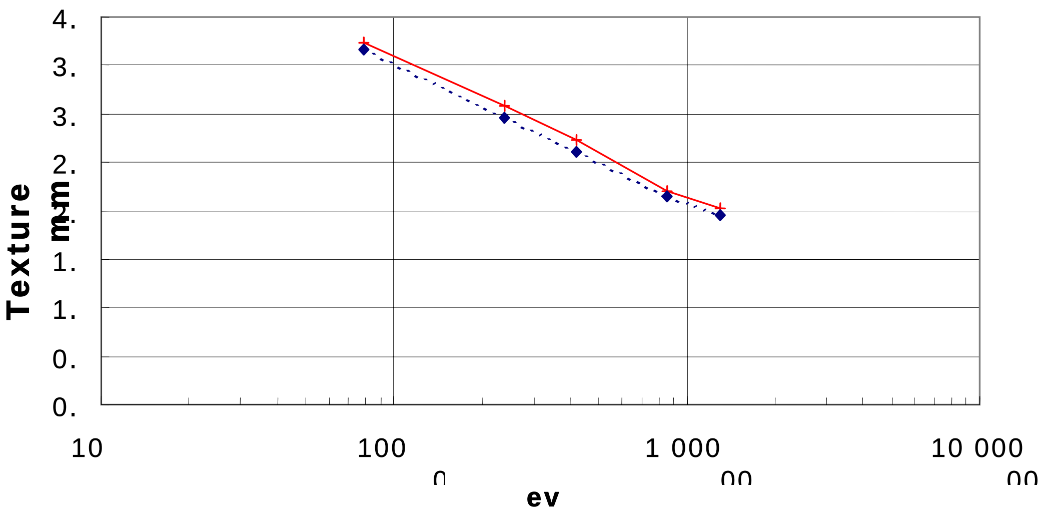

Figure C.9 **The Wilderness SH94 RS 115 180/200+3 pph kerosene.**

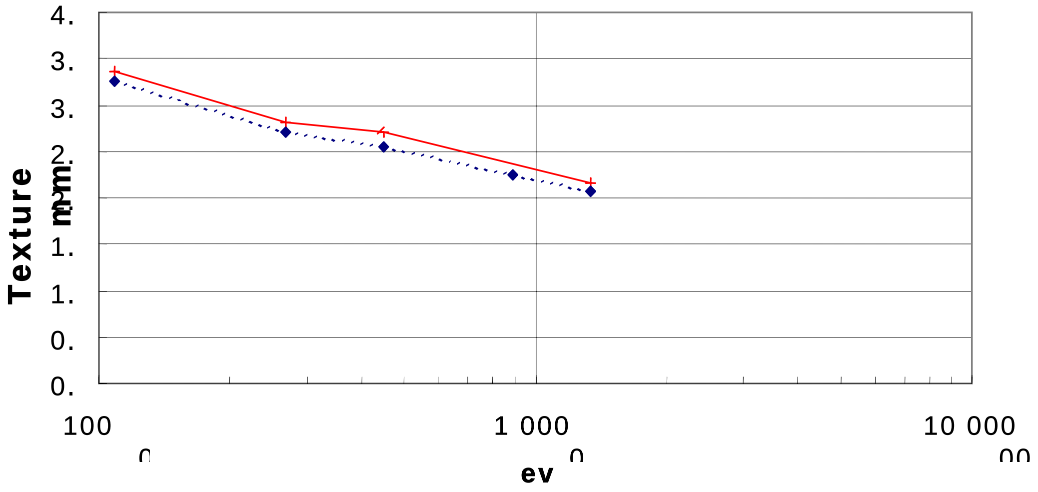

Figure C.10 **The Wilderness SH94 RS 115 130/150+3 pph kerosene.**

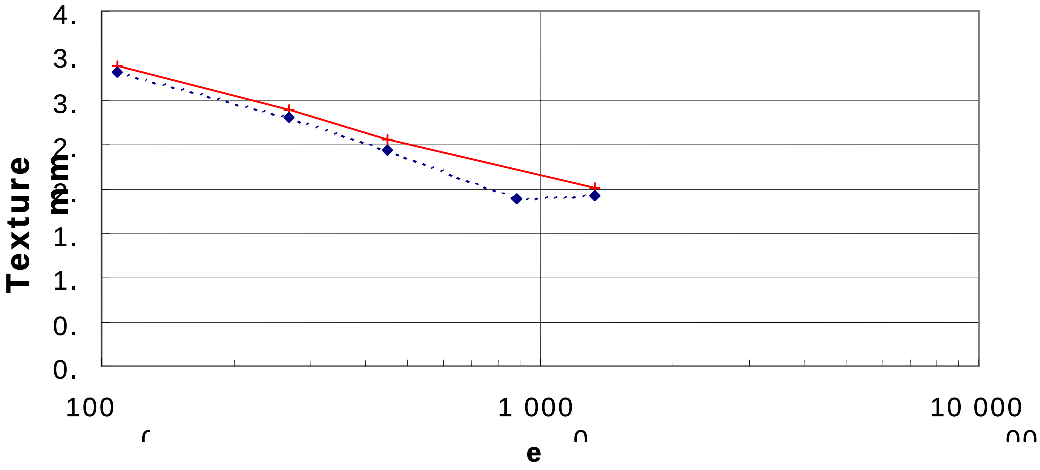

Figure C.11 The Wilderness SH94 RS 115 80/100+3 pph kerosene.

C5. Kingston Crossing trial site

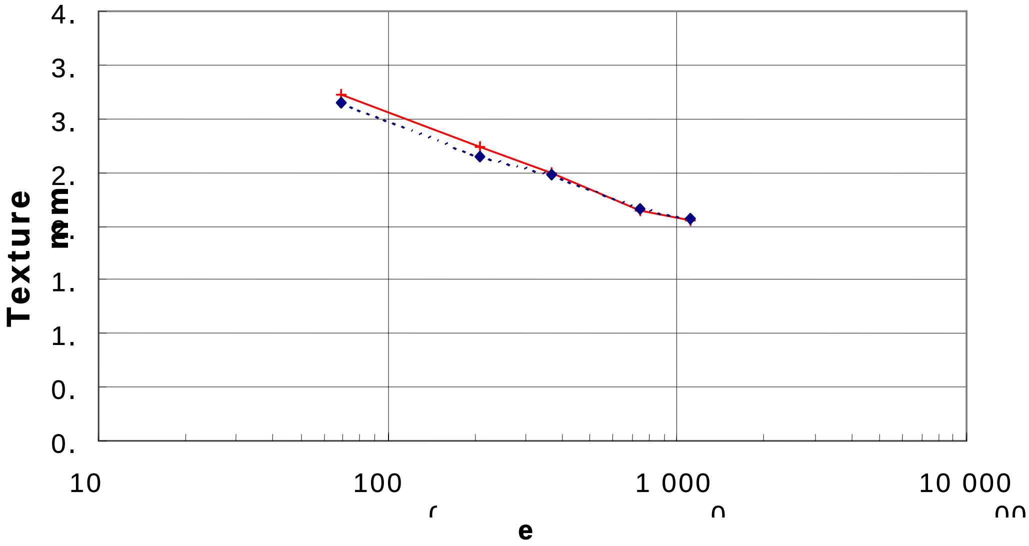

Figure C.12 Kingston Crossing SH94 RS 16 180/200+3 pph kerosene.

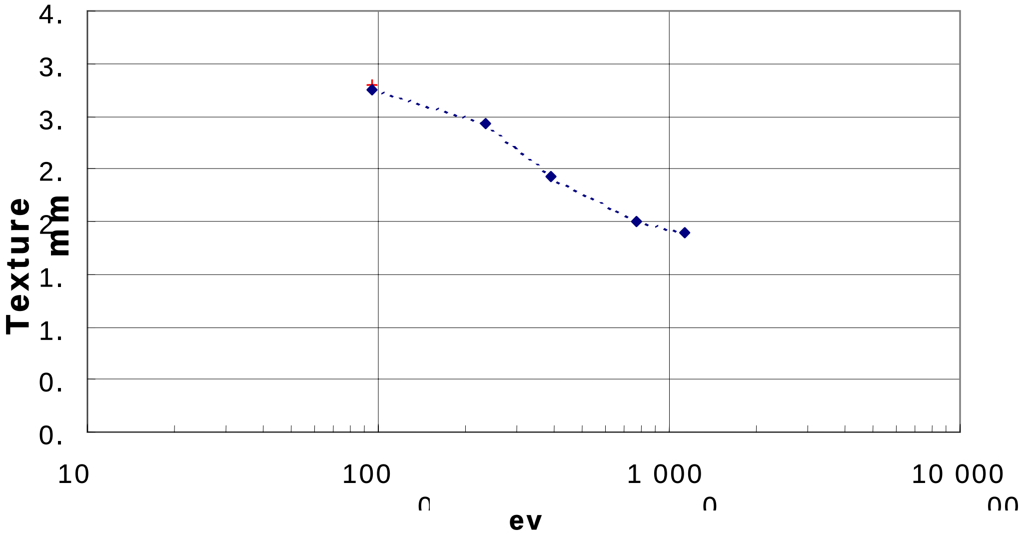

Figure C.13 Kingston Crossing SH94 RS 16 130/150+3 pph kerosene.

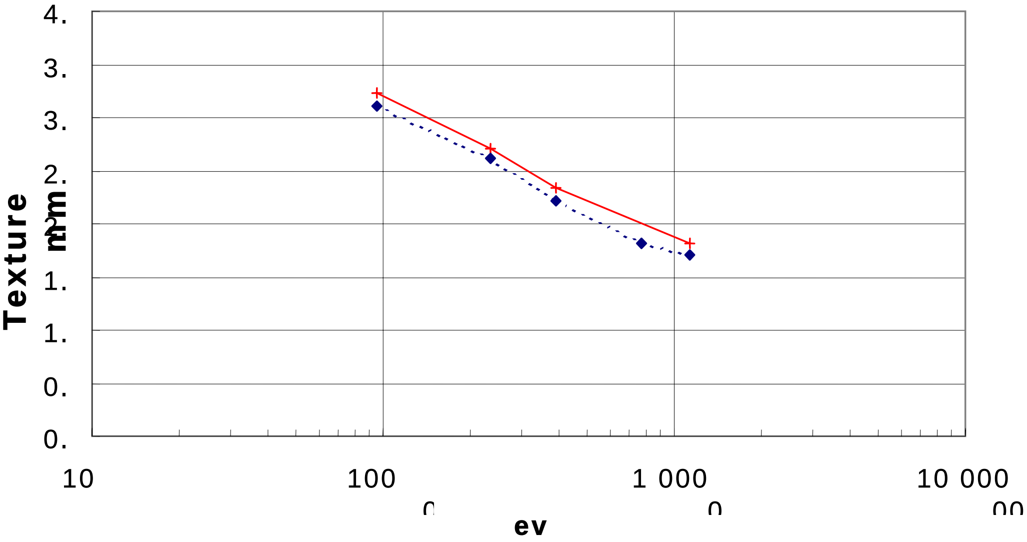

Figure C.14 Kingston Crossing SH94 RS 16 80/100+3 pph kerosene.