Reduced bitumen application rates using bitumen emulsions

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Abbreviations and acronyms

AADT	annual average daily traffic
AAR	aggregate application rate
ACE	apparent cohesive energy
EAR	emulsion application rate
Lm^{-2}	litres per square metre
PMB	polymer-modified bitumen binders
pph	parts per hundred
RAMM	Road Asset and Maintenance Management database
REA	Road Emulsion Association
Transport Agency	New Zealand Transport Agency
w/w	weight for weight

Contents

Executive summary

This NZ Transport Agency research project investigated the possibility of reducing the amount of bitumen (and, *par infra*, cutters such as kerosene) used in chipseal road surfaces if the bitumen is applied as an emulsion rather than as a hot cutback bitumen. The experimental design provided an indirect calculation of the 'apparent cohesive energy' (ACE) of the bitumen layer in sample chipseals. These samples were prepared with two different non polymer-modified bitumen binders (of different viscosities from different suppliers) and the emulsions manufactured from those binders.

Experimental results for the different emulsions (after curing) were compared with each other, with the base bitumen from which each emulsion was prepared, and with those same base binders diluted with kerosene. Two different bitumen emulsions were used and for each two residual bitumen application rates and one cutback dilution rate were investigated. A single aggregate application rate was examined. The swinging pendulum 'knock-off' test directly measured the momentum lost from a pendulum of known momentum as a result of 'knocking off' a tower that was firmly attached to the top of a sample chipseal surface. From this loss of momentum the energy required to dislodge a patch of chip from the seal was observed and used to infer the ACE. The ACE is a function of several variables: bitumen-chip adhesion, chip application rate, binder film thickness and inherent cohesion. The differences in ACE between emulsions, base binders and cutback binders were compared.

The results showed clear, statistically significant, differences in ACE between seals constructed with the emulsions, the base binders and the cutback base binders. For the same residual bitumen application rate the ACE increased in the order: cutback base binder, cured emulsion seals, base binder seals. The preliminary conclusion was that if the ACE value rankings measured were representative of the same binders in the field then it might be possible to apply bitumen emulsions at lower residual bitumen rates than a cutback prepared from the same bitumen (assuming that the emulsified bitumen was not itself cutback).

The difference in ACE value was probably mainly due to the cutback binders having lower viscosities than the emulsified bitumens (even after curing to evaporate the kerosene), rather than any inherent advantage conferred by application as an emulsion. In fact the results suggested that emulsification might actually be disadvantageous for seal performance. The emulsified binders, even after extensive curing, did not reach the strength of the base binders. The implication was that if a given bitumen were to be applied hot (no cutter) or as an emulsion, then the resulting emulsion seal would also be weaker than the hot base-binder version. This would mean that residual bitumen application rates would need to be higher to achieve the same performance.

It must be stressed, however, that the laboratory results can only go so far towards replicating an actual chipseal surface. The overall strength of a real world chipseal is built by more than just the bitumen cohesive energy. Aspects such as stone mosaic interlock also contribute, but the results discussed here isolate and focus on the cohesion within the bitumen film. In summary, the results obtained indicate statistically significant differences in the bitumen cohesive energy component of laboratory-produced chipseal samples when the bitumen is applied in different forms (cutback, emulsion, base binder).

Abstract

This research project investigated the differences in cohesive energies of model chipseal samples prepared from bitumen emulsions, the base binders, and the kerosene cutback base binder. The aim was to determine if it was possible to construct chipseals by using a lower residual bitumen application rate whilst still retaining adequate performance. Analysis of the NZTA RAMM (Road Asset and Maintenance Management) database indicated that chipseals are indeed being prepared using emulsions at lower residual bitumen application rates than cutback binders. But also that emulsion seals have neither yet seen sufficiently long service, nor in sufficient numbers, to determine any differences in lifetimes compared with cutback seals. Laboratory results from Opus Research, Petone 2014 have indicated that cohesive energies of the bitumen layer in single layer chipseals prepared from cutback binders are lower than those prepared from emulsions of the same base binder, which are lower than those prepared from the base binders themselves. The suggestion, based on the balance of the data, is that viable chipseals may well be possible at lower bitumen application rates when applied as emulsions (provided the emulsified bitumen was not itself cutback).

1 Introduction

This NZ Transport Agency (the Transport Agency) research project investigated the possibility of reducing the amount of bitumen (and, *par infra*, cutters such as kerosene) used in chipseal road surfaces if the bitumen was applied as an emulsion rather than as a hot cutback bitumen. The experimental design provided an indirect measurement of the ‘apparent cohesive energy’ (ACE) of the bitumen layer in model single layer chipseals. These samples were prepared with two different non polymer-modified bitumen binders (of different viscosities from two different local suppliers) and the emulsions and cutbacks formed from those binders.

Experimental results for the base binders, the emulsions, and the kerosene cutbacks prepared from the two binders were all compared with each other. One cutback dilution rate, one aggregate application rate (AAR) and two residual bitumen application rates were investigated.

The Opus Research swinging pendulum ‘knock-off’ test (derived from the Vialit pendulum bitumen cohesive energy test, hereafter the ‘ACE test’) directly measured the momentum lost by a pendulum of known mass as a result of ‘knocking off’ a tower that was firmly attached to the top of a laboratory prepared sample chipseal surface. The momentum lost by the pendulum is considered to be equal to (other losses are considered to be negligible) the cohesive energy of the bitumen film. The ACE is a function of several variables: bitumen-chip adhesion, chip application rate, film thickness and inherent cohesion. The differences in ACE between emulsions, the base binders and the cutback base binders were compared. The results showed there were clear, statistically significant, differences in the ACEs of cutback, emulsified and base binders.

The research aimed to understand if and how chipseal performance might be affected if residual bitumen application rates were reduced when using emulsions. If a reduction in emulsion application rates (EARs) could be achieved while at the same time maintaining performance of model chipseal samples, then it might be possible to infer a reduction in overall construction costs.

2 Literature review

2.1 Bitumen emulsion application rates in chipseals

Chipseal road surfacing in New Zealand is generally done using hot ‘cutback’ bitumens of various grades. The sealing chips are very often greywacke, but this depends on the geology of particular regions, with basalts being used in the Auckland region, for example. While emulsion sealing has been used in New Zealand for more than 40 years, the use of emulsions has been gaining more traction over the past 20 years. Proponents of emulsion sealing suggest a number of important economic, safety and environmental advantages over cutback bitumen sealing in addition to potential performance advantages[1]. However, regardless of the documentation of emulsion use in New Zealand for the past 20–40 years, analysis of the NZ Transport Agency (the Transport Agency) RAMM database (see chapter 3) indicates that the number of road surfaces in New Zealand constructed using emulsions is only 10% of those made using cutback bitumens. Furthermore, while the quantitative data on emulsion seals from the RAMM database is scant beyond 10 years ago, it does indicate that the use of emulsions is increasing.

It is generally considered that emulsification of bitumen is simply another method for the delivery of the bitumen. Theoretically at least, after the emulsion has ‘broken’, and the water has left the emulsion, the residual bitumen that remains should be fundamentally the same as the bitumen prior to emulsification. Few researchers, however, discuss the fact that the emulsifier and other non-volatile additives are likely to remain in the bitumen and may either disrupt or enhance the bitumen chemistry. In many countries, especially in Europe, bitumen in the form of emulsions has been used for many years. Indeed, in the United Kingdom for example, availability of cutback bitumen for use on road surfaces is very restricted. Surface dressing emulsions in the United Kingdom are designed around the specification EN13808 and Road Note 39 (Roberts and Nicholls 2008). Early emulsions contained up to 70% residual bitumen but recent products using polymer-modified bitumen binders (PMBs) are raising the contents above 70%. Most emulsions applied in roading contexts are cationic emulsions.

The text, *Chipsealing in New Zealand* (Transit NZ et al 2005, p327) outlines the various details that can be manipulated in the design of a chipseal. While no absolute values are provided for application rates, the design guide for hot cutback bitumen application rates is given in chapter 11 of that text (Transit NZ et al 2005, p415). The textbook does not raise the question of differential emulsion-cutback residual bitumen application rates. The implicit assumption is that once the water has evaporated, the emulsion seal is essentially the same as a hot cutback (once all the kerosene has evaporated). Ball studied the implications of increasing emulsion use in New Zealand (Ball 1995). It was noted that a significant proportion of emulsions was polymer modified, but also that contractors continued to dilute or cut back emulsified bitumen with up to 2pph (parts per hundred) kerosene as opposed to typically 3pph kerosene in a hot cutback. The latter observation is relevant to the present study (see below), but the possibility of reducing residual application rates was not mentioned.

A field study on the application of polymer-modified bitumen emulsions (PMEs) in high-stress road areas was undertaken in New Zealand in 1993–95 (Patrick 2000). One of the sites contained a control section at the same residual application rate but this was prepared using 180/200 penetration grade ‘straight bitumen’ (presumably cutback) not polymer-modified bitumen, so the seals are not directly comparable and no direct conclusions on relative performance can be drawn.

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[1] For more information, see the websites of the Asphalt Emulsion Manufacturers Association (AEMA) www.aema.org.uk and Road Science www.roadscience.co.nz

At the same time another field trial was carried out in the 1993/94 season looking at the performance of two bitumen emulsions, which would now be considered to be low bitumen contents (60% and 68%), compared with cutback 180/200 penetration grade bitumen. In this trial the roads were low-stress, straight rural roads and the residual bitumen emulsion application rates (EARs) were varied by up to ±0.3 Lm^{-2} from the original design value. The cutback control (4pph kerosene) sections were constructed at the design application rate for the site. Presumably the 180/200 grade emulsified bitumen did not contain kerosene although this was not stated explicitly (and was a common practice at the time). Chipseals with Grade 5 aggregates were constructed using both emulsions, while a Grade 4 seal was prepared with only the 68% emulsion. The control sections were prepared with both grade chips and with design residual application rates of 1.4Lm^{-2} and 0.96Lm^{-2} respectively. Of the four emulsion sites with below design residual application rates, three had lost significant amounts of chip and had had to be resealed after the first winter. The conclusion was drawn that the design application rates were appropriate. This trial would suggest strongly that lower residual bitumen application rates for emulsified binders is not possible. However, as mentioned above, it is not clear whether the emulsified bitumen contained kerosene or not, ie whether the two binders were exactly comparable.

Gransberg (2009) analysed a large study from Texas that compared hot asphalt cement (which in this case refers to hot bitumen binder, not a complete asphalt, although no comment on cutting was made) and emulsion chipseal binder performance. A single application rate was used for both binder types of 1.8Lm^{-2} with a Grade 3 chip, except that with the hot binder the chips were pre-coated, and a single AAR of 1m^{3}121m^{-2}. The change in surface texture of the chipseal roads was measured using the Transit NZ T/3 ‘sand circle’ test. Overall the results suggested that chipseal surfaces prepared with the emulsion lost their texture at a lower rate than the hot-bitumen sealed roads. No comment on different application rates or performance of cutback bitumens was made. Incidentally, this paper also offered an economic analysis that suggested emulsion chipseals were more cost effective for maintaining macrotexture over time (Gransberg 2009).

In an analysis of the ASTM D7000 chipseal sweep test for chip loss, Johannes et al (2011) investigated the sensitivity of the test to different bitumen EARs and to aggregate gradation. Three different emulsions (cationic CRS-2, anionic HFRS-2, latex anionic HFRS-2L) were tested along with a granite and a limestone aggregate with different gradations. While the study was focused on analysing the ASTM D7000 sweep test itself rather than the performance of chipseals, the chip loss results were found to be somewhat insensitive to the different application rates chosen, which ranged from 1.36 to 3.17Lm^{-2} residual bitumen, depending on the percentage of voids being filled. These results suggest that adequate aggregate chip retention in a given chipseal surface could be achieved within a range of EARs, but comparisons with cutback bitumens were not made.

Attempts have also been made to understand the effects of EAR and AAR on the performance of chipseal surface treatments using the model mobile loading simulator test along with digital image processing (Lee and Kim 2008). The occurrence and extent of chip loss and bitumen bleeding were analysed in a lightweight slate aggregate and a granite aggregate. The work included field trials and ultimately ideal aggregate/emulsion application rate ratios were decided on but comparisons with hot cutback seals were not made.

An extensive analysis of the best practice for chipsealing in the USA was made in 2005 by Gransberg and James (2005). They analysed all aspects of chipsealing practice in the USA and compared it with the practice in New Zealand, Australia and South Africa. However, while cutback and emulsion binders were discussed, no analysis was made to describe the possibilities for successfully using the different binder types at different application rates (Gransberg and James 2005).

2.2 Summary

Internationally the use of hot cutback bitumen for chipsealing is uncommon and the literature provides little insight into comparative emulsion/cutback application rates.

In New Zealand the literature indicates that the use of bitumen emulsions for chipseal surfacing in New Zealand is increasing for a range of reasons, but the effects of differential application rates for emulsion and cutback seals has not been studied or discussed. The only work that enables direct comparison of emulsion seals and cutbacks is Patrick (1998), which reported on field trials in this area. Patrick examined the effect of emulsion residual bitumen application rate in the field and showed that application rates of $0.2Lm^{-2}$ to $0.3Lm^{-2}$ below design values were unacceptable. Failure occurred, whereas a cutback seal (and emulsion seals) at the design application rate did not. This suggests that lower residual application rates for emulsion seals would not be possible without adversely affecting performance. It was not made clear, however, in the report whether the emulsified bitumen was also cutback, which may have been the case and is an important point in light of the findings discussed in chapter 4. It should also be borne in mind that the Patrick study was done over 20 years ago and that emulsion technologies and techniques have developed since that time so that contemporary results may differ.

3 RAMM database analysis

3.1 Introduction

Analysis of the Transport Agency RAMM database was performed to assess the current state of the art with regard to EARs. Several questions were investigated: Are emulsions being applied at lower residual application rates than equivalent cutback bitumens in New Zealand? Are those seals achieving equivalent or longer lives? This objective was analysed in two parts: ‘application rates’ and ‘achieved lives’ based on a set of general sample assumptions documented separately.

3.2 RAMM analysis assumptions

Data for this analysis was extracted from the RAMM database, ‘Entire Network Security Zone’ on 20 September 2013.

The tables extracted from RAMM included:

- surface table: c_surface
- surfaces sectioned by carriageway: surface_structure
- carriageway table: carr_way

The following assumptions were made:

- Regions defined by cway_area in the carriageway table (24 total) were represented by historical contract areas (note these do not align with new network outcome contract regions).
- Only surfaces which had been sectioned by carriageway were included in the analysis. Any surfaces which did not exist in the surface_structure table were excluded. This included a number of older surfaces (pre-2000) for which a reseal date could not be defined.
- Both top surfaces and expired surfaces were included. Expired surfaces: only one layer under was included (layer_no=2).
- Only reseals and second coats were included. First coats and membrane seals were excluded.
- To normalise data, surface life was described as a percentage:
    - achieved life/default life where default lives were based on a simplified RAMM life table.

Table 3.1 Segmentation of surface types/years of service life

Surfacing type	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7
	(<100 vpd)	(100-500vpd)	(500-2,000 vpd)	(2,000–4,000 vpd)	(4,000–10,000 vpd)	(10,000–20,000 vpd)	(>20,000 vpd)
Grade 4	12	10	8	7	6	5	4
Grade 3	14	12	10	9	8	7	6
Grade 2	16	14	12	11	10	9	8
Grade 4/6	14	12	10	9	8	6	4
Grade 3/5	16	14	12	11	10	8	6
Grade 2/4	18	16	14	13	12	10	9

- To normalise the data, the binder application rate was described as a differential (Lm^{-2}): actual – design or percentage differential (%): (actual – design)/design
- Where design was taken from Transit NZ et al (2005) (this design algorithm might, however, not be accepted as the industry standard)

$$(ALD+0.7*Td)*(0.291-0.025*LOG10(AADT/2*(1+0.09*HCV)*100)) \qquad \text{(Equation 3.1)}$$

  - ALD:

Chip grade	ALD
2	11
3	9
4	7

  - Td: avg texture depth at reseal (mm); default 1.2mm
  - AADT: annual average daily traffic
  - HCV: percentage of heavy commercial vehicles
- A positive differential or percentage occurs when actual binder application rate was higher than the design rate.
- All analyses were completed based on sealed area.
- Only certain chipseals, deemed to be applied in ‘normal’ sealing circumstances were included as shown in table 3.2 (highlighted yellow) (JE Patrick, E Beca, pers comms. 2013).Patrick, 2013).

Table 3.2 Surface types

surf_binder	Binder Name
B130	Bitumen 130/150
B180	Bitumen 180/200
B45	Bitumen 45/55
B60	Bitumen 60/70
B80	Bitumen 80/100
E130	Emulsion 130/150
E180	Emulsion 180/200
E80	Emulsion 80/100
EPM	Emulsion Polymer Modified
PMB	Polymer Modified Bitumen
POLY	Polyurethane
UNKN	Unknown

Only cutback bitumen (highlighted green) and bitumen emulsion (highlighted orange) binder types have been included as shown in table 3.3.

Table 3.3 Binder types

aly	Material Name	Count	use
CONC	Concrete	30	n
BOLID	BOLIDT Polyurethane Mix	13	n
COMB	Combination Seal	1	n
TEXT	Texturising Seal	3461	n
LOCK	Locking Coat Seal	96	n
RCHIP	Red Chip Seal (McCullum)	125	n
PSKID	Premium skid surface PSV >70	61	n
OGEM	Open graded emulsion mix	147	n
3CHIP	Blended Chipseal	2	n
CAPE	Capeseal	34	n
VFILL	Void fill seal	7042	n
1CHIP	Single Coat Seal	28343	y
SLRY	Slurry Seal	538	n
OTHER	Other material type	55	n
PSEAL	Prime Coat	53	n
RACK	Racked in Seal	3392	y
SMA	Stone Mastic Asphalt	1869	n
UTA	Ultra Thin Asphalt	42	n
2CHIP	Two Coat Seal	19859	y
OGPA	Open Graded Porous Asphalt	4428	n
OGPAH	High Strength Ogpa	49	n
AC	Asphaltic Concrete	3702	n
B/S	Sandwich Seal	1753	n
BBM	Bitumen Bound Macadam	444	n

Note: 45/55 and 60/70 are not often used as sealing binders

Table 3.4 shows the network level summary of data available (sealed areas). The regions highlighted have been selected as having significant areas of (>10%) emulsion seals for analysis.

Table 3.4 Summary statistics

	Cutback bitumen (000m^2)		Emulsion (000m^2)		% Emulsion	
cway_area	**Layer2**	**Top**	**Layer2**	**Top**	**Layer2**	**Top**
AUCK ALLIANCE	491	248	3	6	1%	2%
BOP EAST	1,911	3,136	39	16	2%	1%
BOP WEST	1,007	1,058	8	0	1%	0%
CENTRAL WAIKATO	2,659	3,999	19	10	1%	0%
COASTAL OTAGO	2,809	1,752	411	3,050	13%	64%
EAST WAIKATO	2,691	3,836	139	134	5%	3%
EAST WANGANUI	2,825	5,009	217	272	7%	5%
GISBORNE	1,414	1,816	20	0	1%	0%
MARLBOROUGH	1,046	1,671	12	16	1%	1%
NAPIER	1,762	2,859	3	49	0%	2%
NELSON	1,598	1,328	231	1,309	13%	50%

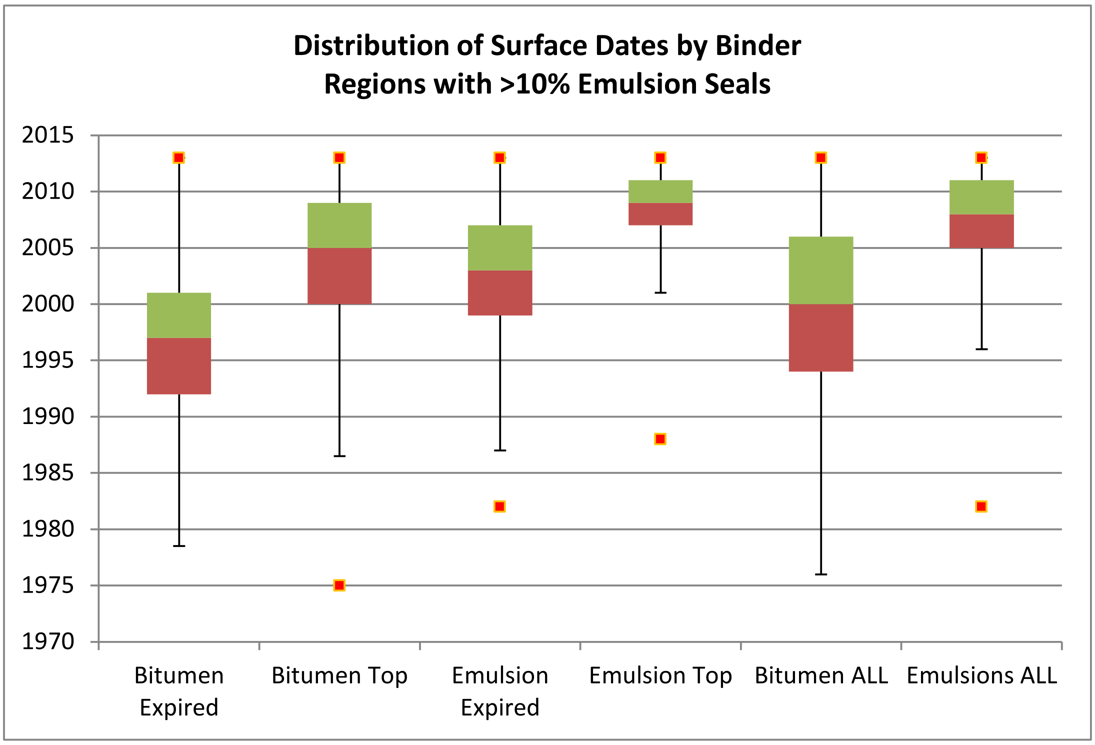
	Cutback bitumen (000m²)		Emulsion (000m²)		% Emulsion	
cway_area	**Layer2**	**Top**	**Layer2**	**Top**	**Layer2**	**Top**
NORTHLAND	2,548	4,671	64	191	2%	4%
NTH CANTERBURY	503	1,829	43	1,685	8%	48%
OTAGO CENTRAL	2,781	2,297	79	1,803	3%	44%
PSMC 005	535	928	19	40	3%	4%
PSMC 006	1,222	2,896	62	30	5%	1%
ROTORUA DIST	1,595	2,072	49	37	3%	2%
SOUTHLAND	2,704	3,544	123	1,300	4%	27%
STH CANTERBURY	1713	841	249	2149	13%	72%
TAURANGA CITY	344	279	0	44	0%	14%
WELLINGTON	1157	1202	26	30	2%	2%
WEST COAST	3289	3845	0	7	0%	0%
WEST WAIKATO	1711	1968	100	60	5%	3%
WEST WANGANUI	2707	5921	394	593	13%	9%

3.3 Preliminary analysis

Can emulsions be applied at lower application rates than equivalent cutback bitumen and achieve equivalent or longer lives?

Although emulsions have been used in New Zealand for longer, it appears from this analysis that robust RAMM data on emulsion use extends back only approximately 10 years. Therefore, this analysis has studied seals applied over the past 10 years only, notwithstanding that emulsions were being used much earlier. The two following box and whisker charts show the distribution of seals split by emulsion and cutback bitumen, and top surface and expired surface for the regions highlighted in table 3.4. Figure 3.1 shows the distribution of surfacing year and figure 3.2 shows the percentage of life achieved. Collectively these charts suggest we do not have sufficient data to answer the question posed above. Note: These charts are based on the number of surfaces (not length or area sealed).

Figure 3.1 Distribution of surface year

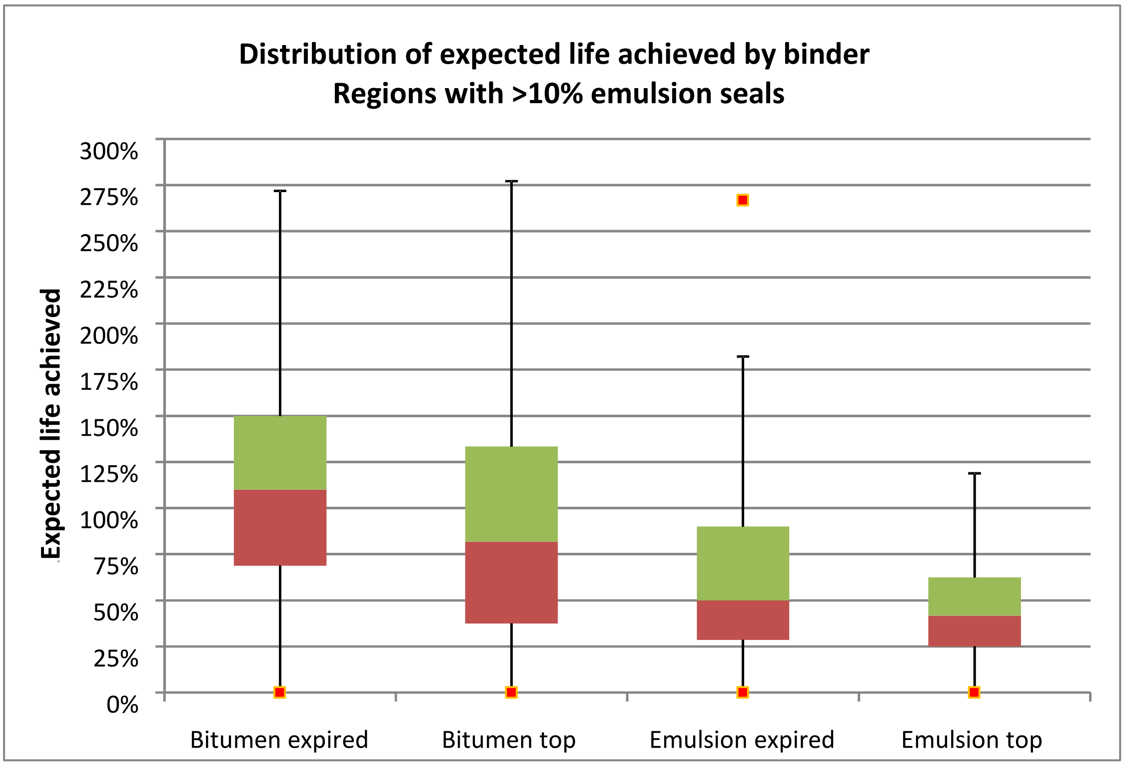


The two right-hand elements in figure 3.1 show the full set (top and expired) of cutback bitumen and emulsion surfaces; the 'box' which represents 25% through 75% of the emulsion distribution sits on top of the cutback bitumen 'box'. This confirms that these two distributions are not comparable. The distribution of expired emulsions by surface year is more closely aligned to top surface cutback bitumen than to expired surfaces.

To compare application rates of cutback bitumen and emulsion seals with their achieved lives, we must analyse the expired surface sets. Again, the expired emulsion box sits on top of the expired cutback bitumen box with 75% of the expired cutback bitumen seals surfaced by 2000 compared with only 25% of expired emulsion seals.

The expired emulsions have on average achieved only 50% of their expected service life (figure 3.2) compared with 100% of the cutback bitumens achieving their expected service life. However, the distributions of the top surface and expired emulsions are quite similar suggesting that the emulsions which have already expired will make up the subset of early failures of a distribution which is yet to develop completely and therefore requires more time to be established.

Figure 3.2 Distribution of life achieved



While it has been shown that the cutback bitumen dataset is not directly comparable to the emulsion dataset, we remain able to examine the application rates within each subset. As described in the assumptions, to allow comparison between different surface types, chip sizes and traffic bands we represent the binder application rate as a percentage differential away from the chosen 'design' application rate. A positive percentage indicates more binder has been applied than the design calculation, while with a negative value, less binder has been applied.

Figure 3.3 Cutback bitumen: % difference in actual and design application rates by % life achieved bins. Expired surfaces only

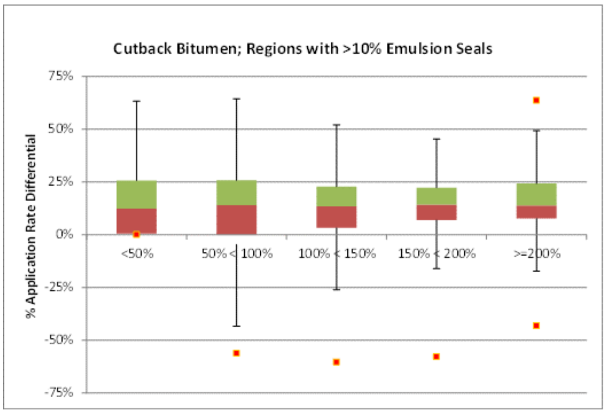
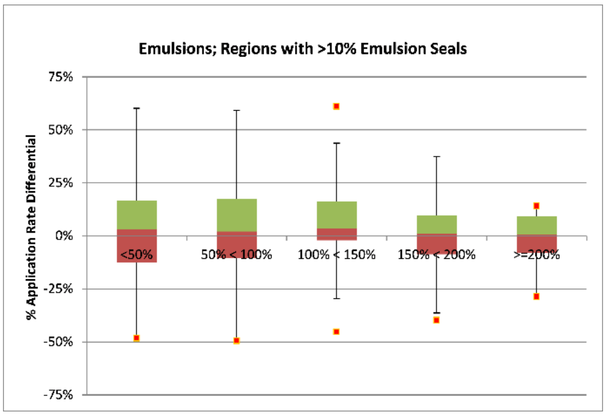
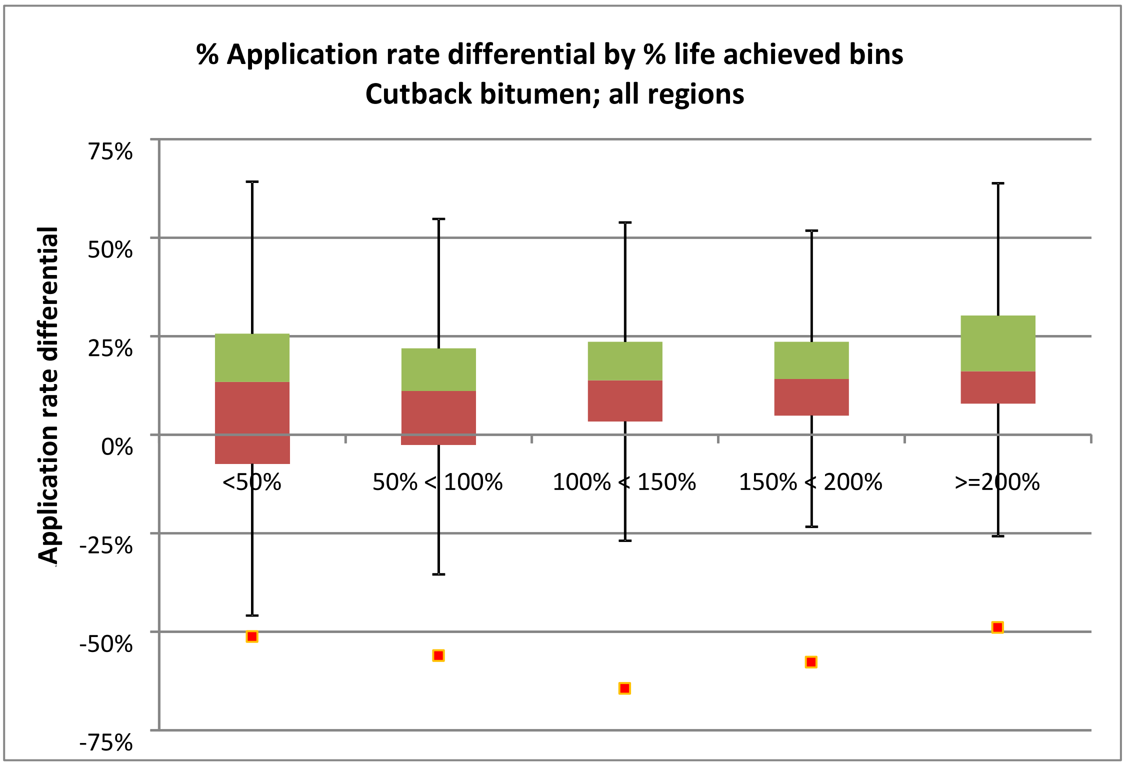


Figure 3.4 Emulsions: % difference in actual and design application rates by % life achieved bins. Expired surfaces only



Figures 3.3 and 3.4 are subsets of the full dataset, including only expired surfaces in regions with significant emulsion seals (>10% by area). Over 75% of the cutback bitumen seals (figure 3.3) within this subset had a higher application rate than the 'recommended' design – on average approximately 15% higher. The trend shows that seals achieving longer lives (figure 3.3 moving left to right) have application rates higher than the chosen design value.

Figure 3.5 Cutback bitumen all regions. % difference between actual and design application rates by % achieved life bins. Expired surfaces only



The distribution for emulsions (figure 3.4) is lower than cutback bitumen seals with the average binder application rate aligning with design rate (0%). While figure 3.5 suggests that emulsions on expired surfaces have indeed been applied at lower rates than both cutback bitumen seals and the chosen design value, figure 3.2 shows that less than 25% of these surfaces achieved their expected life. As suggested earlier, given the short period of time that emulsions have been used on the New Zealand network we are not able to draw any firm conclusions from this data, only highlight the current trend it displays.

The trend derived from the 'fully expired cutback bitumen' dataset suggests that increasing binder application rate has increased the 'life achieved', ie the surface lifetime, and of course the converse could well be true.

3.3.1 How does the cutback bitumen application rate compare with the emulsion application rate?

A number of further assumptions were made to define the sample to ensure directly comparable analyses. These assumptions included:

- Group the samples by the same surface type, chip size and traffic loading.
- Sample regions with >10% emulsions as defined in table 3.4.

- Use top surfaces only.
- Make an approximate estimate of traffic by pavement use bands (1 through 7). Traffic loadings below 100 AADT and over 20,000 AADT have been excluded due to very low sample (band 1 and 7).
- Remove polymer-modified binders (both cutback and emulsion) as these are not typically applied in ‘normal’ (JE Patrick, E Beca, pers comms 2013) sealing circumstances. As shown in figures 3.6 and 3.7 below, within the sample regions the majority of emulsions (47%) are polymer modified particularly North and South Canterbury thus reducing the sample size significantly. Coastal and Central Otago and Nelson are the only three regions applying a majority of emulsions without polymer modification. Note: All seals in the sample regions that are not polymer modified have been included in the sample.
- Remove minor seal types: single coat GD2, GD3 and GD4 which collectively make up less than 10% of the emulsion sample. Combine RACK and 2CHIP grouped by largest chip size.

Figure 3.6 Cutback bitumen binder types: sample regions, top surface (7% polymer modified)

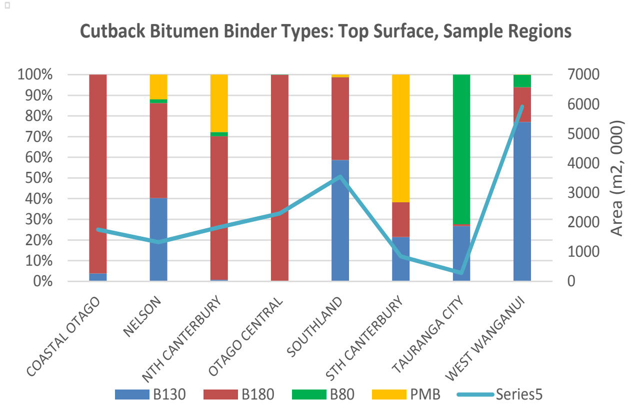


Figure 3.7 Emulsion binder types: sample regions, top surface (47% polymer modified)

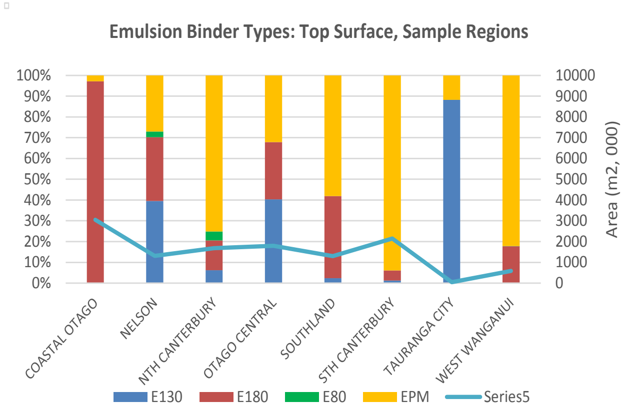


Figure 3.8 Cutback bitumen surface type/chip size: sample regions, top surface

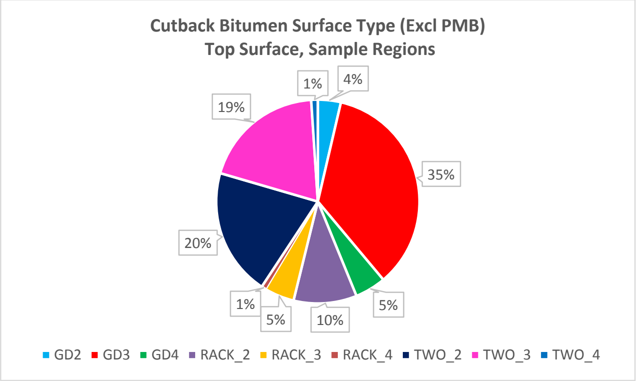
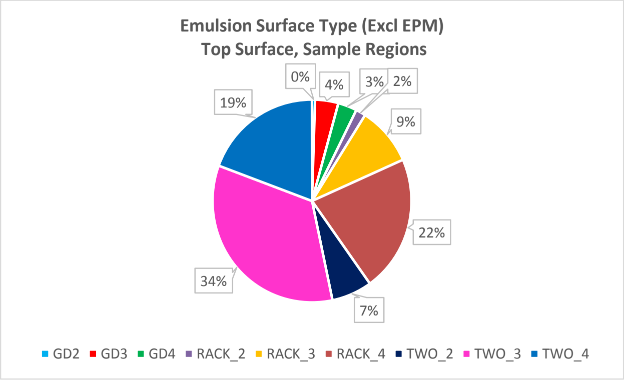


Figure 3.9 Emulsion surface type/chip size: sample regions, top surface



For each surface within the sample, the actual application rate was subtracted from the design application rate with data grouped by traffic band, largest chip size and binder (cutback bitumen and emulsion). The distribution of application rate differentials was compared with 25th, 50th and 75th percentiles shown in table 3.5. The yellow highlighted groups have very small sample numbers.

There is a range of design application rates within each sample group due to the relatively wide traffic bands and the inclusion of %HCV in the calculation. These ranges are all under 0.2Lm^{-2}.

The difference % design column provides an indication of the magnitude of values as a percentage rather than application rate (Lm^{-2}) calculated only for the 50th percentile. It was calculated for each sample group as the difference/average design application rate.

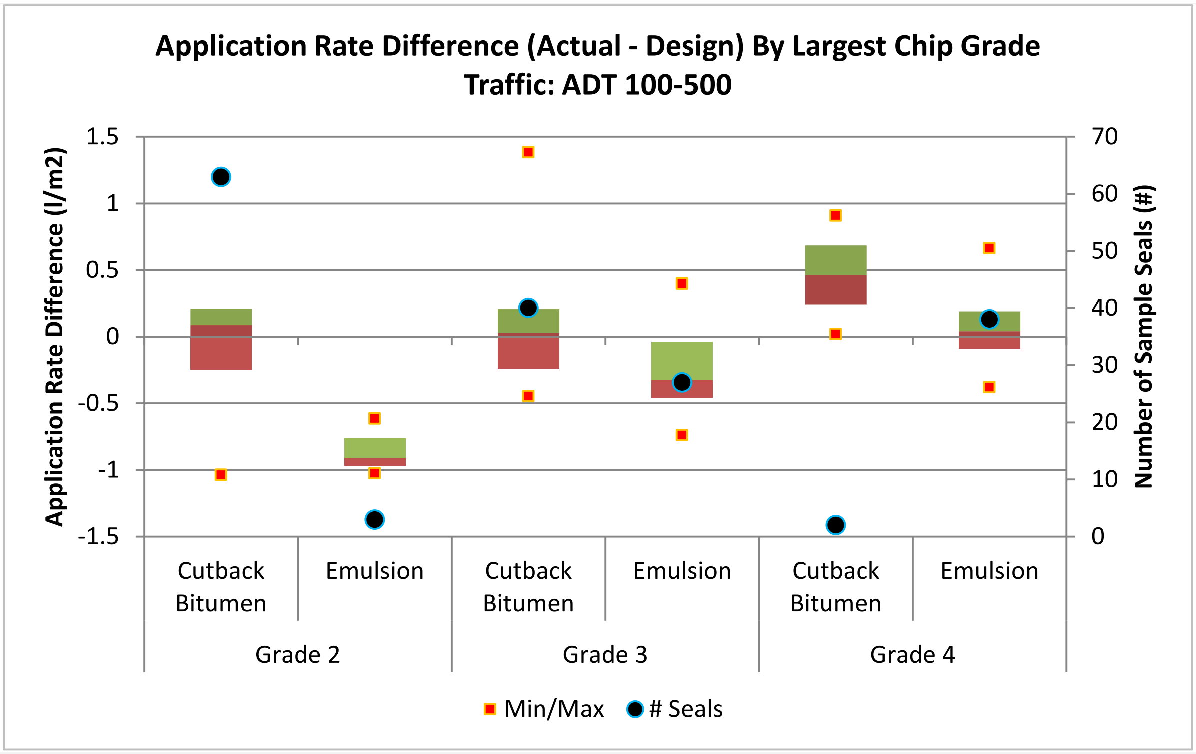
Table 3.5 Application rate differentials (actual – design) (Lm^{-2}) for the defined sample split by traffic band and chip size

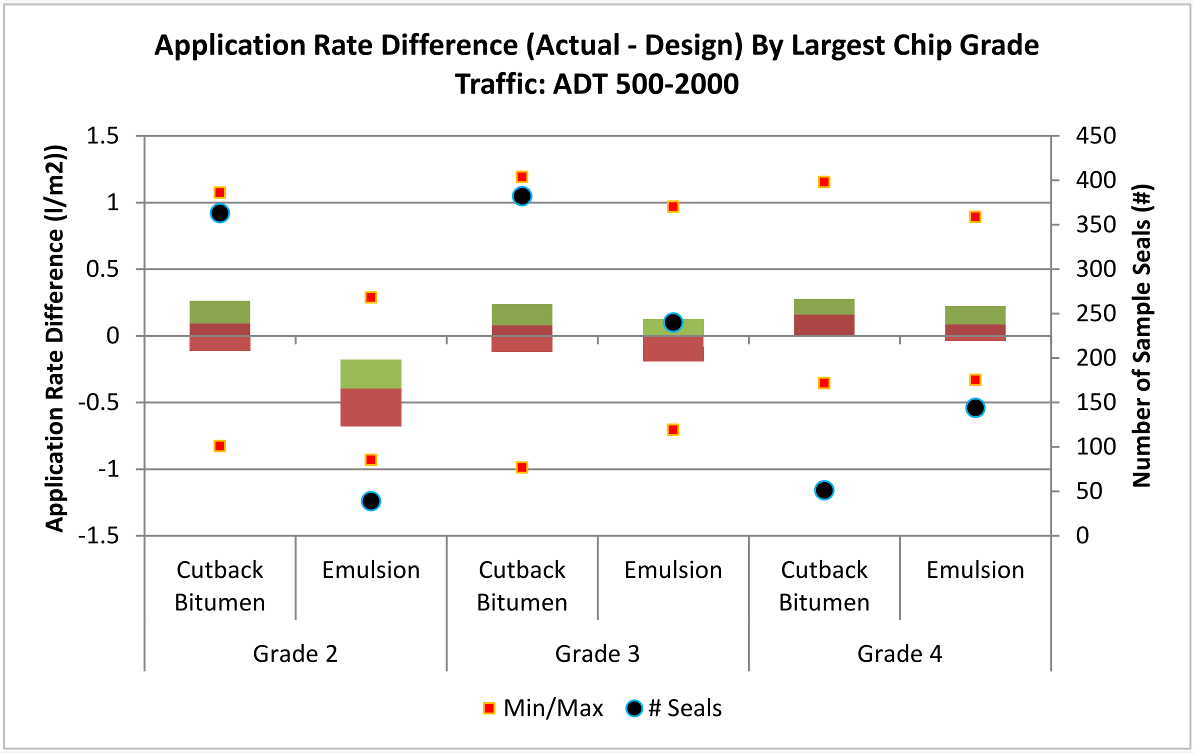
		Count		25th Percentile			50th Percentile				75th Percentile			Inter Quartile Range			Design Rate Range	
Traffic Band	**Chip Grade**	**Cutback Bitumen**	**Emulsion**	**Cutback Bitumen**	**Emulsion**	**Difference**	**Cutback Bitumen**	**Emulsion**	**Difference**	**Difference % Design**	**Cutback Bitumen**	**Emulsion**	**Difference**	**Cutback Bitumen**	**Emulsion**	**Difference**	**Cutback Bitumen**	**Emulsion**
ADT 100-500	Grade 2	63	3	-0.25	-0.97	-0.72	0.09	-0.91	-1.00	**-48%**	0.21	-0.76	-0.97	0.46	0.21	-0.25	2.05 to 2.24	2.1 to 2.1
	Grade 3	40	27	-0.24	-0.46	-0.22	0.03	-0.33	-0.36	**-21%**	0.21	-0.04	-0.24	0.45	0.42	-0.03	1.7 to 1.86	1.7 to 1.75
	Grade 4	2	38	0.24	-0.09	-0.33	0.46	0.04	-0.42	**-30%**	0.69	0.19	-0.50	0.44	0.28	-0.17	1.38 to 1.38	1.36 to 1.43
ADT 500-2000	Grade 2	363	39	-0.11	-0.68	-0.57	0.09	-0.40	-0.49	**-25%**	0.26	-0.18	-0.44	0.37	0.50	0.13	1.83 to 2.05	1.87 to 2.04
	Grade 3	382	240	-0.12	-0.19	-0.07	0.08	-0.08	-0.16	**-10%**	0.24	0.12	-0.12	0.36	0.31	-0.04	1.52 to 1.71	1.52 to 1.7
	Grade 4	51	144	0.00	-0.04	-0.04	0.16	0.09	-0.07	**-5%**	0.28	0.22	-0.05	0.28	0.26	-0.02	1.23 to 1.35	1.22 to 1.36
ADT 2000-4000	Grade 2	161	16	-0.03	-0.65	-0.63	0.10	-0.29	-0.39	**-22%**	0.27	-0.09	-0.36	0.30	0.56	0.26	1.76 to 1.9	1.77 to 1.84
	Grade 3	197	119	-0.02	-0.09	-0.07	0.15	0.08	-0.07	**-5%**	0.30	0.20	-0.09	0.32	0.29	-0.02	1.47 to 1.58	1.46 to 1.56
	Grade 4	18	125	0.14	0.02	-0.12	0.20	0.16	-0.04	**-3%**	0.38	0.27	-0.11	0.23	0.24	0.01	1.17 to 1.25	1.16 to 1.25
ADT 4000-10000	Grade 2	149	26	0.05	-0.60	-0.65	0.24	-0.27	-0.51	**-29%**	0.42	-0.23	-0.65	0.37	0.37	0.00	1.67 to 1.81	1.68 to 1.78
	Grade 3	177	157	0.12	-0.05	-0.17	0.25	0.08	-0.17	**-12%**	0.34	0.18	-0.16	0.22	0.23	0.01	1.37 to 1.52	1.36 to 1.51
	Grade 4	18	128	0.15	0.02	-0.14	0.29	0.10	-0.19	**-16%**	0.32	0.27	-0.05	0.17	0.26	0.09	1.13 to 1.21	1.1 to 1.2
ADT 10000-20000	Grade 2	27	9	0.19	-0.20	-0.39	0.34	0.10	-0.24	**-15%**	0.44	0.30	-0.14	0.25	0.50	0.25	1.6 to 1.69	1.6 to 1.69
	Grade 3	75	35	0.06	0.02	-0.04	0.23	0.14	-0.09	**-6%**	0.42	0.27	-0.16	0.36	0.24	-0.12	1.32 to 1.43	1.32 to 1.42
	Grade 4	10	21	0.17	0.02	-0.15	0.48	0.14	-0.35	**-31%**	0.93	0.46	-0.48	0.76	0.44	-0.33	1.06 to 1.14	1.08 to 1.13

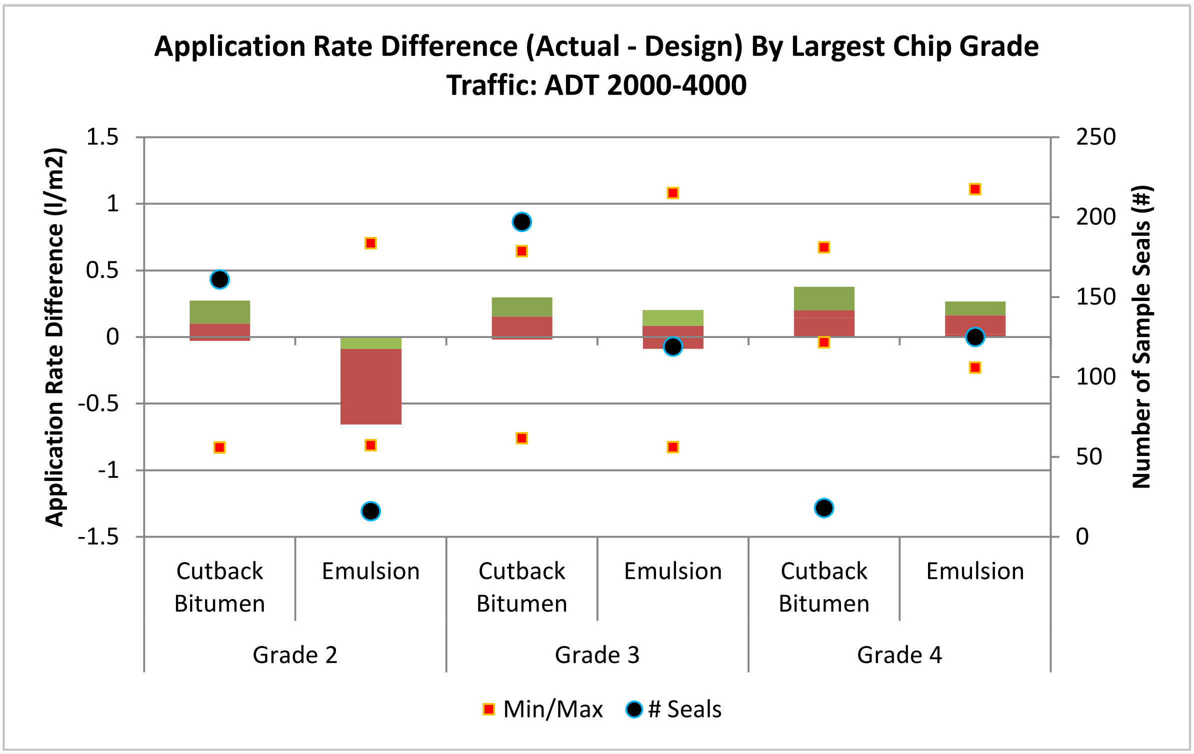
- The data in figure 3.10 suggests emulsions are being applied at lower application rates than corresponding cutback bitumen binders with every sample group showing a negative difference.
- Larger first chip size and lower traffic groups show the greatest differential.
- Across all traffic bands the Grade 2 emulsion sample is small and the Grade 4 cutback bitumen sample is small.

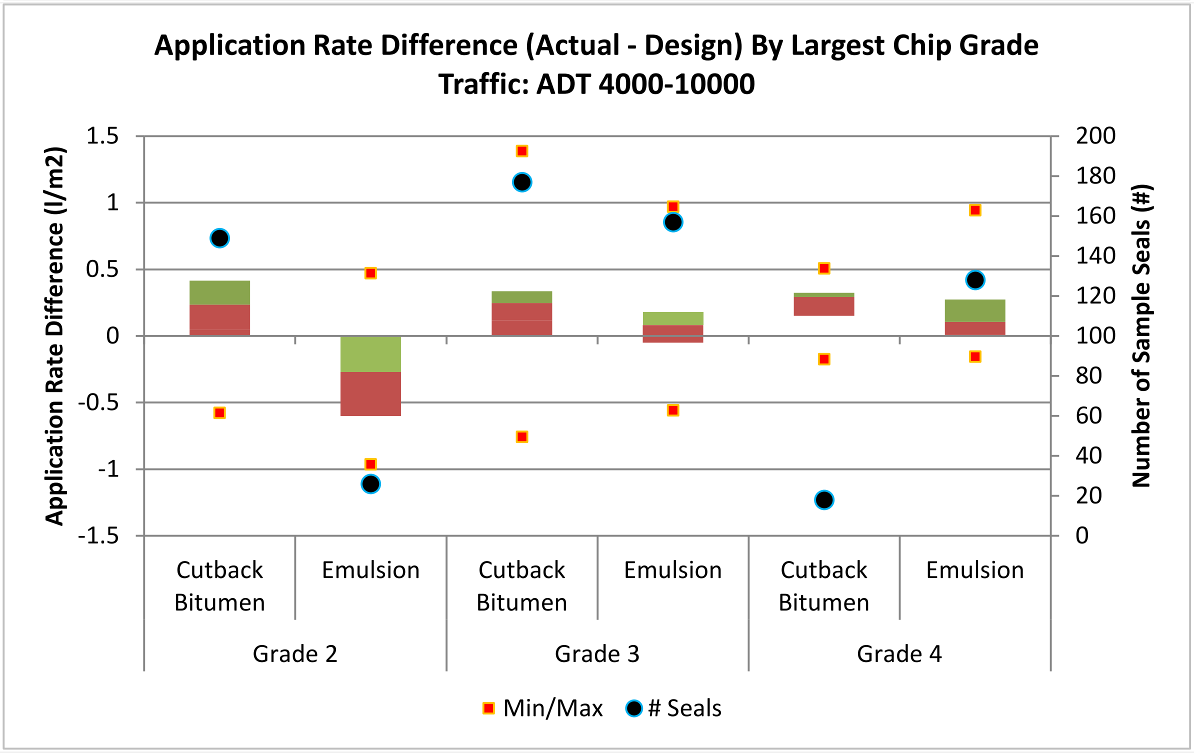
The charts in figure 3.10 show the 25th, 50th and 75th percentile range, minimum and maximum values and sample size for each sample group.

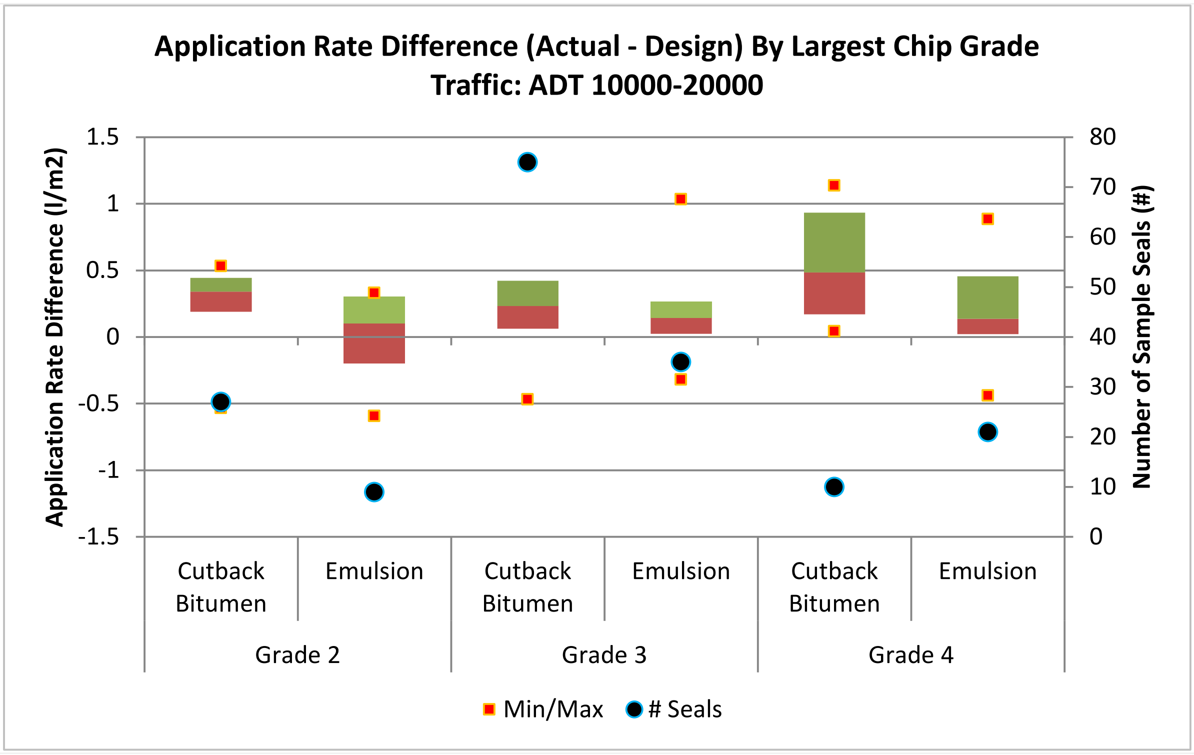
Figure 3.10 **Application rate differences by traffic volume**






Application Rate Difference (Actual - Design) By Largest Chip Grade
Traffic: ADT 2000-4000
Application Rate Difference (l/m2)
1.5
1
0.5
0
-0.5
-1
-1.5
Number of Sample Seals (#)
250
200
150
100
50
0
Cutback Bitumen
Emulsion
Cutback Bitumen
Emulsion
Cutback Bitumen
Emulsion
Grade 2
Grade 3
Grade 4
Min/Max
Seals


Application Rate Difference (Actual - Design) By Largest Chip Grade
Traffic: ADT 4000-10000
Application Rate Difference (l/m2)
1.5
1
0.5
0
-0.5
-1
-1.5
Number of Sample Seals (#)
200
180
160
140
120
100
80
60
40
20
0
Cutback Bitumen
Emulsion
Cutback Bitumen
Emulsion
Cutback Bitumen
Emulsion
Grade 2
Grade 3
Grade 4
Min/Max
Seals



3.4 Achieved lives

To assess the achieved lives of a surface we had to look at surfaces which had reached the end of life or had been sealed over, ie expired.

Emulsions have been widely used in New Zealand for approximately the past 10 years, at least with regard to the data contained in RAMM. It seems also that the majority of the emulsion seals in New Zealand still exist as top surfaces and have not yet reached their 'end of life'.

3.4.1 Identify whether emulsions fail at a different rate than cutback bitumen seals.

This analysis was carried out using the full national dataset including 1CHIP, 2CHIP and RACK seal types, both top surface layer and one layer under top surface and all binder types including PMB and EPM.

The dataset was split into three core groups:

1. Failed early: surfaces that failed prior to reaching their expected lives.
2. Achieved life: surfaces that were resealed after they had reached or exceeded their expected lives.
3. Yet to fail: surfaces that have yet to fail or be sealed over (top surface layer).

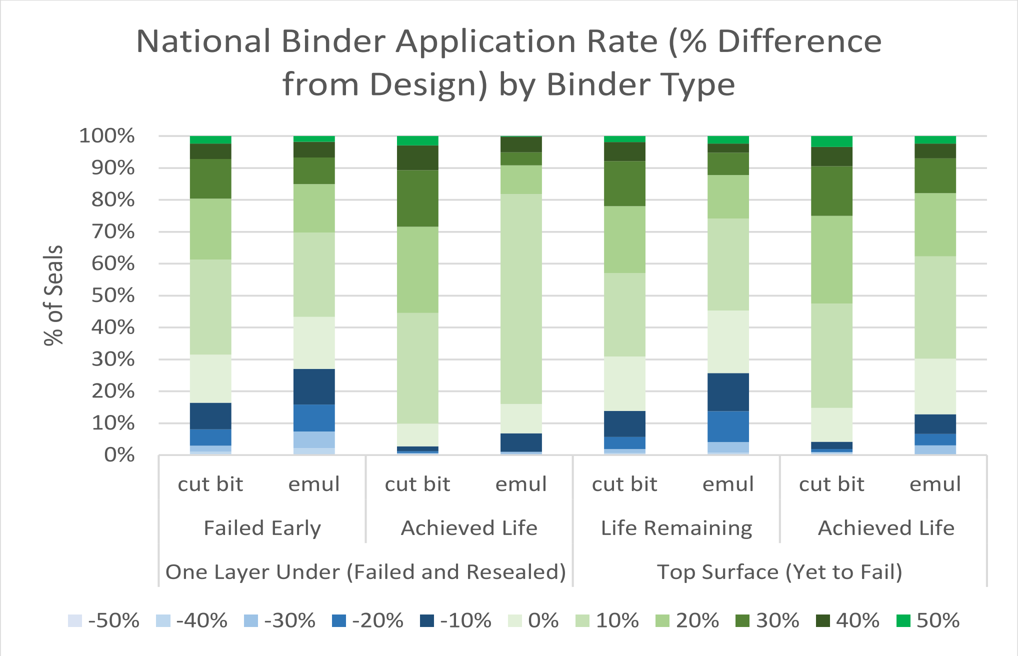
Each of the three groups was split into cutback bitumen and emulsion.

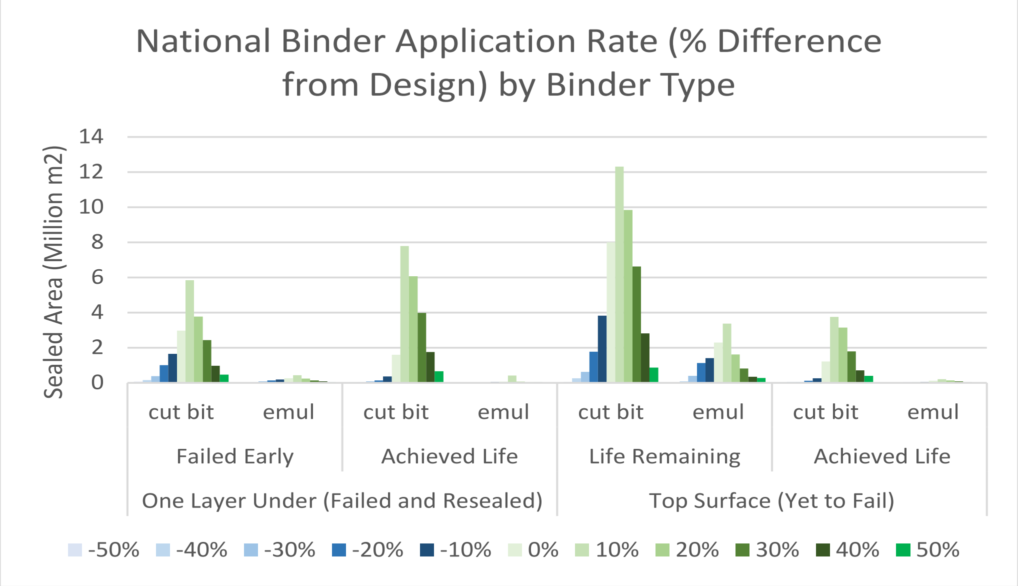
The analysis compared the percentage application rate differential ((actual – design)/design) of each group. The range of recorded application rate data was from 50% below design through to 50% above design at 10% increments. The charts in figure 3.11 show the distributions of the analysis. The blue bars represent binder application rates below design and green bars represent rates above design.

The data suggests that over 70% of all the emulsion seals one layer under the current top surface failed early, without the specific failure mode being expressed. That compares with just under 50% of the equivalent cutback bitumen seals. If the emulsion seals behave similarly to the cutback seals, one would expect this figure to sit around 50% once the dataset reaches a steady state (ie a normal distribution). This aligns with the earlier conclusion that the emulsion dataset has not yet reached steady state and therefore results are not yet fully reliable.

However, it is evident that the percentage of surfaces with application rates below design (blue bars) is higher in seals that are failing early than those achieving their expected lives, for both cutback bitumen and emulsion seals. Interestingly, the application rates of the ‘failed early’ group and ‘yet to fail with life remaining’ group are quite similar. Very few (<9%) emulsion seals, whether sealed over or still in service, have met their expected lives compared with approximately one-third (33%) of the cutback bitumen seals.

Figure 3.11 National binder application rates by binder type





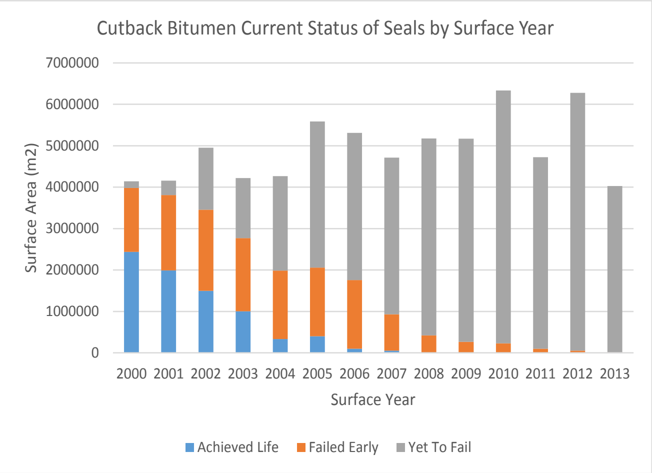
In conclusion:

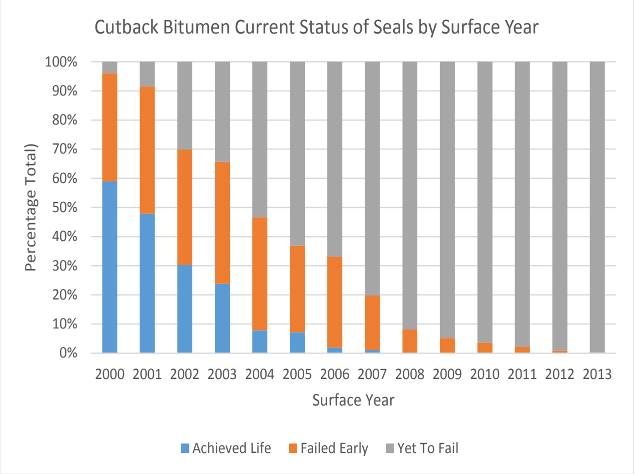
- The dataset of emulsion seals that have been sealed over is very small, so the expected distribution of 50% seal failure may not have reached a steady state because we currently have over 70% of these seals failing early. It is therefore difficult to draw a conclusion that is firm about the seal failure rates from the available data.
- Cutback bitumen and emulsion seals are more likely to fail early if the binder application rate is low. 16% and 27% of cutback bitumen and emulsion seals respectively that failed early, had an application rate of less than design compared with only 3% and 7% with an application rate below design that met or exceeded expected life.

The following charts show the current status (in terms of failed early, achieved life and yet to fail) split by emulsion and cutback bitumen:

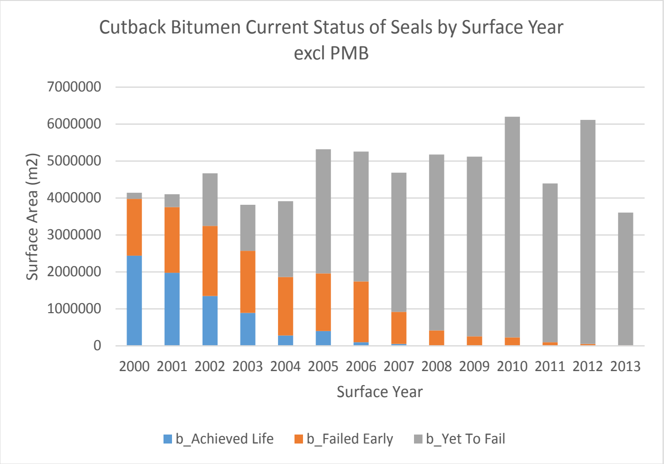
Figure 3.12 Status of seals by surface year 2000–2013

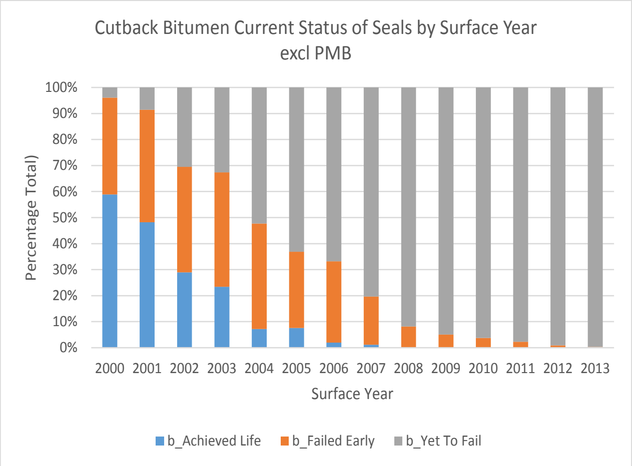
All surfaces in the dataset (1CHIP, 2CHIP, RACK excluding first-coat) seals



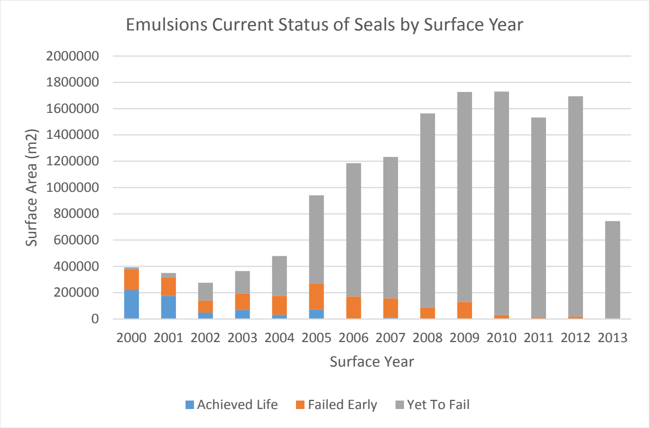


All surfaces in datasets including polymer-modified seals





All surfaces in datasets excluding polymer-modified seals



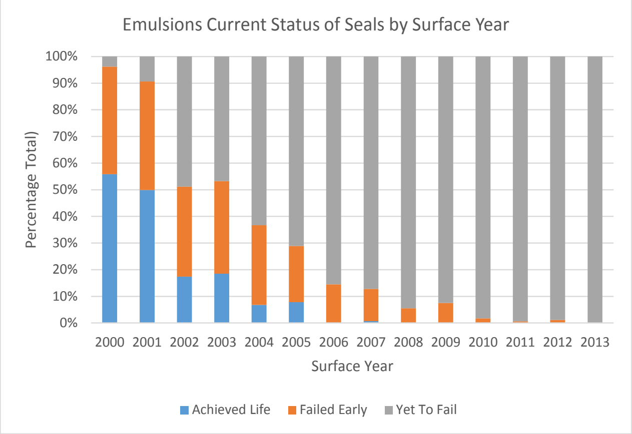


Figure 3.13 Status of seals by surface year 2005

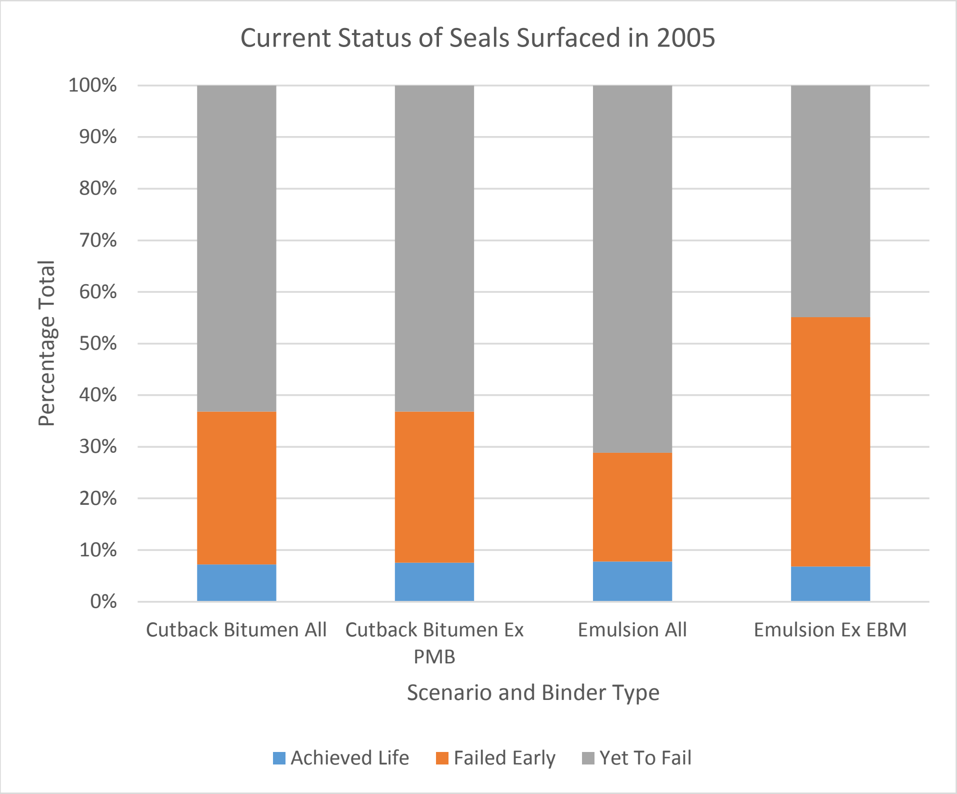


Figure 3.13 shows all seals surfaced in 2005 with the percentage in each group. Distributions are fairly similar across all groups.

3.4.1.1 Significance test (*z*-test two sample means)

Table 3.6 shows results for a full dataset *z*-test of sample means, comparing the percentage of life remaining at the time of reseal for two samples: cutback bitumen seals failing early and emulsion seals failing early. These included PMB and PME. The full dataset analysed together suggests that the means are in fact significantly different. However, when analysed by surface year (much smaller samples) no year produced a result with significantly different means.

Table 3.6 Sample mean significant tests

Scenario 1	Mean % life remaining at failure			Significant?
	Cutback bitumen	Emulsion	z	
2000	40%	34%	1.75	two samples the same
2001	35%	40%	-1.54	two samples the same
2002	37%	42%	-1.12	two samples the same
2003	43%	47%	-1.33	two samples the same
2004	47%	48%	-0.22	two samples the same
2005	49%	49%	-0.22	two samples the same
2006	55%	60%	-1.91	two samples the same
2007	63%	68%	-1.72	two samples the same
2008	72%	71%	0.12	two samples the same

Scenario 1	Mean % life remaining at failure			Significant?
	Cutback bitumen	Emulsion	z	
2009	77%	76%	0.12	two samples the same
2010	84%	82%	0.85	two samples the same
2011	88%	86%	1.06	two samples the same
2000–2013	52%	57%	-5.24	**significantly different**

We concluded that we had not yet reached a steady state of expired emulsion seals and therefore could not assess the achieved lives of emulsion seals.

3.5 Application rates

The application rate was assessed by comparing the actual application rate as recorded in RAMM with the most recent design application rate presented in Transit NZ et al (2005) (it should perhaps be noted that this algorithm might not necessarily be recommended by the industry):

- A number of assumptions were made to define a comparable sample of emulsion and cutback bitumen surfaces (see section 3.3.1).
- Based on median, 25th and 75th percentile values, all sample groups supported the hypothesis that emulsions were applied at a lower rate than cutback bitumen. When the full sample was compared, and we assumed that the application rates were correct, the mean application rate for:
  - emulsion was 4.6% higher than design,
  - cutback bitumen was 8.3% higher than design.
- Statistical tests (*f* test and *z*-test) indicated this difference in means was significant.
- Significant outliers in actual *vs* design application rate differential led to concerns over the reliability of RAMM application rate data. Many RAMM recorded application rates appeared to be unrealistic in a practical sense. There was no identifiable trend in the outlying data so we were unable to identify and remove statistically relevant outliers.

We can confirm that within the data sample analysed, emulsion seals had, in general, been applied at lower rates than cutback bitumen. However, we were concerned about the reliability of the RAMM application rate data for both cutback bitumen and emulsion seals and suggested that until data quality improved we should not draw any firm conclusions.

3.6 Recommendations

- Continue to improve RAMM data quality. Ensure automated checks are in place to flag any application rates entered in RAMM which fall outside a defined design application rate tolerance.
- Re-analyse data once expired emulsion seals have reached a steady state to test whether they are meeting expected lives.
- Interestingly, following the conclusion of this analysis another independent RAMM analysis on a similar research question was released by the Transport Agency (Wanty 2014). The overall conclusions regarding the ability to use the RAMM data, as it stands at the present time, to make statements about emulsion seal lifetimes were fundamentally the same as those obtained here.

4 Experimental

4.1 Introduction

The experimental section of this project focused on determining the differences in apparent cohesive energy (ACE) within the bitumen films of model chipseal samples, as measured by a swinging pendulum 'knock-off' test (figure 4.1). The pendulum test is a development of the Vialit Pendulum test and has been used previously by Opus Research (Herrington et al 2011) to determine the ACE within chipseal layers prepared with multigrade bitumen binders. This work compared the ACE values of chipseal samples prepared with emulsions, the base binders and cutback base binders. Inferences were then made regarding the relative performances of the three different types of binder application in the field.

Figure 4.1 Opus Research pendulum tester with chipseal sample in place

4.2 Materials and sample preparation

The chipseal samples tested were prepared using 10/20 'Grade 3' crushed greywacke chip supplied by Kiwi Point Quarry, Wellington, New Zealand. The as-supplied chip was sieved (passing 13.2, retained on 9.5mm), washed well with water, dried at approximately 120ºC overnight and stored until required.

Two non-polymer modified cationic bitumen emulsions and the base binders from which they were prepared, were obtained. Emulsion A was a cationic emulsion, with no additional modifiers, prepared from a 180/200 base at a concentration of 70.8% w/w. Emulsion B was a cationic emulsion, with no additional modifiers, prepared from a 130/150 base bitumen at a concentration of 72% w/w (values as provided by suppliers). Emulsion B was much more viscous and thixotropic than Emulsion A. Both of the emulsion samples were used as supplied, and all masses were calculated so as to apply a given rate of residual bitumen. Emulsions and the base binders were used as supplied, except for the cutback experiments where the base binders were mixed or 'cutback' with kerosene to a level of 2pph by mass, immediately prior to use so as to avoid evaporation of the cutter.

Aluminium square extrusion (30 x 30 x 100mm x 1.5mm wall) for the knock off towers was sourced from Ulrich Aluminium, Petone. Construction epoxy for attaching towers, Sikadur 31, was sourced from Sika (New Zealand). The pendulum tester (figure 4.1) and steel sample plates which raised walls to create shallow sample wells of 120 x 130 x 4mm (surface area = 0.016m^2), were all fabricated in-house (figure 4.2).

4.3 Pendulum knock-off test – preparation

Model chipseal samples were prepared on the sample plates using the different bitumen materials. The base binders were heated for two to three hours at 120°C in order to flow evenly across the hot sample plates, which were also heated to 120°C. Emulsions and sample plates on the other hand, were heated to 80°C. In order to be confident that the base bitumen had not hardened significantly during the heating, the penetration values of the two base binder samples after being heated for an additional 3.5 hours were measured. The penetration values were found to be within the standard error of the technique, ie those of the original specification. This indicated that the extent of heating in this experiment had not significantly hardened the base bitumen.

A layer of bitumen, emulsion or cutback at one of two different residual bitumen application rates was formed by pouring the appropriate mass (as determined by the desired application rate) of hot binder onto the sample plates. These were left standing for a few minutes to level out. The sample plates were still warm (approximately 40°C) at the point of adding the chip. The base binder still flowed slowly and the emulsions had not broken. A known mass of the Grade 3 chip was then spread onto the bitumen layer by hand and rolled in with a 5cm wide rubber printers' roller. This ensured good chip spreading and lay-down of the individual chips ensuring as much binder coverage as possible (figure 4.2). The emulsions were still not fully 'broken' at this point. Six (6) replicate sample plates of each base binder, emulsion and cutback bitumen were prepared at 1.5Lm^{-2} and 1.93Lm^{-2} bitumen application rate (BAR) or EAR (as residual bitumen) coverage and 14.4kgm^{-2} AAR.

Figure 4.2 Chipseal plate sample

Figure 4.3 Chipseal plate with tower attached and after knock-off

The sample plates were covered with as many chips as possible to completely cover the bitumen layer. The purpose of the experiment was to test the cohesion of the bitumen layer *via* a chipseal (bitumen/chip) interface. We did not want any opportunity to arise for the knock-off tower to become bound directly to the bitumen layer.

In the samples prepared with emulsions, the chips drew water out of the emulsions very rapidly. This wet the upper chip surfaces visibly and thereby created an effective drying surface for the emulsions. This ‘wicking’ of the water out of the emulsion *via* capillary action, meant that water loss and emulsion breakage was not controlled solely by evaporation directly out of the uncovered emulsion film surfaces. The wicking phenomenon may prove to be relevant to chip adhesion and also to the mechanisms of emulsion breakage in other mineral chip systems, where the chips are not as hydrophilic or as porous as greywacke systems (eg granite). This phenomenon contributes to, but is not the same, as the meniscus effect which describes the chip surface coverage achieved by the emulsion binders.

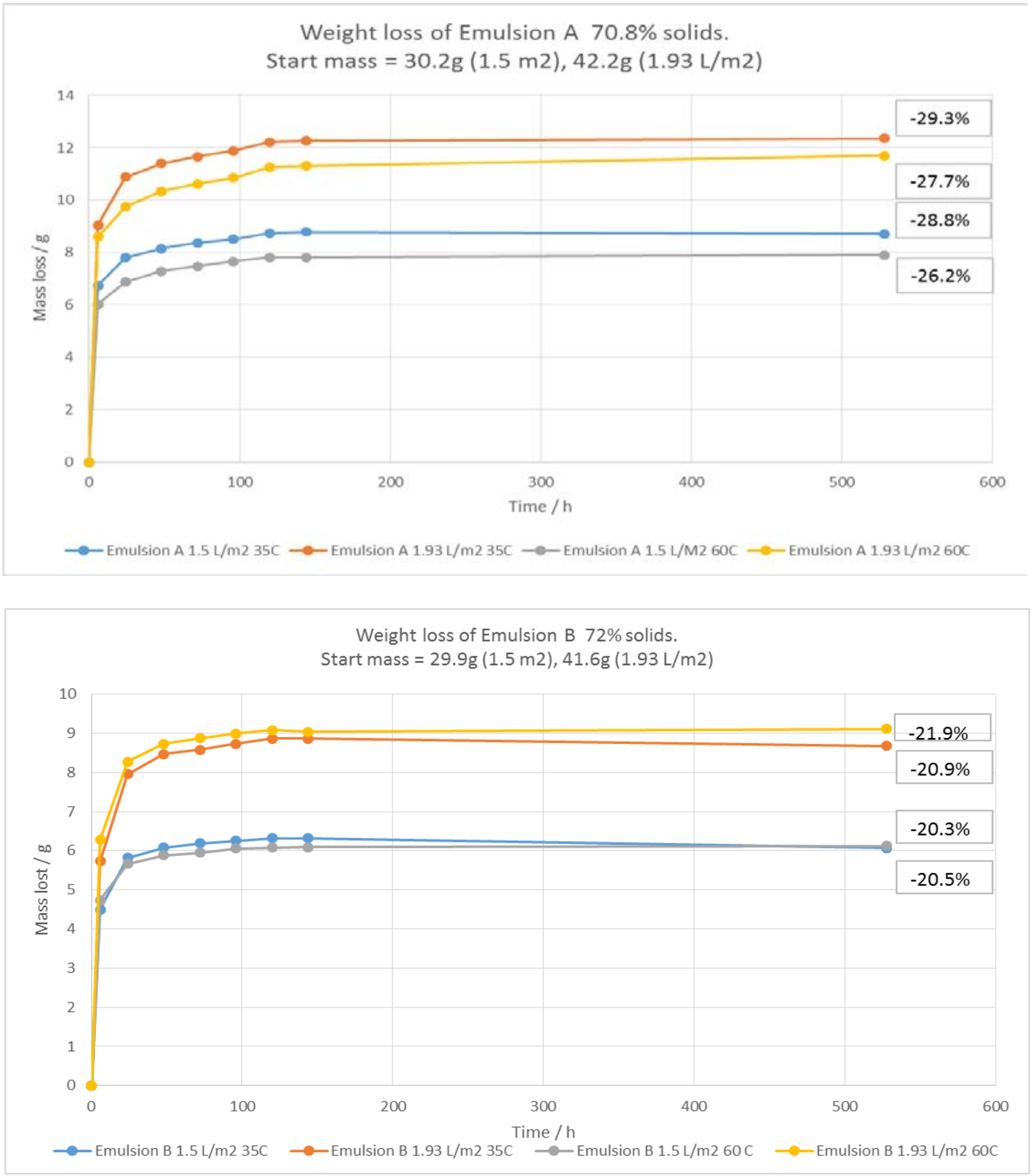
Emulsion samples were then ‘cured’ in a vented, temperature controlled oven at 35°C over 48 hours to allow the emulsions to break, and for as much water as possible to evaporate from the emulsion in a manageable time. Cutback samples were subjected to the same conditions even though they did not need ‘curing’ as such but did require evaporation of some of the kerosene cutter. In the interests of comparison and to simulate any bitumen oxidation that might occur during this treatment, the base-binder samples were also subjected to the same conditions.

After ‘curing’ for 48 hours at 35°C, the aluminium knock-off towers were attached to the upper surface of each chipseal sample using a strong construction epoxy filler (figure 4.3). Approximately the same mass of the epoxy filler was spread over the same defined area of each plate so as to contact as many and as much of the chip upper surface as possible in that defined area and to make the mass knocked off each sample as close as possible. The area of the epoxy was determined to produce reliable knock-off results in previous experiments (Herrington et al 2011). The epoxy was then allowed to cure at 35°C over a further 48 hours.

In order for the pendulum to knock out the tower, we needed to reduce the actual bitumen cohesion, so prior to testing all samples were heated to 60°C for 4 hours (noting that this could also allow additional water/kerosene to evaporate from the sample). Each sample plate was fixed into the pendulum device, separated from the steel structure by a wood insulating plate, so that the test was performed as close to 60°C as possible. The pendulum was then raised to a constant height (90° from vertical) and released. The ‘tower’ was knocked out of the chipseal using a single blow of the pendulum so that it carried the section of the chipseal (tower/epoxy/chip/bitumen) with it (figure 4.3). The extent of travel of the pendulum following knock-off was determined by an electronic potentiometer that displayed the value of the maximum swing height for each swing and was recorded. The speed of the head of the pendulum just before impact was 3.9ms^{-1} (14km/h^{-1}), imparting an energy pulse of approximately 20J. Mechanical and air friction losses were considered to be negligible in this work.

The tower with the attached epoxy/chipseal was then placed back onto the plate with two sheets of tissue paper separating the tower from the plate, to prevent any adhesion between the bitumen surfaces. It was subjected to a second blow from the pendulum, recording the swing value achieved after this. In this way we measured the energy required to dislodge the mass contained in the tower/epoxy/chips/binder sample but not resisted by the cohesion of the binder. The difference between the two blows was defined as the ACE of the bitumen layer.

Figure 4.4 Water loss from emulsion chipseals at 35°C and 60°C



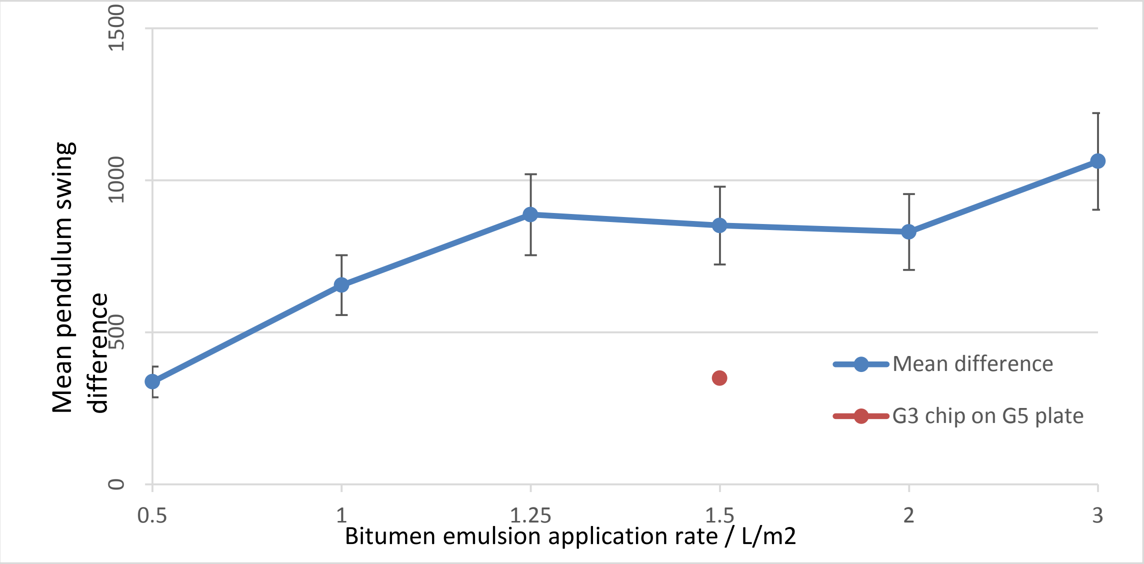
At this time, a selection of emulsion chipseal samples was prepared in order to monitor their weight loss over time so that we might understand how much water remained trapped in the bitumen after curing/aging for several days at 35° and 60°C. The data (figure 4.4) showed very rapid early loss of water followed by slow continued water loss over the next 48 hours, with the rate reducing even further over longer time. We observed approximately 100% water loss from the emulsion A at 35°C, while interestingly at 60°C, the weight loss was slightly lower. However, the weight loss from emulsion B was only between 73% and 78% of the theoretical maximum and the differences between 35° and 60°C were much smaller than emulsion A. The reasons why emulsion B retained some water were not clear but the physical forms of the two emulsions were different and may have had bearing on the water loss. The samples were also placed into hot ovens rather than having the temperatures raised slowly. This may have caused surface skinning which could have resulted in restricted water loss in the higher temperature experiments, but both emulsions were treated in the same way.

The length of time taken to pre-treat our samples corresponded approximately to the time required to reach virtual maximum water loss (approximately 100 hours) for emulsion A. We did not measure directly the kerosene that was lost from the cutback samples. In practice emulsion seals are expected to carry traffic after only a few hours or less after construction so that the water content of the seal may well be greater than that remaining in the test seals after the curing process used here.

4.4 Pendulum knock-off test – verification

The experimental method was then tested for consistency and reproducibility with four replicates of samples of a stock cationic bitumen emulsion (approx 70% w/w) at EARs of: 0.5, 1.0, 1.25, 1.5, 2.0 and 3.0Lm^{-2} and constant AAR of 14.4kg m^{-2}. Our initial testing of the experiment produced consistent results between the replicates with an acceptable 12 ± 3% variation for each of the application rates tested. The experiment also demonstrated reasonable trends of increasing mean ACE with increasing application rate up to a level where one might reasonably expect the ACE to not significantly increase further (figure 4.5). We were therefore able to be confident that the test procedure would be suitable to provide us with results from which we could draw fair conclusions about this aspect of the chipseal system.

Figure 4.5 Verification of pendulum test. Graph shows mean values of untextured steel plate samples (blue) and mean of the Grade 5 plate data (red)



A group of samples was also prepared where a layer of Grade 5 chips was epoxied onto the surface of the steel sample plates in order to produce a textured surface. We then prepared the Grade 3 chipseal, at 1.5 Lm^{-2} only, on top of the Grade 5 layer in the same manner as the other samples. We could see that the ACE value of the sample prepared on the Grade 5 chip surface was significantly lower than the values obtained from chipseals prepared directly on the steel plate surface and the spread was somewhat greater. Examination of the post-test sample indicated this was due to a significant reduction in Grade 3 chip/bitumen contact due to the chips not all sitting into the bitumen wells formed in the Grade 5 chip base. We decided at that point not to continue testing this type of sample and to focus only on the samples prepared directly on the steel surface. But this result makes it very clear how the texture of a given road surface plays an important role in the design of subsequent surfaces.

4.5 Theory of pendulum test

Although it was not necessary to calculate the actual cohesive energies of the bitumen films (we were only interested in the differences in behaviours), we present below the theoretical background of the test. At the point of impact, the swinging pendulum loses energy through dis-bonding and ‘knocking out’ the seal patch. The remaining kinetic energy in the pendulum is converted to potential energy as it rises to its maximum height and swings past the knocked out sample. The potential energy at that point is given by equation 4.1:

$$U = mgL(1 - \cos\theta) + \tfrac{1}{2}m'gL(1 - \cos\theta) \qquad \text{(Equation 4.1)}$$

Where:

- U = the potential energy (J)
- θ = the angle the pendulum rises from the vertical position after impact (rad)
- m = the mass of the pendulum bob (1.53kg)
- m' = the mass of the pendulum shaft (2.04kg)
- L = the length of the pendulum shaft (0.783m)
- g = acceleration due to gravity (9.81m/s).

The maximum potential energy of the pendulum attained after impacting the bonded stud was subtracted from that of the respective ‘unbonded’ test to give the energy absorbed by the seal (equation 4.2). We make the assumption that masses of the samples displaced are all approximately equal, or at least within the experimental uncertainty, given the construction technique.

$$\Delta U = mgL(\cos\theta - \cos\theta t) + \tfrac{1}{2}m'gL(\cos\theta - \cos\theta t) \qquad \text{(Equation 4.2)}$$

Where:

- ΔU = the energy absorbed by the seal (J)
- θ = the angle to which the pendulum rises from the vertical position after impacting the unbound stud (rad)
- θt = the angle to which the pendulum rises from the vertical position after impacting the bound stud (rad).

In this way therefore, the energy lost by the swinging pendulum equals the energy required to remove the seal patch. In all cases the failure as the patch was removed from the sample was inside the bitumen film and not at the chip/bitumen or the bitumen/plate interfaces. We are therefore confident that the energy lost by the pendulum equates to the apparent cohesive energy of the bitumen film.

4.6 Chip coverage: degrees of binder rise or ‘uppage’

One of the questions posed in this project was related to the apparently improved degree of chip surface coverage by the bitumen, or ‘uppage’ or ‘binder rise’ that might occur with bitumen emulsions as opposed to cutback binders. Would the hydrophilic nature of the greywacke chip surface, in particular, allow better wetting of the chip surface by the water-based bitumen emulsion; and would this lead to better wetting and surface coating by the emulsion, thereafter potentially leading to improved chip retention?

As the traditional methods for measuring this effect were not available to us, we resorted to qualitative observational methods. We were able to observe that different levels of chip coverage were achieved for the three different types of binder (base binder, emulsion, cutback binder) and also for the different application rates of each type. For emulsion A at different application rates these differences can be seen in figures 4.6 to 4.9. As the EAR increased (1.25 to 3.0Lm^{-2}) the bitumen showed increasingly higher coverage of the chip surfaces, but at the same time increasingly more bitumen became squeezed out of the spaces between chips. Emulsion B behaved similarly, albeit not quite as dramatically, which may have been due to its lower viscosity and more thixotropic nature.

Where the unmodified base binder was used, even at an elevated application rate, (figure 4.10) the bitumen was sufficiently stiff so that rolling the chip into the bitumen layer squeezed the bitumen only enough to provide contact with the lower faces of the chips. The bitumen did not climb up the sides of the chips.

In samples where the cutback binder was used, we saw still less surface coverage of the chips (not shown). One possible suggestion is that diluting or ‘cutting’ the binder lowered its viscosity enabling it to flow readily. However, owing to its overall hydrophobic nature, there could be no capillary action along the chip surface as occurs with emulsions. The outcome of this was that the actual chip surface coverage achieved by a cutback binder was lower than that of either a base binder or an emulsion.

Observations of the samples showed that a common factor in their different behaviours was the very different viscosities/flow characteristics of the different bitumens. The high viscosity of the base binder produced a poorly flowing layer into which the chips were pushed. In these cases the bitumen was simply pushed aside and flowed only slightly around the base of the chip, producing an effective contact only around the lower chip faces.

At the other extreme, the very low viscosities of the emulsions allowed the bitumen to flow very easily between chips and in fact, to be squeezed out of the gaps between chips and up the sides of the chip surfaces. This physical action combined with the capillary action of the aqueous emulsion produced the so-called ‘uppage’ effect, figure 4.11). Emulsions therefore afford much greater chip coverage than do base binders. However, that should not necessarily be equated with better chip retention.

Figure 4.6 1.25Lm^{-2} emulsion A, Grade 3 chip

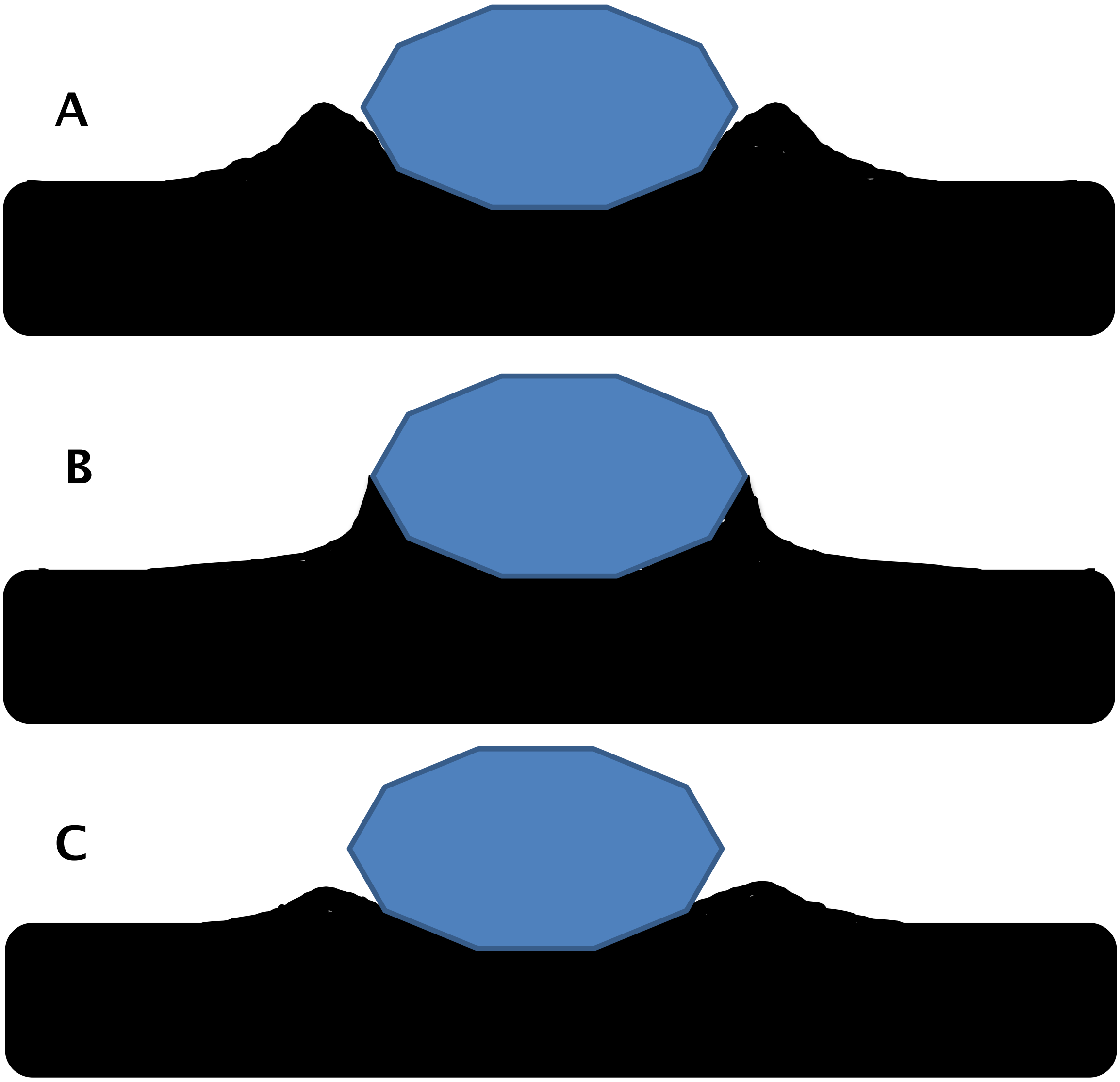
Figure 4.7 1.5Lm^{-2} emulsion A, Grade 3 chip

Figure 4.8 1.93Lm^{-2} emulsion A, Grade 3 chip

Figure 4.9 3.0Lm^{-2} emulsion A, Grade 3 chip

Figure 4.10 1.93Lm^{-2} bitumen base binder A, Grade 3 chip

Figure 4.11 Schematic diagram of suggested modes of bitumen/chip interaction: A) Base binder, high raised shoulders; B) Emulsion, capillary-induced surface coverage; C) Cutback binder, flow-induced low shoulders



The diluted cutback bitumen on the other hand, appeared to have a viscosity that was low enough to allow it to flow more than the base binder, but not as much as the emulsified binder. Because the cutback remained hydrophobic it did not exhibit capillary action around the chip surface and did not flow up the chip surfaces. This means that the cutback bitumen flowed enough to level out after the chip was embedded into the bitumen and therefore offered the least chip surface coverage.

While the higher chip coverage for emulsions might improve the chip retention outcome, it might be just as likely to result in a thinner base film as the emulsion covered the chip surfaces, and was squeezed out from under the chips. This might possibly manifest as a lower ACE. If the application rate was too high the squeezing of the bitumen might also lead to tracking and flushing of the bitumen at elevated temperatures in service. It seemed likely from these observations that the lower chip coverage observed for the cutback binder would lead to lower ACE values.

4.7 Apparent cohesive energy tests (ACE) – pendulum knock off

Following the verification of the test procedure, samples were prepared with the bitumen base binders, emulsions and cutbacks supplied by our two local manufacturers (see for example figure 4.12). If the ACE values for the different bitumen application types were statistically different, that would allow us to suggest that either higher or lower application rates of emulsion over cutbacks might be applicable. While our experiment did not directly measure an actual road surface, suitable inferences regarding the relative performances in the field could be made.

We can summarise the results qualitatively here and quantitatively in table 4.1 and figure 4.13:

- The higher application rate of any type of bitumen had higher ACE than the lower application rate. The ACE differences between application rates for the emulsions were smaller than those observed for the cutbacks and base binders.
- Cutback bitumens had the lowest ACE, about 35%–65% of base binder.
- Emulsions had intermediate ACE values.
- Base binders had the highest ACE values.
- All samples exhibited good chip/bitumen and plate/bitumen adhesion, ie the failure was entirely cohesive in nature.
- The differences between the lowest (cutback) and highest (base binder) ACE values were greater at the higher application rate.
- The differences in ACE between cutback and emulsion were smaller than those between emulsions and base binder.
- Lower application rates of any type of bitumen (1.5Lm^{-2} vs 1.93Lm^{-2}) produced less variation between ACE results.

For each of the groups of results, at each application rate, an analysis of variance (ANOVA) test was conducted. The results showed, in each case, that the difference between the means of the cutback, emulsion and base binder pendulum tests were statistically significant at the 1% probability level.

The key finding from these experiments therefore, is that at the same residual bitumen application rate, (1.5Lm^{-2} and 1.93Lm^{-2} tested here), emulsion seals had lower ACE than pure base binder seals, but higher ACE than cutback binder seals.

Figure 4.12 1.5L/m2 G3 on plate binder A 180/200 base binder

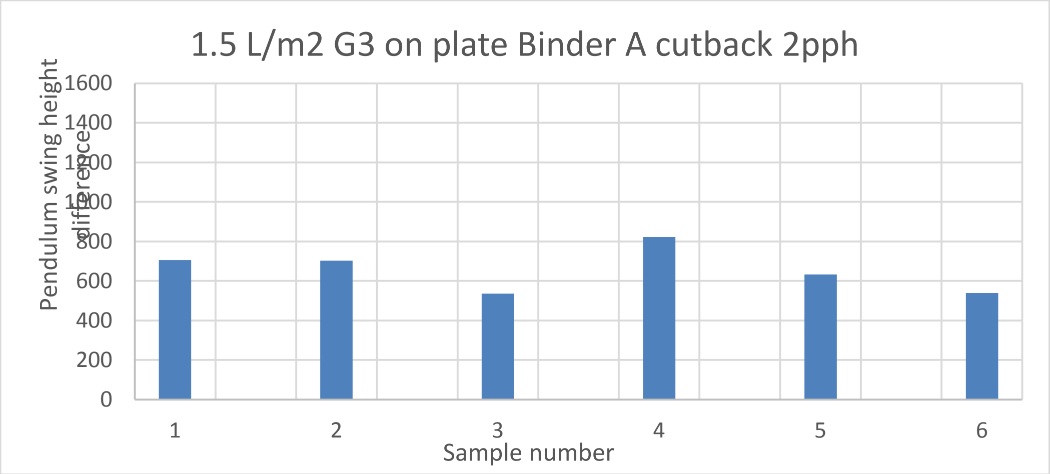
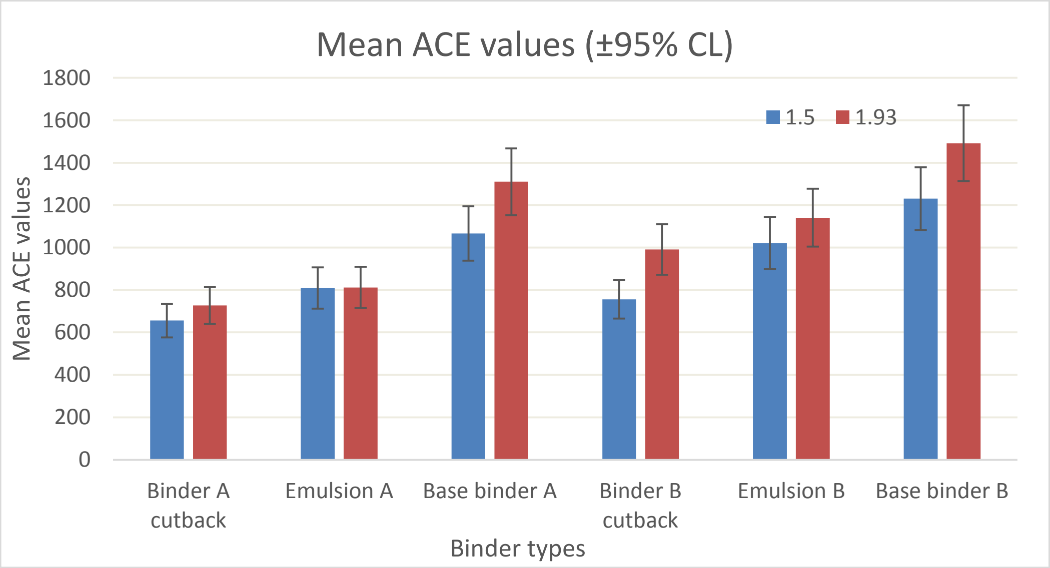


Table 4.1 Mean ACE values (±95% CL) from pendulum experiments

Binder type	Residual bitumen application rate	
	1.5Lm⁻²	1.93Lm⁻²
Binder A cutback	656 ±110	727±170
Emulsion A	810±107	812±175
Base binder A (180/200 PEN)	1066±137	1310±149
Binder B cutback	759±40	991±100
Emulsion B	1022±192	1141±89
Base binder B (130/150 PEN)	1231±161	1492±136

Figure 4.13 Mean ACE values (±95% CL) from pendulum experiments



5 Conclusions, specifications and recommendations

A review of available literature did not provide any clear indications that applying bitumen emulsions at lower residual rates than cutback bitumens would be acceptable.

Analysis of the Transport Agency's RAMM database tentatively indicated that bitumen emulsions are, in practice in New Zealand, being applied at residual bitumen rates lower than those of cutback bitumens. However, RAMM also suggested that road surfaces prepared with bitumen emulsions are not yet sufficiently old enough to indicate, with confidence, if they are failing prematurely or performing adequately. We suggest therefore, that no firm conclusions about emulsion seal lives may be drawn currently from the RAMM database analysis. The analysis should be revisited after another few years of road use.

Laboratory pendulum knock-off experiments demonstrated that the differences in ACE values of model chipseals were statistically significantly depending on the type of binder. The test is also sufficiently sensitive to differentiate between the 180/200 bitumen and the slightly 'stiffer' 130/150 bitumen provided by our suppliers. Observed cohesive energies of the cutback binders were 15%–20% lower than the emulsified binders. The cohesive energies of the emulsions were 20%–30% lower than those of the base binders.

The implication is therefore, that if all other aspects are equal and they are applied at the same rates, the cohesion of a bitumen chipseal may be improved through using an emulsion compared with a cutback bitumen, but that both will be inferior to the unmodified base binder. This finding is not unexpected in the case of the cutback seals as previous research has shown that about 20% of the added kerosene remains permanently in the binder and does not evaporate, resulting in a softer binder than the original (Herrington et al 2006). In the case of the emulsified seal, however, it has generally been assumed that the bitumen properties after evaporation of the water will be essentially those of the base binder. The results presented here show that this might not be the case.

The reduced cohesion of the emulsified bitumen over that of the base binders does not appear to be related simply to water retained in the emulsion seals because the differences between the base binder and emulsion seals are about the same in both cases although much more water was retained in emulsion A compared with emulsion B.

Observations of increased 'uppage' or binder rise when the bitumen is applied as an emulsion might suggest that emulsions could exhibit greater propensity for bitumen tracking or flushing at higher application rates ($>1.5 Lm^{-2}$). At the same time, the cutback bitumens appeared to have lower chip coverage than both emulsions and base binders, which may have contributed to their low ACE values.

5.1 Specification of emulsion chipseal application rate

The suggestions for implementation or specification of emulsion use to be drawn from this work require making assumptions about current chipseal performance. In practice, in the field, cutback bitumens such as those used here generally provide adequate seal performance in terms of chip retention. If a reasonable assumption is made that the ACE values measured here reflect the relative ranking likely to be found in the field, then it should be concluded that the higher ACE values provided by emulsions will allow lower EARs to be used until ACE values equal to those of the cutback bitumens are reached. This of course is only the case if the emulsified bitumen is not itself cut back.

Verification of the conclusions drawn here will necessitate the construction and long-term monitoring of new road field trials where different emulsion, cutback and base-binder application rates can be trialled over an appropriate time scale. The trial must include at least one winter and of course will need to include sections where we will observe seal failure in order to establish the bounds of the specification.

A preliminary conclusion can be reached from analysis of the ACE values measured on model chipseal samples. If it is assumed that the model ACE values are representative of those observed in real chipseals then it may be possible to apply bitumen emulsions at lower residual bitumen application rates than an equivalent cutback bitumen and achieve the same ACE. This reduction would be about 10%–15% as residual bitumen. This value is consistent with the anecdotal evidence that has been provided by users and contractors who have suggested that emulsions can, or indeed are, being applied at rates between 10%–15% lower than cutbacks.

5.2 Recommendations for further research

It is clear from the results of this investigation that the laboratory based experiments provide insight into the nature of the cohesive behaviour in the chipseal layer, but that they may not provide insight into the cohesive behaviour in the field.

We note also that there are some gaps in the experiments that could not be filled in this particular investigation. We recommend therefore that additional experiments be undertaken to take into account the addition of both solid phase and solution phase adhesion agents. It would also be advantageous to repeat the experimental set with emulsions prepared from the same grade of base binder from the two different sources (ie have the Binder B supplier prepare emulsion from a 180/200 binder). Most importantly, however, will be to test the contention that chipseals can be successfully prepared with lower emulsion application rates by preparing and monitoring field trial test seals. These trials will need to include seal sections that will unambiguously fail and sections that are based on current best practice and hence less likely to fail, along with sections prepared with different application rates of both emulsion and cut-back binder. Monitoring of the sections will need to continue through at least one winter season, preferably two or more.

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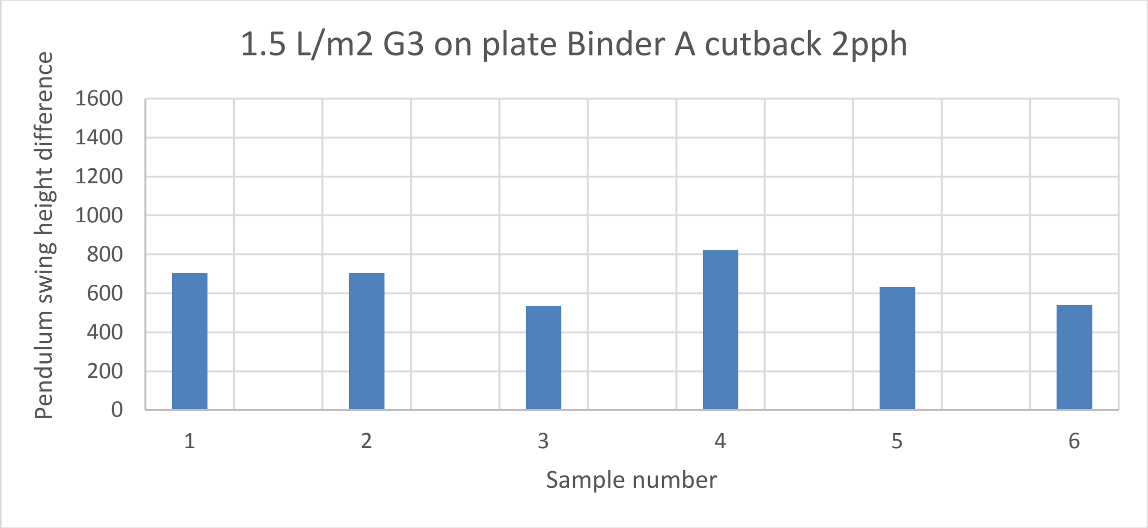
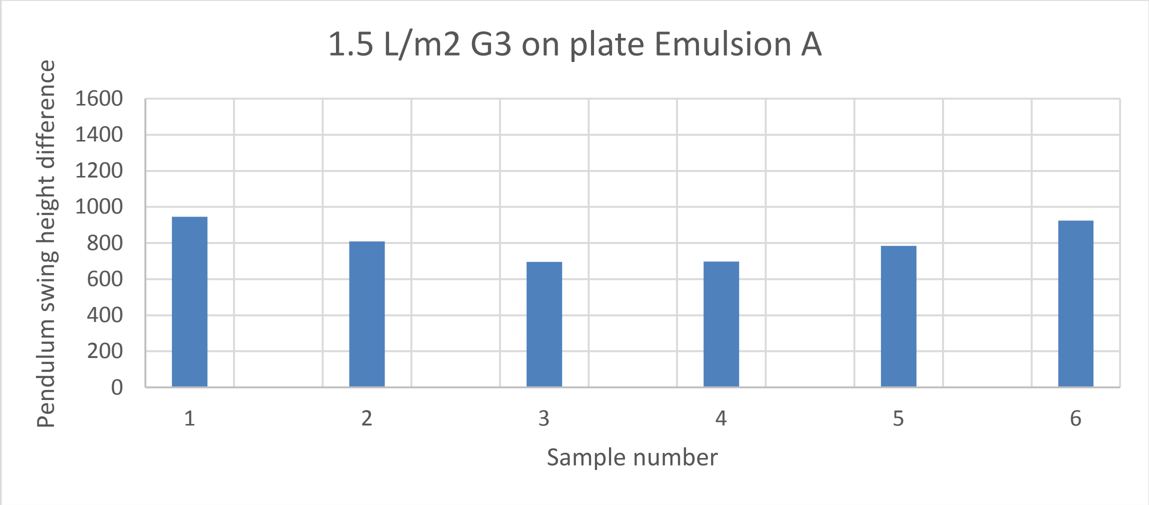
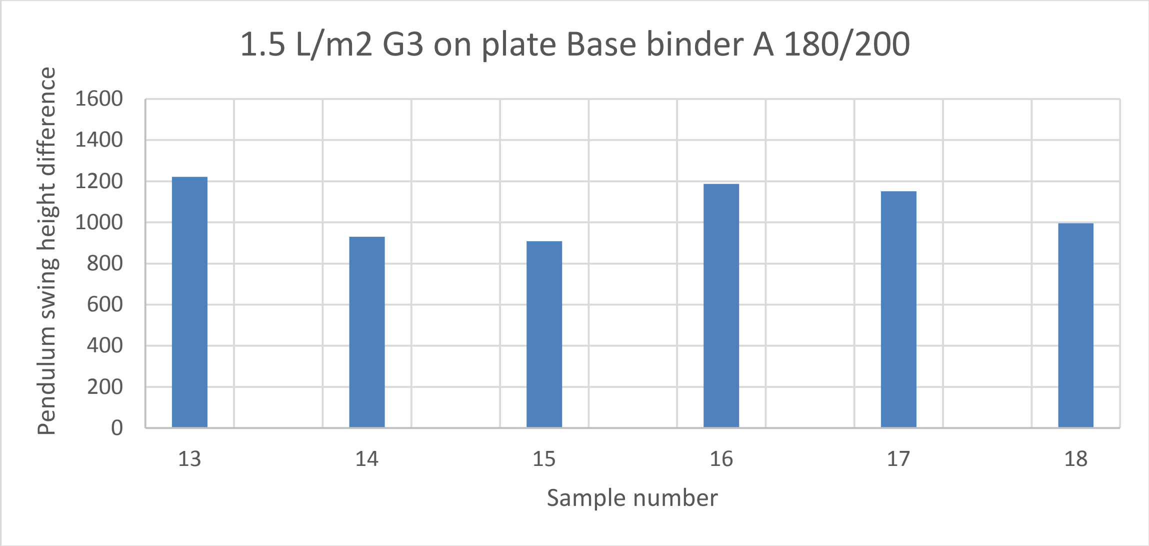
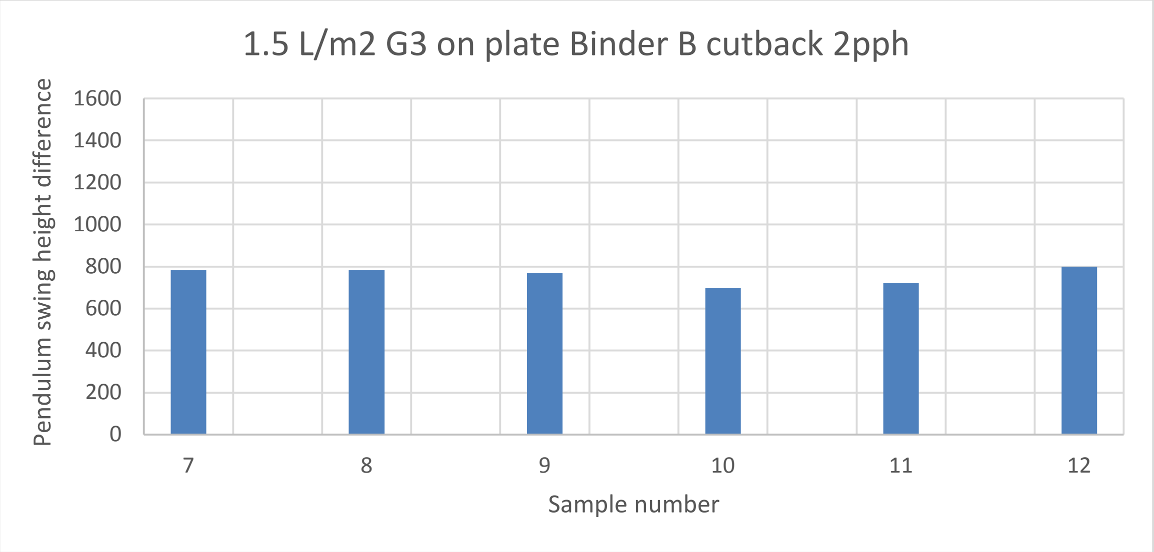
Appendix A: Graphs of pendulum test results








1.5 L/m2 G3 on plate Binder B cutback 2pph
Pendulum swing height difference
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800
600
400
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7
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10
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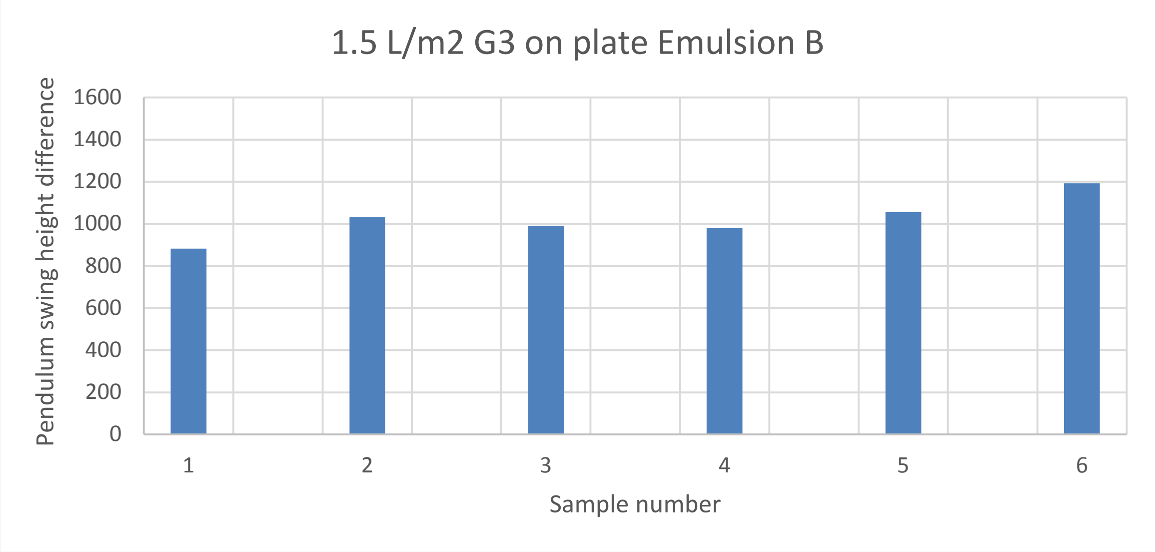
12
Sample number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Pendulum swing height difference
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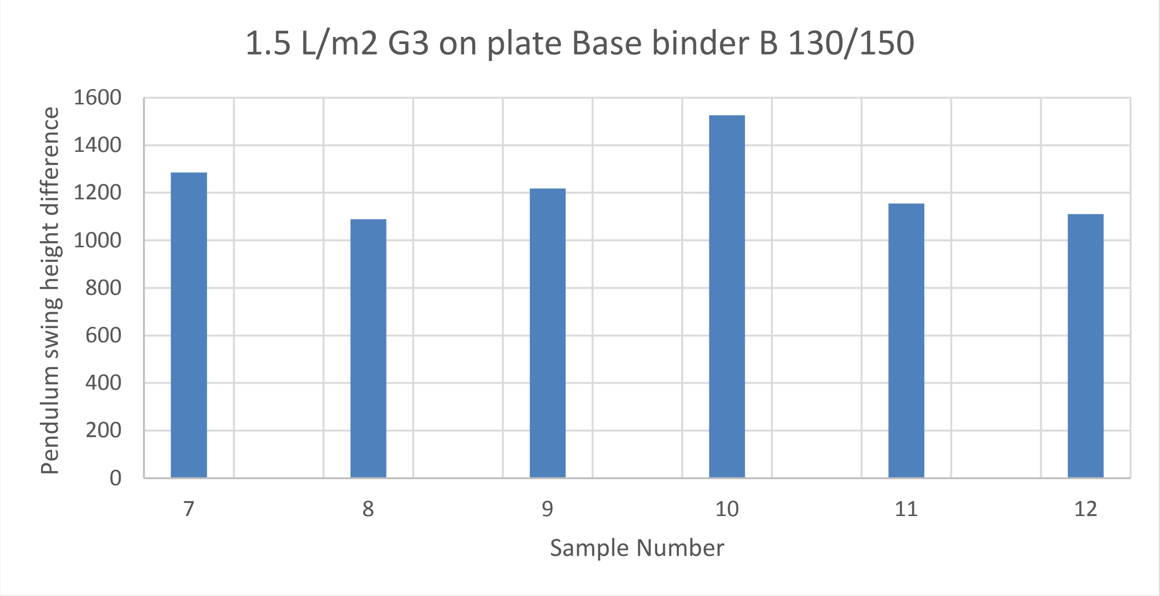
Sample number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Pendulum swing height difference
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1400
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1000
800
600
400
200
0
7
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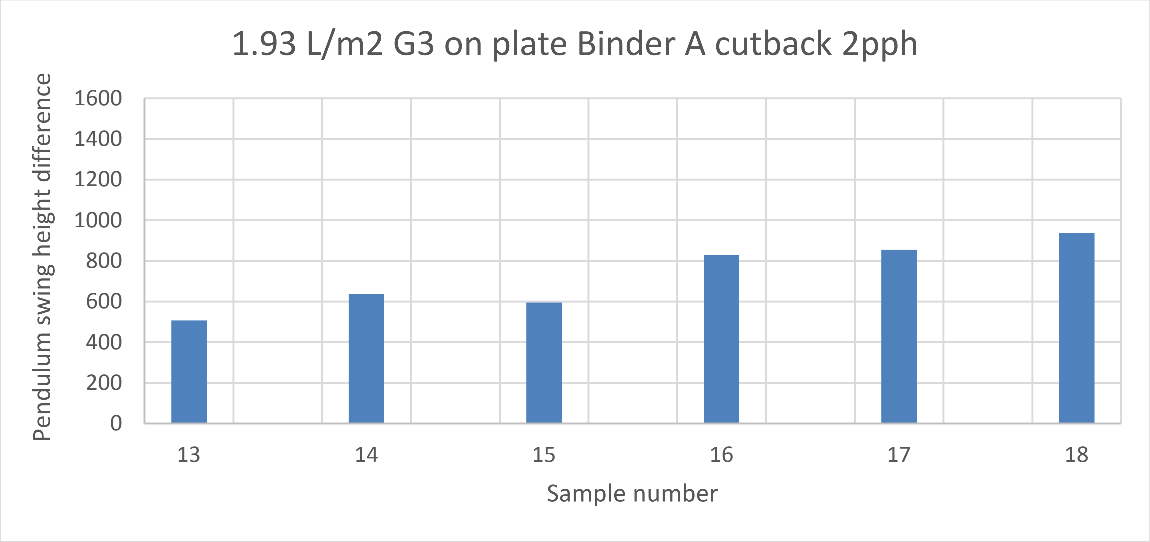
9
10
11
12
Sample Number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Pendulum swing height difference
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1400
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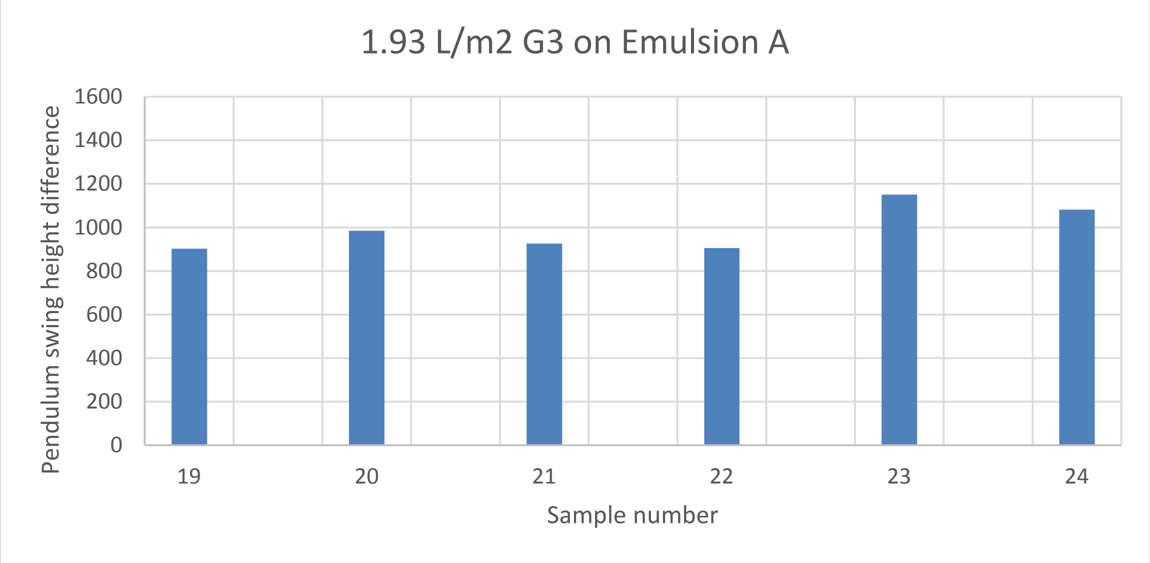
Sample number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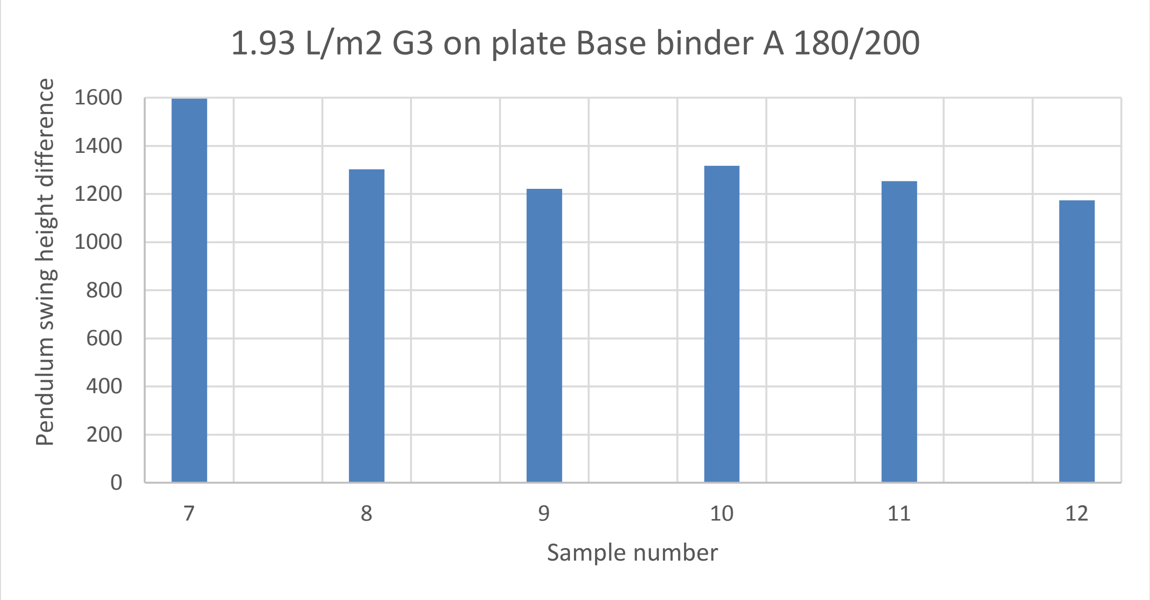
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Pendulum swing height difference
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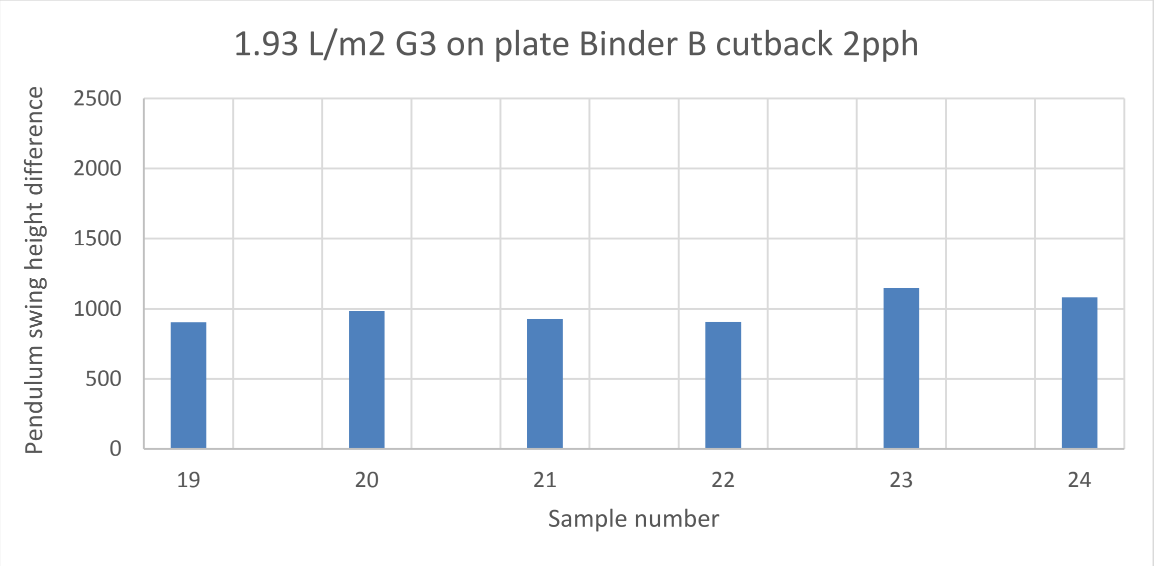
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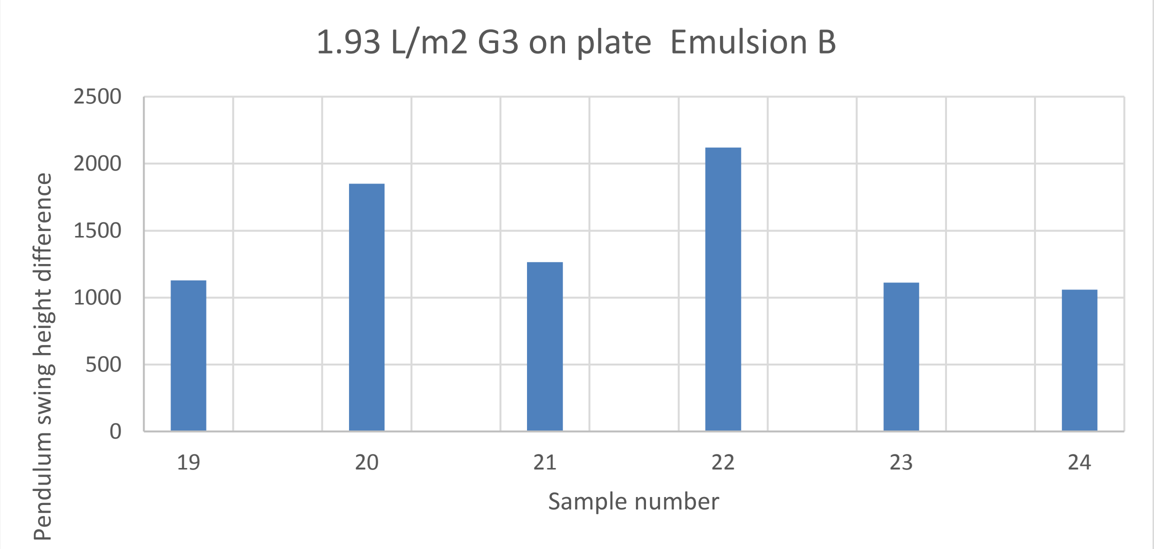
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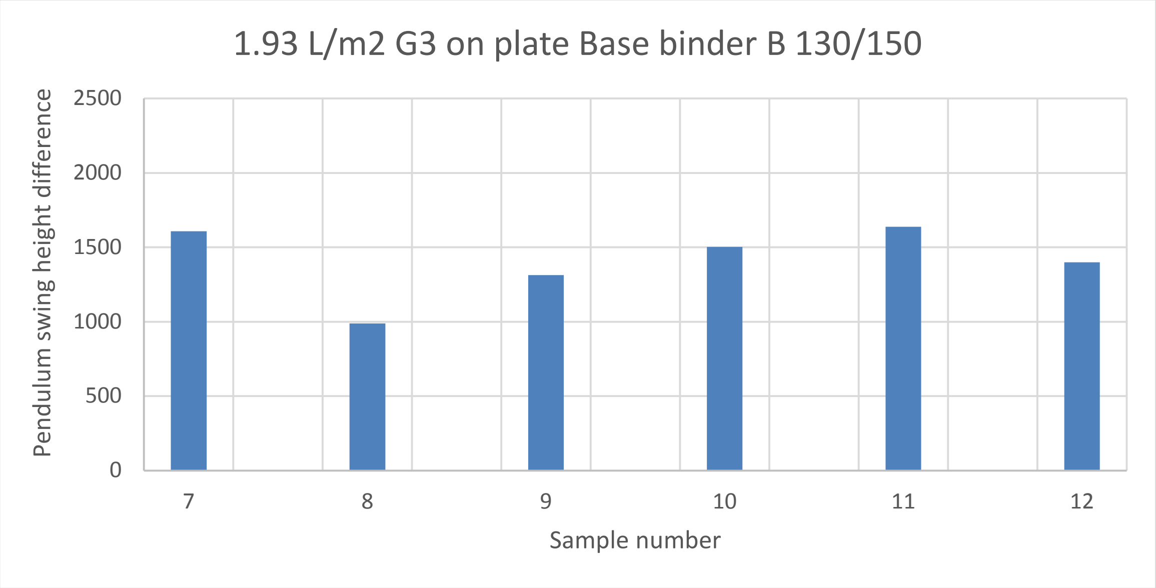
1.93 L/m2 G3 on plate Base binder B 130/150