Epoxy modified bitumen chip seals
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An important note for the reader

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Abbreviations and acronyms

EMOGPA	epoxy modified bitumen open-graded porous asphalts
OGPA	open-graded porous asphalts
pph	parts per hundred
SBS	styrene-butadiene-styrene
SH	state highway
Transport Agency	New Zealand Transport Agency
wt	weight

Contents

Executive summary

This report presents the results of exploratory investigations to assess the potential benefits of epoxy modified bitumen chip seals.

Epoxy bitumen is a form of polymer modified bitumen that has demonstrated advantages and is finding increasing application as a binder in asphalt mixes but has not been used in general chip sealing operations. The use of epoxy modified bitumen as a sealing binder was investigated as a potential means of reducing or eliminating some of the problems associated with conventional seals. In particular the research investigated whether epoxy modified bitumen seals might:

- be able to provide a treatment for flushed chip seal surfaces at reasonable life cycle cost
- act as a lower cost binder for high skid-resistant surfacing systems employing calcined bauxite aggregates
- have a lower rate of binder oxidation and offer the potential for very long-life seals (on low-volume roads where polishing is not an issue) and if so what are the estimated lifecycle costs
- provide enhanced binder to chip adhesion and resistance to water-induced stripping.

The epoxy modified bitumen used in this study was formulated and supplied curtesy of ChemCo Systems Ltd in San Francisco, USA. The epoxy materials studied were prototype materials supplied by ChemCo Systems Ltd with added accelerator to increase the rate of cure.

Curing rates and field test

Initially epoxy bitumen has a very high penetration (>200) compared with conventional New Zealand sealing grade bitumens and rapid curing (over a few hours) to a level comparable with normal binders was thought important to provide adequate strength for chip retention and prevent bitumen tracking. The curing rate was found to be more than adequate at realistic summer road temperatures. A test patch applied to SH73 near Darfield confirmed that the curing rate of the epoxy bitumen was sufficiently rapid to allow seal construction within the same time constraints as conventional seals. The test patch was constructed in cold winter conditions in August 2014 and a problem with chip loss through brittle failure of the bitumen was observed. This might have related to an inherent property of epoxy bitumen or could have been due to the use of an additive to accelerate curing (in general too rapid curing can have adverse effects on epoxy materials and increase brittleness). It should also be noted that cohesive energy measurements at 0.2ºC suggest that standard 80–100 or even 180–200 bitumens might have failed similarly under the cold conditions at the test site. The road test highlighted the need for additional work focusing on the low temperature properties of the epoxy bitumen especially as it cures.

Adhesion and resistance to water-induced stripping

The epoxy binders showed excellent adhesion and resistance to water stripping without the need to add adhesion agents. This is an important finding as commonly used amine-based adhesion agents would probably react with the epoxy resin and become ineffective and also reduce the ability of the epoxy resin to cross link.

Application as binders for high-friction surfacings

Although curing at a rate suitable for normal chip sealing operations, the epoxy bitumens did not achieve cohesive energy levels comparable to those of commercially available high-friction surfacing binders quickly enough to be useful.

Durability

Experiments to assess the durability and resistance to oxidation of the epoxy bitumen did not highlight any problem with the epoxy bitumen. The epoxy bitumen demonstrated a large increase in strength after accelerated ageing probably due to extensive curing rather than oxidation and reached a level comparable to or exceeding that of the commercial, high-friction surfacing binders tested.

Prevention of flushing

A major finding of this work was that (after at least five days curing at 35ºC) the binders were able to prevent chip embedment in a simulated soft, flushed seal. The low 'tack' of the cured binders also meant they did not retain aggregate fines; an epoxy bitumen seal would be less likely to lose texture through the void volume filling with fines compared with conventional seals. Both of these observations indicate that epoxy bitumens may have significant practical benefits in reducing or eliminating flushing in chip seals.

Recommendations

The results of this exploratory study demonstrated the potential for epoxy bitumens to resist flushing and this should be explored more thoroughly. Laboratory and field trial work is needed to explore the effect of important parameters such as temperature and higher tyre loadings on flushing resistance in order to assess the practical benefits and costs more accurately.

The low temperature behaviour of epoxy bitumen needs to be studied in more detail to investigate the causes of the apparent brittle behaviour observed in the field test. The materials used in this study were prototype formulations and changes may be needed to optimise low temperature flexibility.

Abstract

The research investigated aspects of the use of epoxy modified bitumen for construction of chip seals. Changes in the shear modulus, needle penetration and cohesive energy of the epoxy bitumen were used to monitor changes in the material as it cured at 35ºC and 45ºC and after accelerated ageing at 85ºC for 177 days. Wheel-tracking tests were used to determine the ability of the material to resist chip embedment and flushing. The adhesion to aggregate and resistance to water-induced stripping was also measured. Epoxy bitumen curing rates would enable seal construction within timeframes used with conventional binders. However, although the ultimate strength of the materials was satisfactory, the curing rate would be too slow for epoxy bitumens to be useful as a lower cost substitute for commercially available high-friction surfacing binders. Epoxy bitumen demonstrated good resistance to water stripping without added adhesion agents. Epoxy bitumen seals were highly effective in resisting chip embedment into a soft substrate and potentially might be a means of controlling or eliminating flushing in the field. The materials used in this study were prototype formulations that may need to be optimised for low temperature flexibility. Further investigation is needed to properly characterise low temperature behaviour.

1 Introduction

1.1 Purpose of the research

Chip seals are the predominant road surfacing used in New Zealand, comprising over 90% of the sealed road network (the rest being asphalt mix of various types). The two key performance requirements for chip seal surfacings are to provide a skid resistant riding surface and to prevent water ingress into the pavement structure beneath. Unfortunately seals often fail to meet these requirements due to problems such as chip loss, texture loss (flushing) and cracking which develop over time and ultimately require resurfacing, rehabilitation (overlays) or complete reconstruction of the roadway.

Epoxy bitumen is a form of polymer modified bitumen that has demonstrated advantages and is finding increasing application as a binder in asphalt mixes (see below). The potential benefits of using epoxy modified bitumen as a sealing binder were investigated during the research as a means of reducing or eliminating some of the problems associated with conventional seals. In particular the research investigated whether epoxy modified bitumen seals might:

- be able to provide a treatment for flushed chip seal surfaces at reasonable life cycle cost
- act as a lower cost binder for high skid-resistant surfacing systems employing calcined bauxite aggregates
- have a lower rate of binder oxidation and offer the potential for very long-life seals (on low-volume roads where chip polishing is not an issue)
- provide enhanced binder to chip adhesion and resistance to water-induced stripping.

The application of epoxy modified binders for general chip sealing operations on the wider road network (as opposed to temporary surfacings on bridge decks) is a new concept and suitable plant and binder materials are not as yet commercially available. The research presented here is thus a preliminary investigation to explore aspects of the likely performance of such surfacings, rather than a comprehensive study.

1.2 Epoxy modified bitumen

Epoxy modified bitumen was originally developed by Shell Oil in the 1960s as a specialist binder for asphalt mixes. Commercially available epoxy bitumen is a two-part system consisting of specially formulated epoxy resin and a hardener-bitumen blend. As with standard epoxy materials the two components are mixed just prior to use and curing takes place over time. Epoxy modified bitumen is significantly different from common, rapid curing epoxy materials such as those used in adhesives or in high-grip surfacing formulations.

Epoxy modified bitumen uses a slow acid-curing chemistry so that it can be handled and applied at high temperatures (100–150°C) without excessive curing. Like other epoxy materials, epoxy modified bitumen is thermosetting (ie it will not melt once cured) and cures to a flexible rubbery consistency at room temperature (rather than a brittle ‘glass’). Chemical changes on curing and oxidation of epoxy bitumen have been studied by Herrington and Alabaster (2008).

The formulation of commercially available epoxy bitumens is proprietary but the mixed product typically consists of about 20% wt epoxy resin and hardener and 80% of an approximately 80 penetration bitumen.

1.2.1 Application in asphalts

Epoxy modified bitumen technology has improved significantly since its first introduction and has found a niche application in providing very long-life asphalt surfacings for high deflection bridge decks (Balala 1969; Rebbechi 1980; Gaul 1996). The Bay Bridge in San Francisco for example was surfaced with epoxy asphalt in 1976–77 which is still in service today (35 years later) carrying 27,000 vehicles per lane per day (Lu et al 2012). Epoxy asphalts are characterised by a high modulus, fatigue resistance, resistance to permanent deformation (rutting) and damage from fuels and oil (Burns 1964; Dinnen 1981; Mayama 1997).

Recently the potential benefits of the application of epoxy modified bitumen in asphalts for general road surfacing applications have been demonstrated through an OECD project involving research agencies in New Zealand, Europe and the USA (Widyatmoko et al 2006; OECD 2008). Research funded by the NZ Transport Agency (the Transport Agency) formed part of the OECD project and focused on epoxy modified bitumen open-graded porous asphalts (EMOGPA). EMOGPA was found to offer the potential for open-graded porous asphalt with lifetimes in the field well in excess of 30 years compared with a typical life of 8–12 years (Bartley Consultants 1999; Fletcher and Theron 2011) for standard open-graded porous asphalts (OGPA). The work resulted in successful full-scale trials being constructed at the Canterbury Accelerated Testing Indoor Facility (CAPTIF) (Herrington et al 2007; Herrington and Alabaster 2008) and on the Main North Road in Christchurch in 2007 (Herrington 2010; Alabaster et al 2012). Several related research projects have been completed since that time, further demonstrating the potential benefits of epoxy OGPA performance and in particular the potential for reducing costs by diluting commercially available epoxy binder with standard bitumen (Herrington 2010). An additional large-scale trial (430 tonnes) of epoxy OGPA was conducted on the Christchurch Southern Motorway in 2012 (Herrington 2013).

In general, epoxy modified asphalts have been found to have very high strength, fatigue resistance and resistance to oxidative degradation. The only drawback with the material from an engineering perspective is the fact that curing limits the handling time available for manufacture and construction of asphalt mixes to about 60–90 minutes. Manufacture of epoxy asphalt is straightforward with only minor modifications needed to the asphalt plant to allow in-line blending of the epoxy components (before entering the drum). No changes to plant or procedures are needed to lay the mix.

1.2.2 Application in chip seals

‘High-grip’ surfacings employing calcined bauxite chip and pure epoxy, polyurethanes or other thermosetting polymer binders have been widely used since the 1970s. However the use of epoxy-modified bitumen for chip sealing operations does not appear to have been reported. The only application of epoxy bitumens in chip seals has been as temporary surfacings on bridge decks undergoing resurfacing with epoxy asphalt. The seal acts as a temporary wearing course and provides a good bond to the steel bridge decking and mechanical interlock with the overlaid epoxy-bitumen asphalt. Construction of these seals involve hand spraying of steel deck sections, application and rolling of a small size chip and accelerated curing (heating) if necessary. The temporary seals can be trafficked but are usually covered within hours or days with an epoxy asphalt wearing course and there is no data on the long-term performance as stand-alone surfacings.

2 Materials and methods

2.1 Binders

The epoxy modified bitumen used in this study was formulated and supplied courtesy of ChemCo Systems Ltd in San Francisco, USA. For practical chip sealing operations it is important that the road can be opened to traffic within a few hours or less of construction. The epoxy bitumen manufactured by ChemCo and used in the earlier work on epoxy OGPA discussed in section 1.2.1 (Type V) has an initial viscosity, on first mixing, much lower than that of 80–100 penetration grade bitumen and was considered too slow in curing for the present application. ChemCo manufactures a faster curing grade as the bond coat for applying epoxy asphalt to bridge decks (Type 1d) and this was further modified by the addition of a proprietary accelerator at the 2% and 5% wt levels (referred to as '2% epoxy bitumen' and '5% epoxy bitumen' respectively.

For testing, the binder was prepared by mixing 86.4% wt part B (bitumen-hardener-accelerator) with 14.6% wt of part A (epoxy resin). The part A material was the same as that used for preparing the epoxy binder used in the epoxy OGPA research. Unless otherwise stated the two components were heated separately to 100–110ºC and mixed for approximately 10–20 seconds before use.

Bitumens used in control experiments were penetration grade bitumens conforming to the *NZTA M/1* specification (NZ Transport Agency 2011).

2.2 Aggregates

The aggregates used were an *NZTA M/6* grade 3 greywacke sealing chip (NZ Transport Agency 2005) from the Horokiwi quarry, Lower Hutt. The aggregates were re-sieved and the fraction passing 13.2mm and retained on the 9.5mm sieve was used. The aggregates were washed and oven dried at 105ºC.

The 'asphalt sand' used in the preparation of the mastics for the flushing study (see section 4.2) was not graded. The largest particle size was approximately 4–5mm.

2.3 Modulus and viscosity measurements

Measurements were made of epoxy bitumen curing behaviour by following the change in the shear modulus value. Binder moduli were measured using a Rheometrics AR2000EX rheometer with an 8mm parallel plate geometry. A slight excess of sample was placed onto the bottom plate at the desired test temperature (±0.1ºC). The upper plate was lowered to 1.05mm, the sample trimmed and the gap closed to 1.000mm. At intervals a set of 10 oscillations at 1% strain and 10Hz were made and the average moduli recorded. Control samples were treated in the same way.

The viscosity at 50ºC (0.005 s^{-1} shear rate) of control bitumens from the durability test work, were measured on the rheometer using a 25mm diameter cone and plate geometry.

2.4 Resistance to flushing

2.4.1 Chip embedment

A wheel tracking device was used to compare the effectiveness of the epoxy bitumen in resisting chip embedment and seal deformation. Test samples were prepared on 4mm steel base plates (800mm x 300mm) with raised wooden borders (40mm deep). Each plate was separated into three equal compartments (approximately 220mm square) in order to prepare three identical samples per plate. Each compartment was filled to approximately 30mm deep with a 10% 180/200 bitumen-sand mastic that acted as the chip seal base. The same 180/200 grade bitumen sample was used for all the mastic samples which, when compacted by hand, reached approximately 9% void volume. The mastic plates were allowed to cool at least overnight prior to chip sealing.

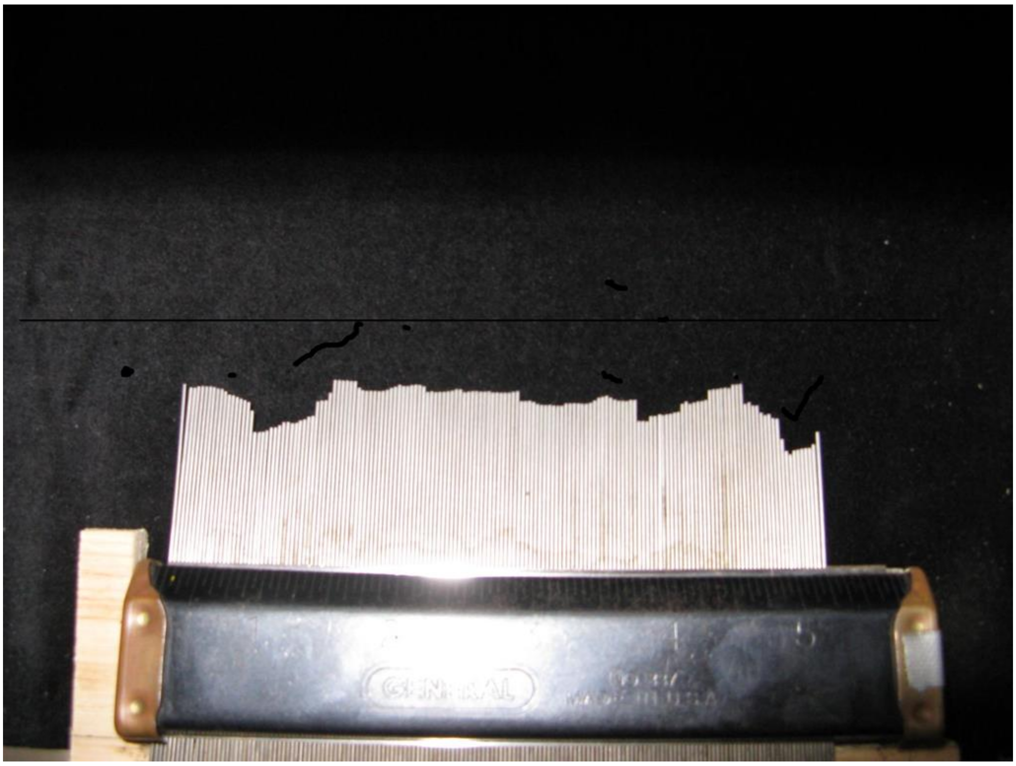
Chip seals were prepared by mixing the epoxy bitumen components at 100ºC to 110ºC for 1–20 seconds and immediately spreading 80 ± 5g of the hot bitumen over the mastic surface so that a layer approximately 1–2mm thick was formed. Chips were then spread over the bitumen layer. As the bitumen rapidly cooled to near room temperature the chips were preheated to 70ºC to ensure good adhesion. The chips were not rolled to prevent premature embedment into the mastic layer. The finished plates were then transferred into the wheel tracker box which was maintained at 35 ± 2ºC for several hours (at least overnight) so that the entire sample would achieve 35ºC prior to tracking. Epoxy-bitumen chip seals were allowed to cure in the wheel tracker box at 35ºC for predetermined times (1–20 days) prior to tracking.

The Opus Research wheel tracker (figure 2.1) has a pneumatic ram inside an insulated, temperature controlled cabinet that reciprocates a 10 inch trailer tyre and 100kg load (207kPa) at 1.6km/h^{-1} over the sample plate. The sample plate can simultaneously be moved sideways to mimic wheel wander, but in the present case a single wheel path was used.

Samples were tracked at 35ºC for pre-determined times (2, 4, 7 and 12 hours) and then measured after each period using a pin-profiler (figure 2.2) On seals showing a significant amount of embedment talcum powder was applied to the tyre to reduce bitumen pick-up and tracking. The profiler was slightly wider than the rut placed in the same position each time on the sample with the aid of reference marks. The profiler was mounted in a jig in a fixed, reproducible, position relative to a reference line and photographed in silhouette. The image was processed using MatLab software to determine average change in pin position from the zero time measurement and hence the change in average depth across the width of the rut.

Figure 2.1 Wheel tracking device with three compartment test plate in position

Figure 2.2 Pin profiler device used to measure texture depth



Control samples using 180–200, 80–100 and 40–50 penetration grade bitumens were tested in the same way (including 'curing' periods) as that described for the epoxy bitumens but the plates were prepared with the bitumen at 120º–130ºC due to the higher viscosity of the standard materials.

2.4.2 Fines retention test

The potential for epoxy bitumen to retain windblown detritus and fines from aggregate was investigated by assessing the 'tackiness' of the epoxy bitumens.

Plates of bitumen were prepared as in described in section 2.6.1, cured for various times at 35ºC and placed in a constant temperature room at 23ºC, 48% humidity for 17 hours to come to temperature. A known mass of asphalt sand (50 ± 1g, see section 2.4) also at 23ºC was sprinkled by hand over the plate and allowed to settle under its own weight (without rolling) for 24 hours. The total weight of the plates plus fines was recorded. After the required test time had elapsed each plate was placed upside down in a test frame where the edges were supported on three pins. The back of the plate was immediately subjected to a single impact from a steel ball (0.641kg) dropped from a height of 0.52m. Each test was repeated on four separate plates. The weight of fines lost was recorded.

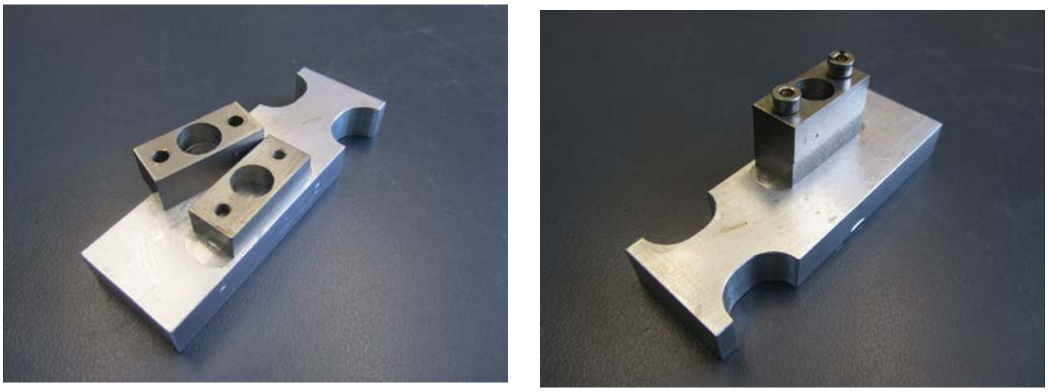
Control samples using 180–200 and 80–100 penetration grade bitumens were tested in the same way as that described for the epoxy bitumens but the plates were prepared with the bitumen at 120º–130ºC due to the higher viscosity of the standard materials.

2.5 Cohesive energy measurements

Changes in the epoxy bitumen properties through curing and oxidation were measured using a Vialit cohesion pendulum (figure 2.3). The energy required to separate two steel blocks glued together by the test bitumen is measured and equates to the cohesive energy of the binder. The instrument is described in European standard *EN 13588*.

Figure 2.3 (a) Vialit cohesion test pendulum, (b) standard sample holder, (c) modified sample holder, the holder is screwed together as shown in (d) and filled with bitumen forming a dog-bone shaped specimen. The screws are removed before the specimen is tested

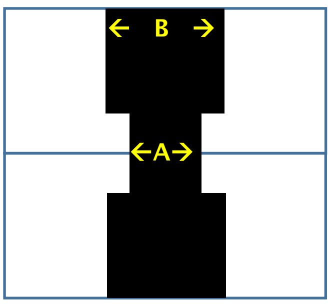
(a) (b)



(c) (d)

Testing of cured epoxy bitumen using the standard sample preparation system often resulted in adhesive failure of the bitumen to the sample holder rather than cohesive failure in the binder itself. For this reason a new sample holder that produced a dog-bone shaped specimen was developed to overcome this problem (figure 2.3(c) and (d) and figure 2.4). Specimens were prepared by mixing the epoxy bitumen components at 100º-110ºC for 10-20 seconds and immediately pouring them into the holders. The specimens were allowed to cool to room temperature for 15 minutes, trimmed of any excess bitumen and placed in a water bath at the test temperature (±0.1°C) for 1-1.5 hours and then tested. The pendulum testing device had no temperature control system so some cooling from the test temperature was inevitable but this was considered negligible given that the specimen could be mounted and tested within five seconds.

Figure 2.4 Schematic of dog-bone specimen A = 10mm, B= 12mm. The overall length of the specimen was 22mm, the neck length was 6mm



Control samples using 180–200 and 80–100 penetration grade bitumens were tested in the same way as that described for the epoxy bitumens but the specimens were prepared with the bitumen at 120º–130ºC due to the higher viscosity of the standard materials (165ºC for the polymer modified bitumen).

2.6 Durability

The effect of oxidation and extensive curing, such as may occur after long periods in the field, was investigated by measuring the change in cohesive energy after accelerated ageing. Specimens of 2% epoxy bitumen and 180–200 bitumen as the control were prepared as described in section 2.5 and placed in an oven at 85 ± 1ºC. At intervals specimens were removed and the cohesive energy measured at 45ºC as above.

After each test the control bitumen was scraped from the holder, mixed and air bubbles removed by treatment in a vacuum oven at 100ºC and –206kPa pressure. The viscosity of the bitumen was measured (section 2.3) and used to estimate the equivalent field age of the test period.

2.7 Adhesion and water-induced stripping

The ability of epoxy seal bitumen to resist water-induced dis-bonding (stripping) of aggregate was investigated using a variation of the Vialit plate test.

The epoxy bitumen to be tested was mixed at 100º–110ºC for 10–20 seconds and immediately poured onto a galvanised iron plate (0.2 × 0.2 × 0.001m thick) maintained at about 100ºC on a hotplate. The plates were modified from the usual flat plates by addition of a 5mm raised lip to prevent bitumen run-off and to more easily obtain a uniform distribution of bitumen across the plate. The bitumen (40±1g) was spread for 30–60 seconds to obtain a 1–1.5mm layer.

The plates were placed in a constant temperature room (23ºC, 48% humidity) to cure for various times. Ninety chips (wet, damp or dry also at 23ºC) were placed on the plates by hand so they did not touch each other and allowed to bond for up to 17 hours with the bitumen without any rolling. The sample plates were immersed in a water bath (housed in the same temperature controlled room) for 24 or 48 hours. Each plate was then removed from the water bath, drained and placed upside down in a test frame where the edges were supported on three pins. The back of the plate was immediately subjected to a single impact from a steel ball (0.641kg) dropped from a height of 0.52m. Each test was repeated on four separate plates. The number of chips leaving the plate were counted, the higher the number, the weaker the chip-bitumen bond. Chips that left the plate with a significant amount of bitumen adhered (ie the bitumen film fractured rather than the chip-bitumen bond), were counted as having been retained.

Control samples using 180–200 and 80–100 penetration grade bitumens were tested in the same way as that described for the epoxy bitumens but the plates were prepared with the bitumen at 120º–130ºC due to the higher viscosity of the standard materials.

For the tests, dry chip was defined as chip that had been washed and dried at 105ºC then stored at 23ºC and 48% humidity. Damp chip was washed and soaked in water overnight then patted 'dry' with a paper towel and wet chip was soaked overnight and drained only (figure 2.4).

Figure 2.4 Wet chip used in the adhesion tests

3 Curing behaviour of the epoxy bitumen

A likely scenario for practical application of epoxy modified bitumen in chip sealing would involve a modified bitumen sprayer in which the two binder components are mixed just prior to the spray bar using a static in-line mixer. The temperature of the components must be such as to allow easy pumping and efficient mixing when combined. Obviously this will depend on the formulation of the products. For the ChemCo binders used in this study, temperatures of 90ºC (for part A) to 130ºC (part B) would be suitable.

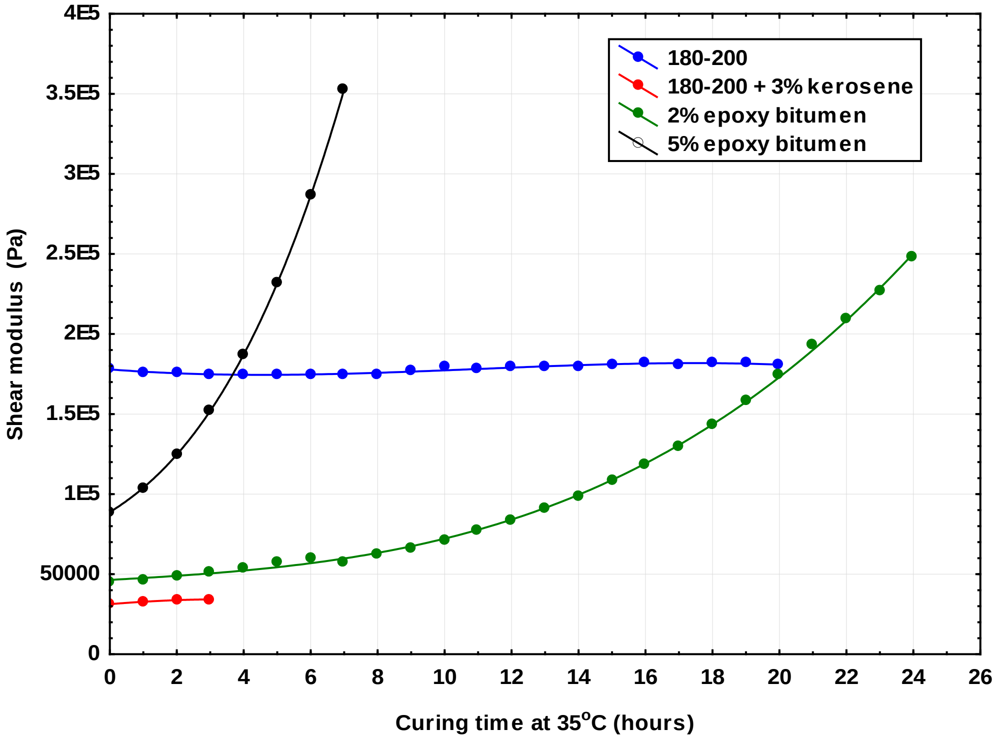
Once sprayed, the thin film of binder will rapidly cool to ambient road temperature (probably 30º–50ºC in summer) and further curing will be much slower. The viscosity of the binder will also increase as the temperature drops. The viscosity must remain low enough to achieve good chip wetting and allow chip movement during rolling and to allow compaction by traffic over the next few days or weeks.

The length of time the mixed components are at a high temperature in the sprayer lines before striking the road will affect the viscosity achieved. In practice this time is likely to be only in the order of seconds so that experiments conducted to measure the behaviour of curing rates have modelled this. Curing was followed by changes in the shear moduli, penetration values and cohesive energy of the epoxy bitumen at two temperatures (35ºC and 45ºC) typical of spring-summer road temperatures. The cohesive energy is the energy required to fracture or ‘pull apart’ the bitumen film and is a simple way of comparing the strength of the materials as curing progresses.

3.1 Changes in moduli and phase angle

Changes in the moduli and phase angle with time are shown in figures 3.1 and 3.2 for the 2% and 5% epoxy bitumen curing at 35ºC in the rheometer, after mixing at 100ºC for 10–20 seconds. The 5% epoxy bitumen cures more rapidly than the 2% and requires only about four hours to reach the modulus of the 180–200 control bitumen. As cutback bitumens are still commonly used in sealing work, results for the 180–200 bitumen with 3% kerosene have been included in the figure for comparison.

Figure 3.1 Effect of curing time at 35°C on the binder modulus (35°C, 10Hz, 1% strain)



The phase angle is a measure of the elastic nature of a bitumen. The lower the phase angle the more elastic the material. Both epoxy bitumens showed a decrease in phase angle as curing progressed but still remained more viscous in character than the 180-200 control over the period of the experiment. Qualitatively it was observed that the binders did become elastic after extended curing but for time periods and temperatures relevant to seal construction the high phase angle should be an advantage and aid in chip wetting and reorientation.

The effect of mixing temperature was investigated for the 5% epoxy bitumen. The mixing time was kept at 10-20 seconds as above but the temperature increased. The results in figure 3.3 show that for the short mixing times used the mixing temperature had little effect on the curing rate until up to about five hours after which the curves deviated with the higher mixing temperature giving rise to a higher modulus.

Figure 3.2 Effect of curing time at 35°C on the binder phase angle (35°C, 10Hz, 1% strain)

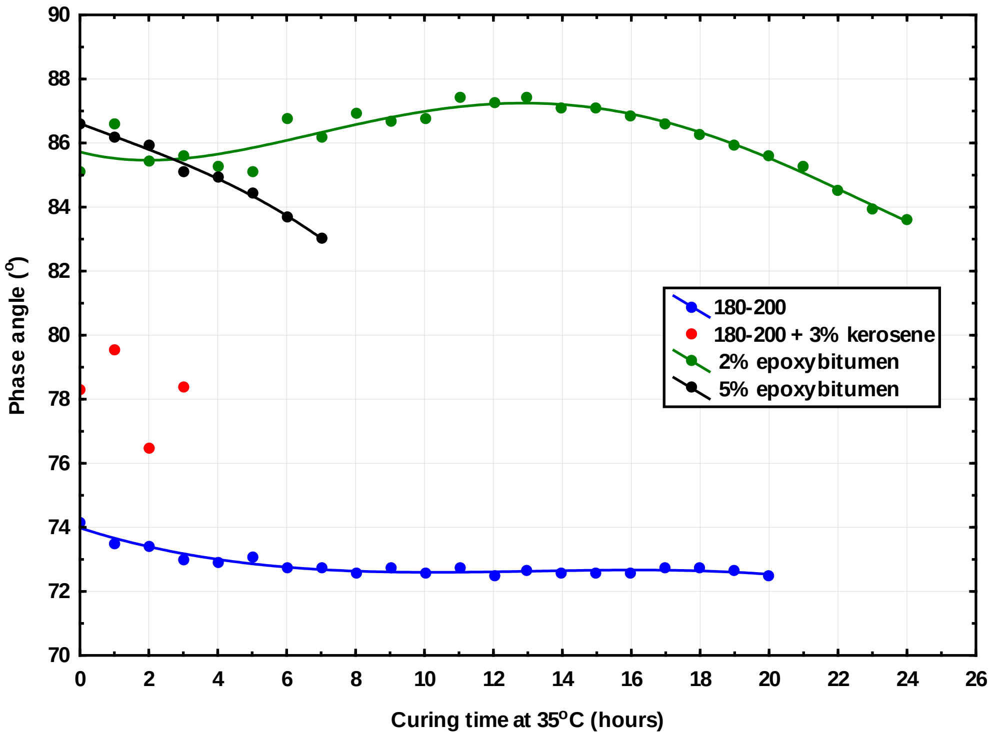
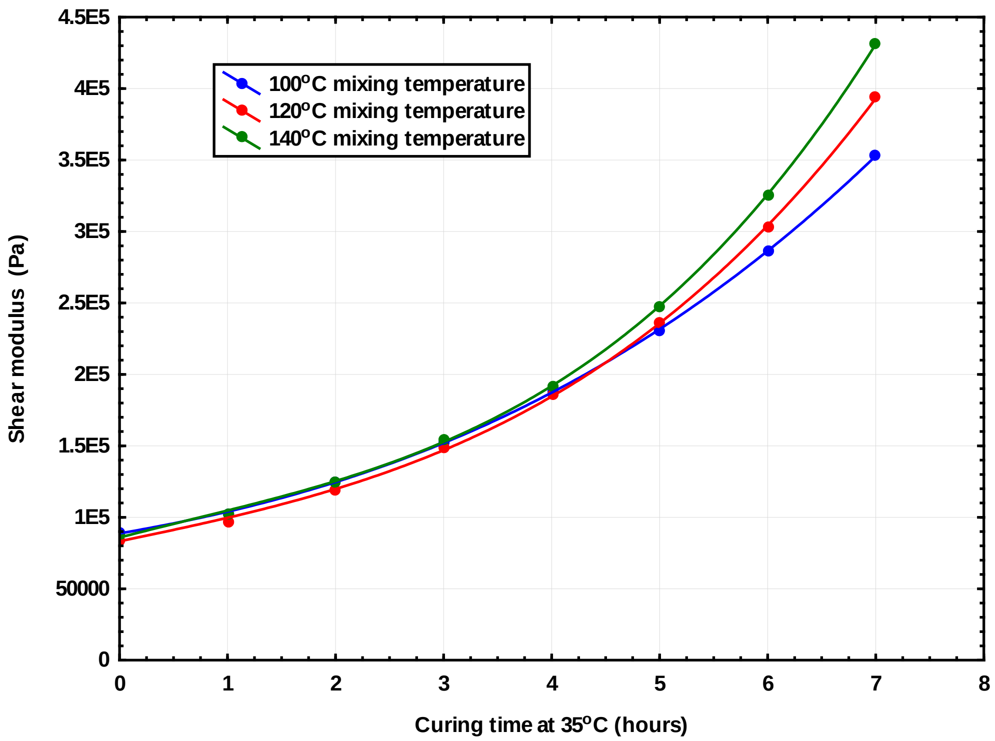


Figure 3.3 Effect of initial mixing temperature and curing time at 35°C on the binder modulus (35°C, 10Hz, 1% strain)

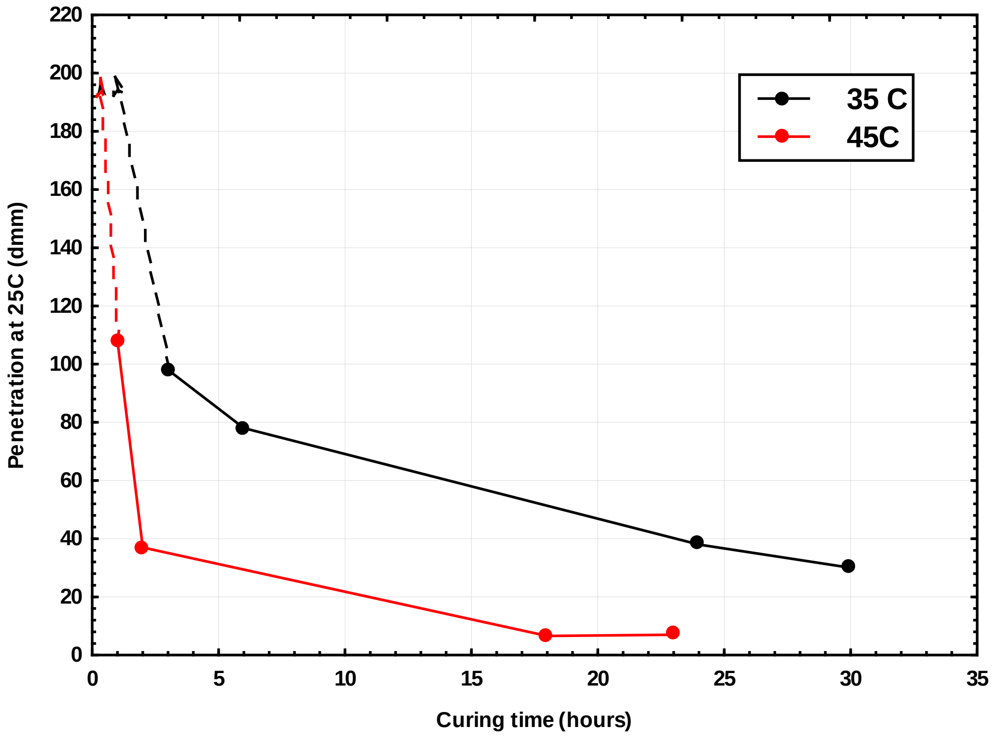


3.2 Changes in penetration

For comparative purposes the penetration of the 2% epoxy bitumen was measured as it cured at 35° and 45°C. The binders were mixed at 100°-110°C for 10-20 seconds and then immediately placed in an oven at the curing temperature. At intervals the samples were removed and brought to 25°C in a water bath (one hour), the penetration measured after a further hour according to ASTM D5 (ASTM 2013) and the samples replaced. Results are shown in figure 3.4. The initial (t=0) value was too high to measure precisely but was >220. The penetration of the unmixed part B was 107.

Curing is rapid initially and reached the 80-100 range after about three hours at 35°C. These times are probably faster than those likely to be achieved in the field as the large mass of the sample would take some time to cool from the mixing temperature. The times to reach control bitumen levels observed in the moduli measurements were somewhat longer at about 20 hours for the 2% bitumen at 35°C, probably because the very small masses of sample used equilibrated to the curing temperature more rapidly. Conventional bitumens (even emulsified bitumen) usually contain 1-3pph of kerosene. In that case the 'target' penetration or modulus level that the epoxy bitumen needs to meet to give confidence that the performance when first trafficked will be satisfactory, is much lower than that of the standard penetration grade bitumens.

Figure 3.4 Change in penetration (25°C) of the 2% epoxy bitumen after curing at 35°C. Penetration at zero time could not be determined but exceeded 220



3.3 Changes in cohesive energy

Due to time constraints only the 2% epoxy bitumen was tested in these experiments. The binders were mixed at 100°-110°C for the epoxy bitumens and higher temperatures for the control materials (see section 2.7) for 10–20 seconds. Measurements were made on the freshly mixed binder (without curing) to compare with penetration grade bitumens and also with a commonly used 4% styrene-butadiene-styrene (SBS) polymer in 80–100 bitumen material. Also tested was a dilution of the 2% epoxy bitumen, ie 25% by weight epoxy bitumen (parts A and B combined and 75% 180–200 penetration grade bitumen. Similar dilutions used in epoxy OGPA had proved to reduce the cost while still retaining significant benefits compared with control mixes (Herrington 2010).

Results are shown in figure 3.5 where the error bars represent the 95% confidence limits of the mean. The energy values are all lower at 45°C than at 0.2°C except for the 4% SBS binder for which the opposite is true. The results for the epoxy binders at 0.2°C are slightly lower than that for the penetration grade bitumens but the difference is not statistically significant. At 45°C, however, the epoxy materials have a somewhat lower cohesive energy than the standard materials which is not generally desirable but the difference was not maintained as curing progressed (see below) and would be unlikely to be of practical significance.

Figure 3.5 Cohesive energy of various binders measured at 45°C and 0.2°C (without curing)

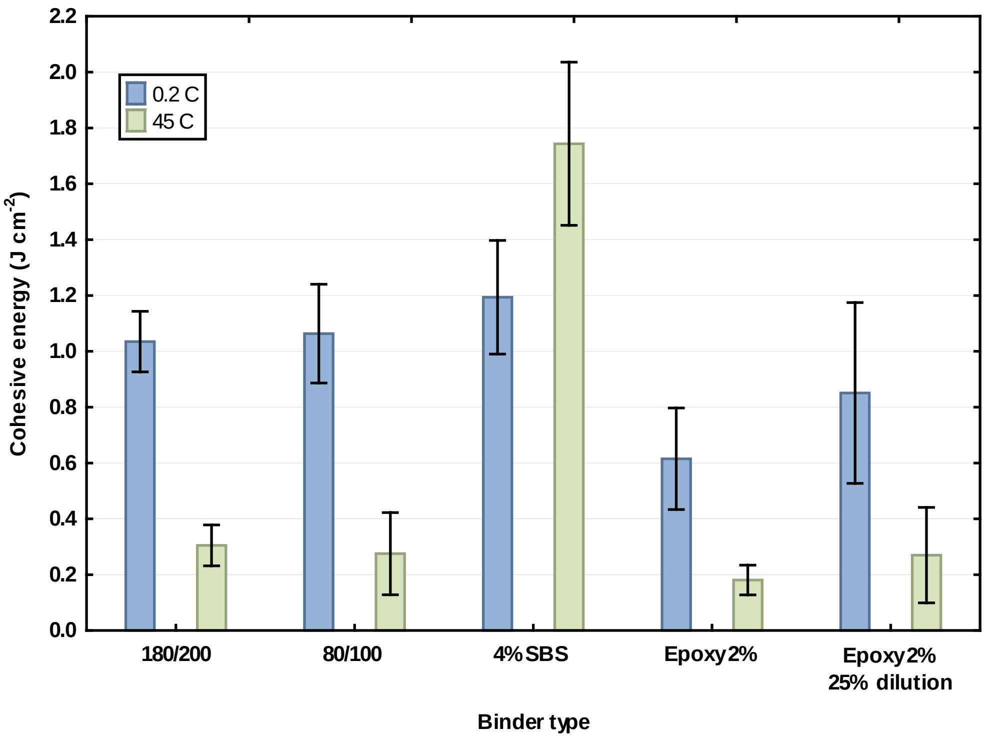


Figure 3.6 Effect of curing at 45ºC on cohesive energy at 45ºC

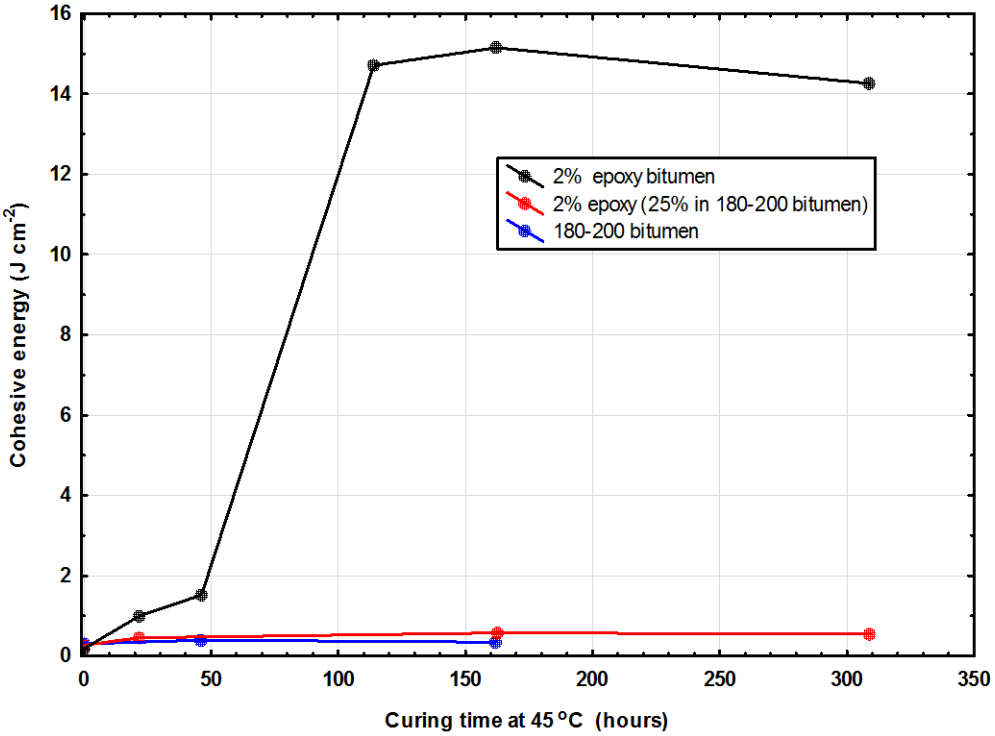
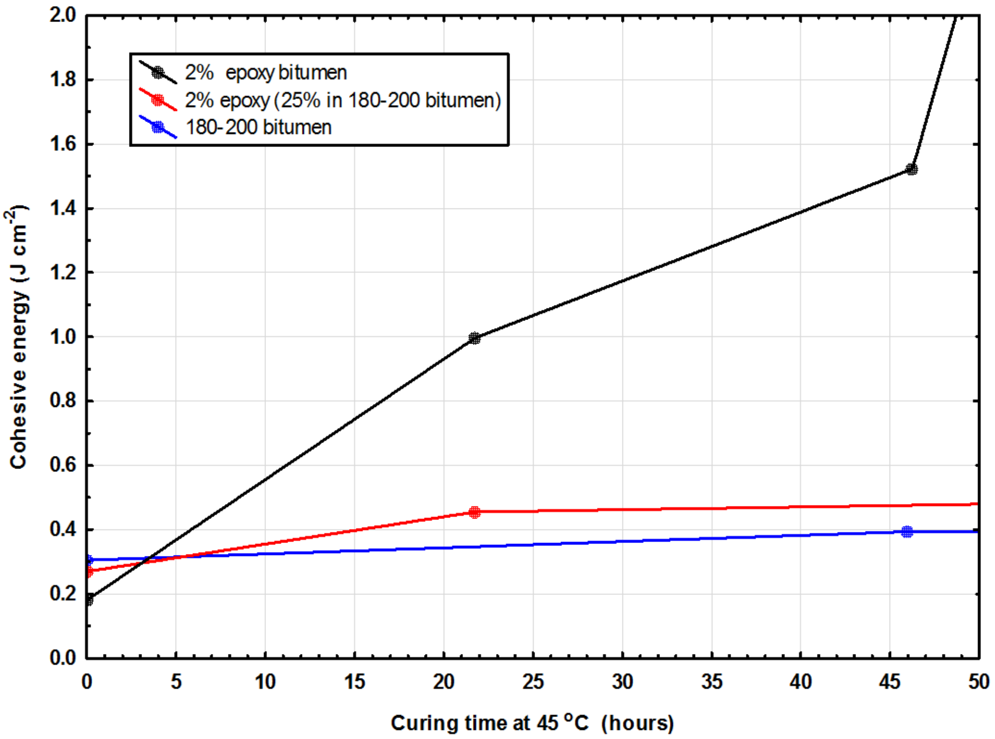


Figure 3.7 Effect of curing at 45ºC up to 50 hours on cohesive energy at 45ºC



To understand how the cohesive energy changed with curing time, test specimens of the 2% epoxy and 25% diluted epoxy bitumen were prepared and cured for various times at 45ºC, while 180-200 specimens were cured in an identical fashion as control. The results (figure 3.6) show that the 2% epoxy bitumen rapidly gained strength up to about 100 hours but changed little after that. Some strength gain was apparent in the 25% diluted epoxy bitumen, which had approximately doubled its cohesive energy after 309 hours, but was still within experimental error of the control bitumen value.

Figure 3.7 shows the data from zero to 50 hours. It is apparent that the 2% epoxy bitumen reached the cohesive energy of the 180–200 after about three hours, comparable to the ≤1 hours predicted by the penetration results in figure 3.4.

3.4 Summary

The experiments discussed above indicate that curing of the epoxy bitumens would be sufficiently rapid at typical summer temperatures to be practically useful, ie the seal could be opened to traffic within a few hours and the binder modulus, penetration or cohesive energy would, at the very least, be similar to that of conventional bitumens. The binders would continue to cure to give a much higher strength binder than conventional bitumens (at least when tested at 45ºC).

4 Resistance to flushing

Resistance of epoxy bitumen seals to flushing might arise in two ways:

1 Based on experience with epoxy bitumen OGPA mixes, the high modulus and elastic behaviour of the cured binder may act to reduce chip reorientation, embedment and shearing of the seal layer.

2 The high viscosity of the cured binder may reduce the 'tackiness' of the binder surface minimising the retention of aggregate wear fines in the bitumen layer (accretion of aggregate fines has been shown to be a major contributor to seal flushing (Herrington et al 2012).

Both potential mechanisms were investigated as discussed below.

4.1 Resistance to chip embedment

To measure the ability of the epoxy bitumen to resist embedment into a soft substrate, wheel-tracking experiments were carried out at 35ºC for up to 12 hours as described in section 2.4.1. The mastic substrate used was intended to simulate a flushed 'soft', multi-layer seal, but formulated to accelerate embedment to obtain results over a practical timeframe. Generally the hardness of flushed seals is likely to be greater that of the substrate used here so that the rates of embedment measured are comparative and cannot be directly related to rates in the field.

Initial experiments were conducted to determine a suitable mastic composition. Figure 4.1 shows the effects of tracking a 180–200 bitumen seal on top of mastics made with different proportions of bitumen (also 180–200) in the sand mastic. A 10% bitumen content was adopted as higher levels resulted in a too rapid embedment of the seal chip. The 10% bitumen content mastic had an air void content of about 9%.

Figure 4.1 Effect of differing proportions of bitumen in the mastic composition after about six hours tracking. The white material apparent on the chips is talcum powder used to minimise bitumen adhering to the tyre

Examples of sample plates after completion of a wheel-tracking experiment are shown in figures 4.2 and 4.3. Figure 4.2 shows the effects of a control test carried out using 180–200 bitumen seal after 12 hours of trafficking. Significant embedment of the chip in the wheel path has occurred. In contrast figure 4.3 shows that the 5% epoxy bitumen seal (after 10 days curing at 35ºC) shows no obvious damage after an equivalent 12 hours of tracking.

Even at low degrees of cure, neither pick-up nor tracking of the epoxy bitumen onto the wheel-tracker tyre was observed. At high degrees of cure (10–20 days at 35ºC) and after 12 hours of continuous tracking, the epoxy bitumen seals were virtually undamaged.

Figure 4.4 shows a cross section cut from the wheel path of 2% epoxy bitumen seal after 10 days of curing and after 12 hours tracking. The boundary between the mastic and epoxy bitumen layer remains very clear and no obvious embedment has occurred.

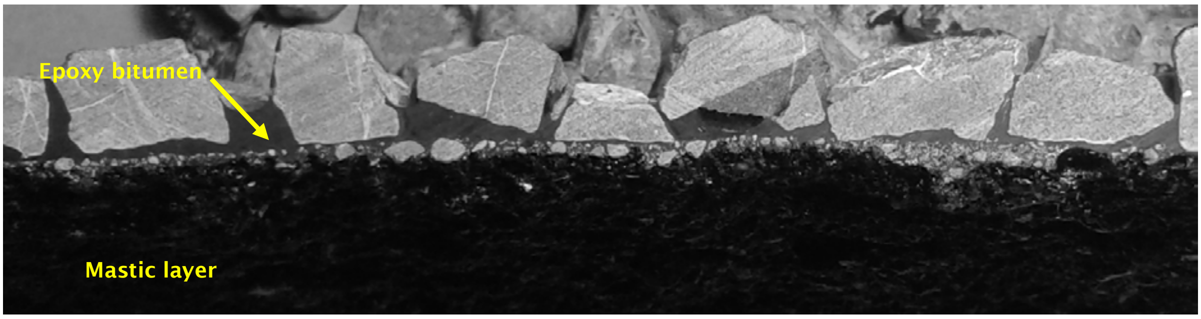
Figure 4.2 Example of the results of wheel tracking a 180–200 seal at 35ºC after (a) 0 hours, (b) 12 hours

(a) (b)

Figure 4.3 Example of the results of wheel tracking a 5% epoxy bitumen (10 days curing) seal at 35ºC after, (a) 0 hours, (b) 12 hours

(a) (b)

Figure 4.4 Cross section of the wheel path for a 2% epoxy bitumen seal after 10 days curing at 35ºC and 12 hours tracking



Measurements of the depth of rut formation were made as described in section 2.4.1 using a mechanical pin-profiler. Typical results can be seen in figure 4.5, which shows rut depth for two compartments of a test run with a 180–200 bitumen seal. The plates were divided into compartments not only for practical reasons to assist in ensuring a consistent mastic compaction density and even bitumen application rate for seal construction but also to increase the number of treatments that could be tested. The seal type in each compartment for any one test plate was randomised as far as possible so that all three compartments did not usually contain the same seal type. To compensate for the variability apparent in the results, mean rut depths were calculated from at least five or six separate compartments. A linear regression was applied to the rut depth-time data and the slopes (ie the average rate of rut formation) used to compare behaviour between bitumens.

Results for three control bitumen seals for the 2% and 5% epoxy bitumen seals cured for various times up to 20 days are summarised in figure 4.6. The mean rates for the 40–50, 80–100 and 180–200 bitumens appear to decrease in a counter-intuitive order but this is coincidental. An analysis of variance (ANOVA) comparing the three control seals, and the 1.67 and 5 days cured 2% epoxy bitumen seals, shows no statistically significant difference between them. A significant difference, however, appears when the 10–20 day cured seals are considered. The mean rate of rut formation for the control seals is 0.9mm/h^{-1} compared with 0.2mm/h^{-1} for the 10–20 day cured epoxy seals, ie about 4.5 times faster. In fact it is likely that the 0.2mm/h^{-1} rate measured for the 10 and 20 day cured epoxy seals largely just reflects deformation of the mastic layer as examination of the cross sections of some of these seals showed no apparent embedment (see figure 4.4).

The results show that epoxy seals have the potential to eliminate or reduce the incidence of texture loss when they are placed over already flushed and weak (unstable) seal layers. In the field, the rates of embedment are likely to be much slower than those measured here so the epoxy binders would have more than sufficient time to reach a satisfactory level of cure to operate effectively.

Although not included in the research, the measurement of seal hardness using a ball penetrometer device and comparing results with those obtained on the mastic used here may enable an approximate correlation to be established, which is useful for estimating field embedment rates for the epoxy bitumen seals.

Figure 4.5 Rut depth growth at 35ºC for three replicate 180-200 seals

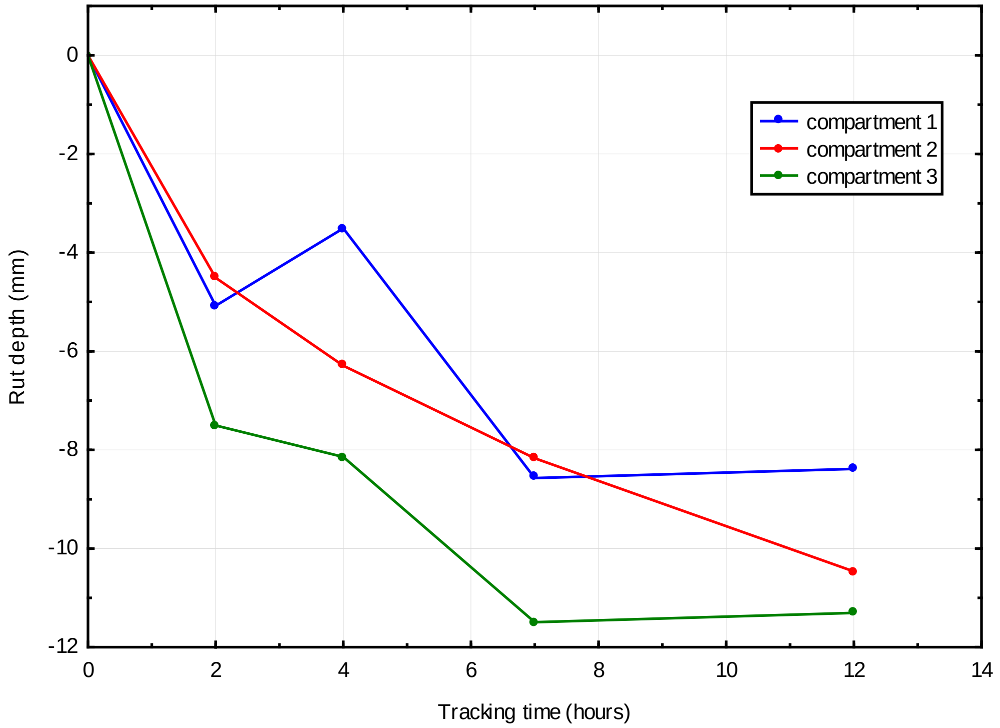
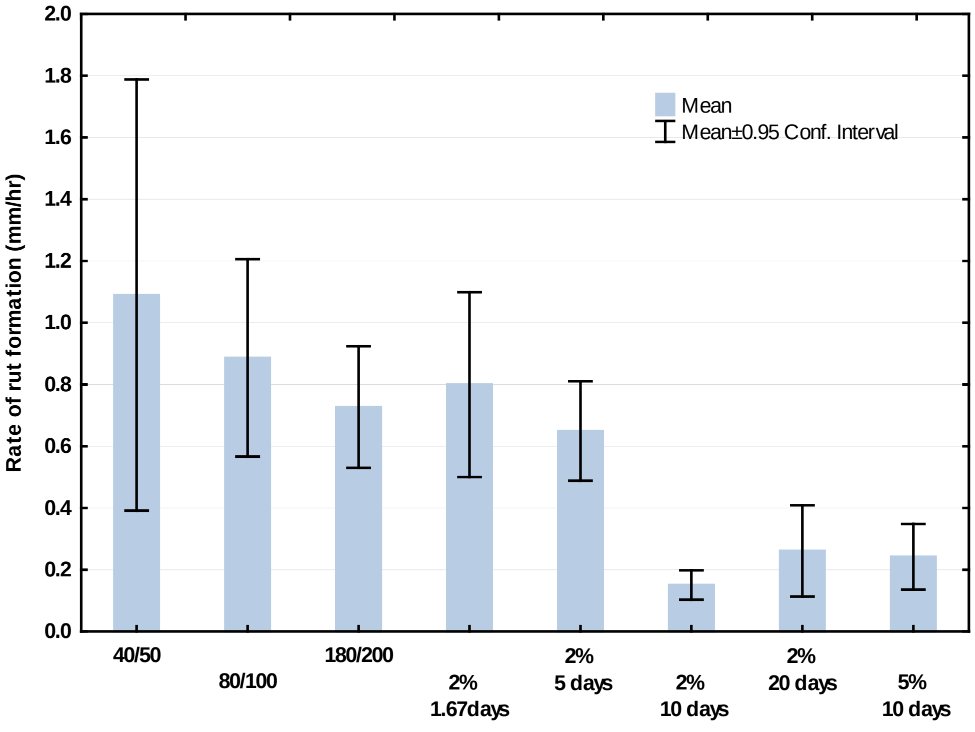


Figure 4.6 Mean rates of rut formation for control bitumens and 2% and 5% epoxy bitumens cured for different periods



4.2 Resistance to fines accretion

Texture loss also results from loss of seal void volume due to build up of fines from the breakdown of sealing chip under trafficking (Herrington et al 2012). Fine aggregate particles and dust are not lost from the road surface but are trapped as a bitumen mastic. As the epoxy bitumen cures it becomes less ‘tacky’, which may prevent fines attaching and allow time for them to be washed from the seal through the action of wind, rain and traffic. Conventional bitumens will also lose tack through oxidation but much more slowly.

A simple experiment was conducted to assess the adhesion of fines on epoxy bitumen. Fines (<4.75mm) were allowed to settle into films of bitumen under controlled conditions for a set time and the weight of material retained measured (see section 2.4.2). Results of these tests are given in table 4.1.

Table 4.1 Adhesion of fines to bitumen films after 24 hours contact at 23ºC

Binder	Curing time at 35ºC before addition of fines	Average % sand retained
2% Epoxy bitumen	0	46
	10 days	1
5% epoxy bitumen	0	33
	10 days	1
80–100 bitumen	0	19
	10 days	22

With little or no curing (except for the 17 hours at 23ºC) the epoxy bitumen shows better fines retention than the 80–100, which is consistent with it being ‘softer’ than the 80–100 allowing better wetting of the aggregate fines. After curing, however, the amount of fines retained is very much reduced as expected.

4.3 Summary

The epoxy bitumens cured for five or more days at realistic summer road temperatures, showed a marked ability to resist chip embedment into a soft substrate, and demonstrated considerable potential as a means to reduce or eliminate the rate of flushing caused by embedment and shearing of multi-layer seals. The cured epoxy bitumen appeared much less effective in retaining fines than 80–100 bitumen which should also help minimise seal texture loss.

5 Resistance to water-induced aggregate loss

When using epoxy seals for any application it is essential that a good bond is established to the chip that will resist water stripping. Conventional adhesion agents are usually added to conventional bitumen seals at 0.5 to 1% by weight. Adhesion agents are surface active compounds that resist the water-induced stripping that can occur if rain falls on the seal in the first few weeks of its life (which in New Zealand is highly likely). Most commercially available agents in use in New Zealand rely on the presence of amine groups in the molecule for their effectiveness. Amine groups may react with the epoxy bitumen, potentially reducing the effectiveness of both materials.

To assess the chip adhesion properties of the epoxy bitumens used in the research, experiments were conducted using a method based on the Vialit adhesion plate test as described in section 2.7. Results of the experiments are given in table 5.1. As expected the control bitumens lost large amounts of chip especially when wet chip was used. When dry chip was applied the epoxy bitumens did not lose any chip even allowing 17 hours curing before chip was added. After 17 hours curing the binder viscosity would have been higher and chip wetting less efficient. In practice in the field chip would be added almost immediately after spraying. Some chip was lost from two of the epoxy bitumen tests due to brittle cohesive failure in the bitumen, not loss of adhesion.

With damp chip, only the 5% epoxy bitumen with a 17-hour cure time lost chip due to adhesion although a significant number of chips were lost due to cohesive failure of the bitumen. The latter observation suggests that the binder may be more brittle than the control although this is not clear as essentially all chip lost from the control plates was because of adhesive failure (see chapter 8 for further discussion).

To further test the adhesive properties of the epoxy bitumen, wet chip was used with a shorter, more realistic, one-hour curing time but with 48 hours immersion. In these experiments large amounts of chips were lost through adhesive failure.

The high level of adhesion achieved by the epoxy bitumen except under extreme conditions suggests some chemical interaction between the epoxy bitumen and the aggregate above that achieved by the standard bitumen. The viscosity of the epoxy bitumen after curing for one or 17 hours at 23ºC is not known but extrapolation of the curing rate data at 35º and 45ºC in chapter 3 indicates that the viscosity is likely to have at least reached the level of the 180–200 penetration bitumen. The greatly superior adhesion observed is thus unlikely to be due simply to better wetting of the aggregate.

Experiments using adhesion agent were not carried out as the adhesion of the epoxy bitumen to the aggregate chips was extremely good under conditions where the control bitumens failed. The results indicate that epoxy seals could be used without the need for addition of adhesion agents.

5.1 Summary

Potential reaction between amine-based adhesion agents and the epoxy groups in the epoxy bitumen is a potential problem if conventional adhesion agents are to be used with epoxy bitumen. The results of adhesion tests, however, show that the epoxy bitumen has excellent adhesion to sealing chip and good resistance to water-induced dis-bonding without the need to use adhesion enhancing additives.

Table 5.1 Results of water-induced stripping experiments using dry chip (chip bonded for 17 hours, 24 or 48 hours immersion).

Binder	% chip lost
Dry chip	
180–200	66
80–100	78
2% epoxy bitumen, 1-hour cure	0
5% epoxy bitumen, 1-hour cure	0[(a)]
2% epoxy bitumen, 17-hour cure	0[(a)]
5% epoxy bitumen, 17-hour cure	0
Damp chip	
80–100	69
2% epoxy bitumen, 1-hour cure	0
2% epoxy bitumen, 17-hour cure	0
5% epoxy bitumen, 1-hour cure	30[(b)]
Wet chip	
80–100	98
2% epoxy bitumen, 1-hour cure, 48-hour immersion	51
5% epoxy bitumen, 1-hour cure, 48-hour immersion	80

[(a)] Several chips were lost with bitumen adhering

[(b)] An additional 30% of chips were lost with bitumen adhering

6 Durability

The resistance of epoxy bitumen to oxidation has been demonstrated previously through both chemical studies and accelerated oxidation studies with epoxy bitumen OGPA (Herrington and Alabaster 2008; Herrington 2010). The durability of epoxy OGPA is predicted to greatly exceed that made with penetration grade bitumen. The earlier work suggests that epoxy bitumen chip seals may also have a much greater durability in the field than those constructed with conventional bitumens. Failures typically ascribed to binder oxidation such as chip loss and cracking may be greatly reduced.

To assess the effect of both oxidation and extensive curing of the epoxy bitumens, the cohesive energy of the 2% epoxy bitumen at 45ºC was measured after 177 days in an oven at 85ºC as described in section 2.6. Ideally, tests would have been conducted at a lower temperature than 45ºC but it was considered likely (and correctly) that the cohesive energies reached might have been beyond the capabilities of the test instrument. Control specimens of 180–200 penetration bitumen were also oxidised for various times and the viscosity at 50ºC ($0.005s^{-1}$ shear rate) measured. The viscosity data was used to estimate an approximate, equivalent field age for the oven oxidation time. This was achieved by correlation with data from a similar-source 180–200 penetration bitumen exposed outdoors for 16 years in Lower Hutt (Herrington et al 2014 in press), shown in figure 6.1. The 177-day oven ageing time is approximately equivalent to 3.5 years in the field.

There was an increase in the cohesive energy for the two binders heated at 85ºC (markedly so for the epoxy bitumen) compared with the binder that was not heated (see figure 6.1). Most of this increase was probably due to curing and a level was reached about equal to that of the high-friction surfacing binders discussed in chapter 7.

Ultimately oxidation of the control bitumen might be expected to produce a brittle, weak material but the relatively thick film necessary for testing purposes reduced the oxygen available for reaction and this state was not reached even after 177 days. 'Brittle' failure in the field would not be expected after only 3.5 years. A longer testing period would have been desirable but was not possible within the scope of the current work. The epoxy curing reaction is, however, independent of oxygen, so the 177 days treatment at 85ºC probably represents much more than 3.5 years of actual field curing, as average road temperatures are 50–60ºC lower. The results indicate that the epoxy bitumen will continue to increase in strength as it ages in the field but further work is needed to investigate long-term behaviour (especially at low temperatures), in more detail.

6.1 Summary

Unfortunately it was not practical within the constraints of the current project to oxidise specimens beyond about the equivalent of 3.5 years in the field. The strength of both control and 2% epoxy bitumens increased, the latter much more so, probably mainly due to curing reactions. The curing process is not affected by oxygen availability and so the 177-day, 85ºC treatment is likely to represent a far greater equivalent field age. The results show that the epoxy bitumen will continue to increase in strength (at least at 45ºC) as the seal ages.

Figure 6.1 Equivalent field ageing time for specimens treated in the 85ºC oven

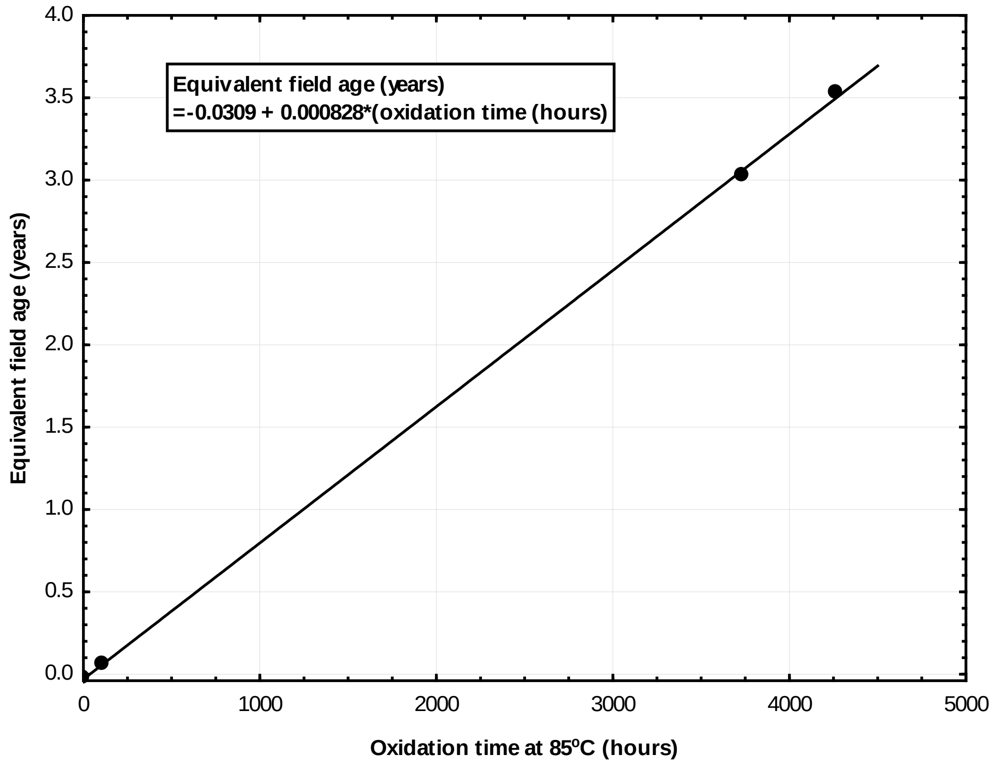
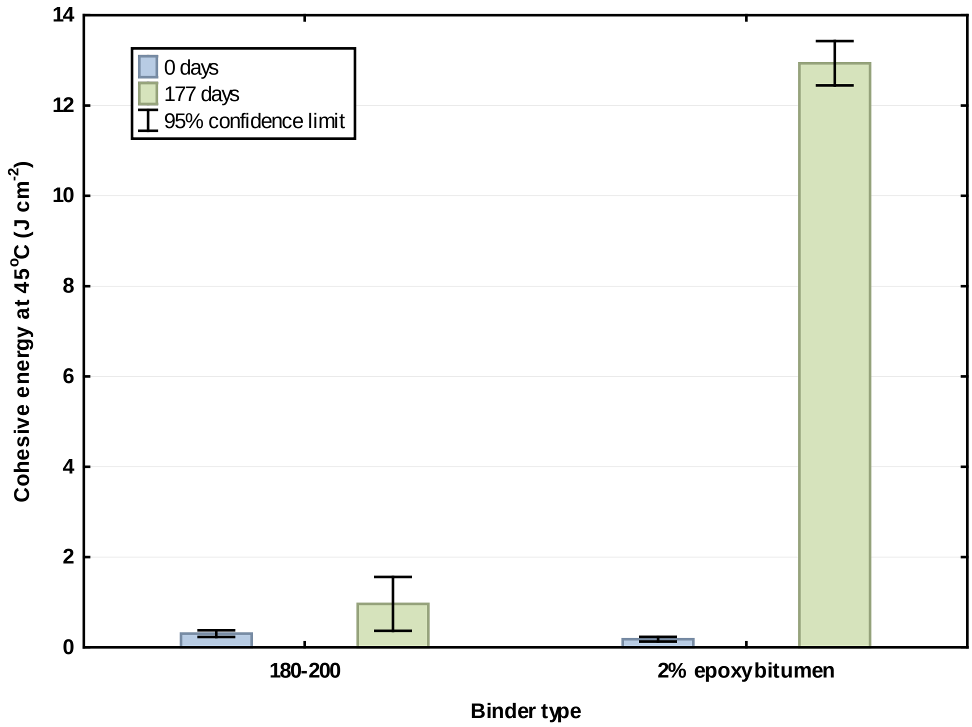


Figure 6.2 Effect on cohesive energy of heating at 85ºC for 177 days



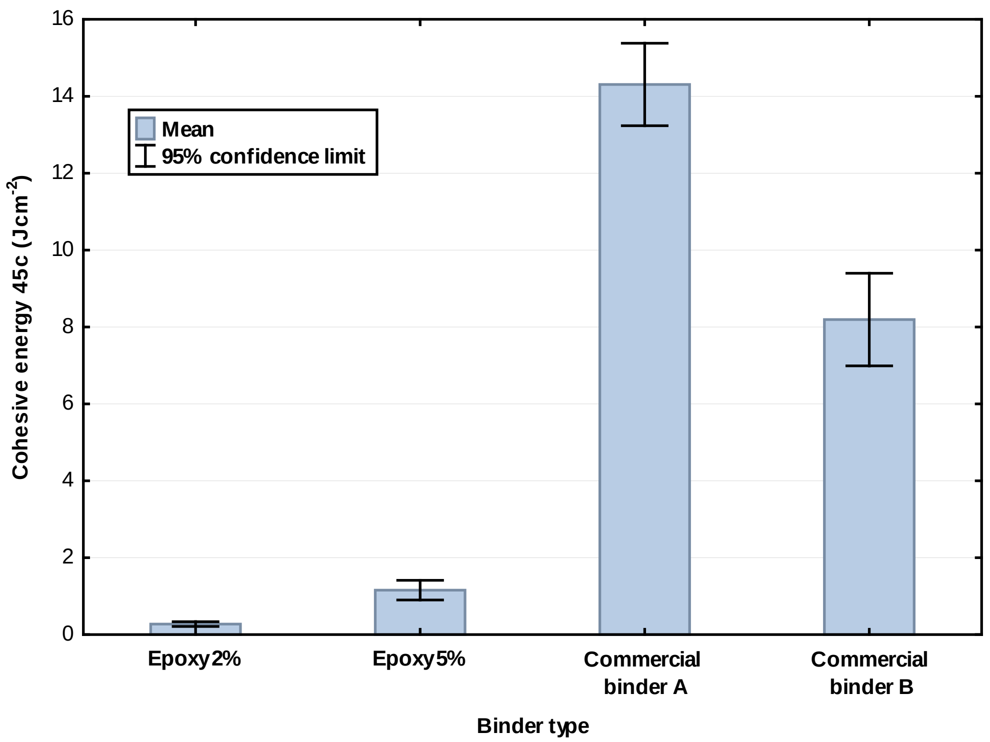
7 Use as a high-friction surfacing binder

High-friction surfaces are seals consisting of a synthetic calcined bauxite chip held to the road surface, usually with a two-part polyurethane or epoxy adhesive. Epoxy bitumen was investigated as possibly providing a cheaper alternative to existing commercially available binders or one that through its known high fatigue resistance may resist the cracking and delamination which can sometimes occur.

For practical reasons a constructed high friction surfacing must be able to be constructed and opened to traffic within a few hours. This is an important performance requirement.

To enable comparisons it was assumed that the strength achieved by commercially available high-friction surfacing binders within one hour of mixing was the minimum required for a satisfactory binder. Cohesive energy measurements using two commercially available polyurethane binders and 2% and 5% epoxy bitumen, made after one hour of curing at 45ºC are shown in figure 7.1.

Figure 7.1 Cohesive energy of high grip surfacing binders at 45ºC after one hour curing at 45ºC



The epoxy binders were found to be substantially weaker than the commercial materials. The results presented earlier in figure 6.2 show that for the 2% binder, curing of about 177 days at 85ºC would be required to reach a cohesive energy level comparable to that of the commercial high-friction surfacing binders. On this basis it is unlikely that the epoxy bitumen (as currently formulated) would be suitable as a high-friction surfacing binder. Such surfacings are used on high traffic demand sites and the epoxy binders would not develop strength sufficiently quickly to withstand the stress imposed by the traffic.

7.1 Summary

The epoxy bitumen formulations used here did not cure rapidly enough for practical application as a lower-cost high-friction surfacing binder. The strength of the epoxy binders reached and might even exceed that of the polyurethane materials tested but certainly not within the four-hour window considered necessary for practical purposes.

8 Field test

A full field trial to evaluate the field performance of the epoxy bitumen was beyond the scope of the research project but a small-scale test patch was constructed in August 2014 using the 2% epoxy bitumen.

A site on SH73 near Darfield on the outer wheel path of the Christchurch bound lane (RS15 12,280m) was selected, which had a heavily flushed patch of grade 3/5 seal adjacent to good texture. The centre of the patch was also badly cracked and water venting holes were apparent (figures 8.1 and 8.2).

The 2% epoxy bitumen components were preheated at 130ºC in the laboratory and mixed on site (figure 8.4). At mixing the temperature of the binder was about 120ºC, the grade 3 chip used was also preheated and was about 140ºC when applied. The road surface was initially damp and the surface temperature was about 15ºC so the patch area was dried and warmed slightly with a gas torch (figure 8.3). The epoxy bitumen was applied at an average of 2Lm^{-2} with a trowel to a rectangular patch of 6m^2 up to about the middle of the flushed seal patch. Hot chip was hand applied immediately after the binder and rolled with a hand roller (three to four passes) with sweeping of loose aggregate to fill in gaps (figures 8.5 and 8.7).

Figure 8.1 General view of the test site

Water

Figure 8.2 Cracking in the centre of the flushed area

Venting holes are also apparent

The site was marked off into four sections as shown in figures 8.6 and 8.7 relating to different substrate conditions. Section 1 of the patch was over good seal, section 2 was the transition between good seal and the flushed surface, section 3 was badly flushed seal and section 4 was badly flushed and cracked seal. Squares were marked on each section to allow chip loss to be measured at some future time. Traffic at

30km/h^{-1} was allowed to run on the patch at 2.30pm (two hours after construction) and at 100km/h^{-1} at 2.45pm.

Figure 8.3 Site was dried with a gas torch

Figure 8.4 2% epoxy bitumen mixed on site

Figure 8.5 Binder and chip application

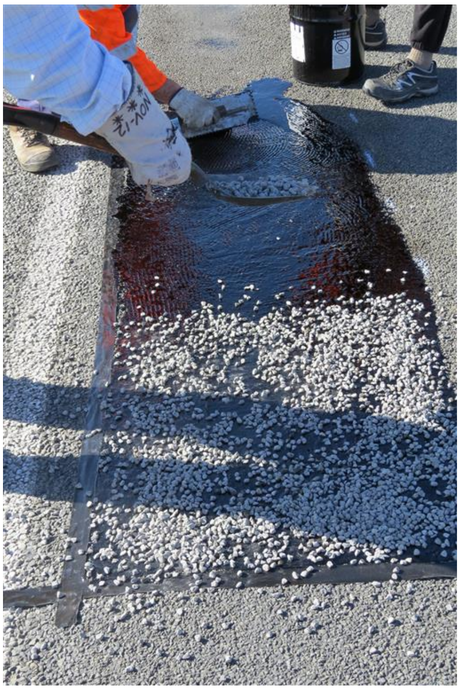


Figure 8.6 Completed patch with marked squares for chip counting

Figure 8.7 Rolling of the test patch and showing sections 1–4

Overnight temperatures at the site following construction were near zero. Photographs taken the day after construction show significant amounts of chip loss (figures 8.8 and 8.9).

The chip in many cases had dis-bonded from the seal with a good coating of binder attached, leaving a glassy fracture face. The failure was thus a cohesive failure of the binder rather than loss of adhesion. This suggests the binder was too brittle for use under the temperatures experienced at the site but other factors were probably also involved. The relatively high mixing temperature might have advanced the degree of cure beyond that desirable given that it took about 10 minutes to complete the seal (in contrast to the few seconds mixing time used in the curing experiments in chapter 3). The road surface temperature was also low (chip sealing at that time of year is generally avoided), so the binder would also cool rapidly. The use of hot chip was intended to assist in adhesion to the chip but would also act to accelerate curing at the interface. Both over-curing and low temperatures impeded effective rolling and wetting of the chip, so that a relatively small area of binder was required to accommodate the traffic stresses imposed and it failed cohesively. The same phenomena can sometimes be seen with conventional bitumen seals constructed outside the usual sealing season or in unusually cold conditions. The cohesive energy test results for freshly mixed 2% epoxy bitumen measured at 0.2ºC (figure 3.5) show that the epoxy bitumen strength was comparable to that of the standard bitumens at that temperature. The degree of curing was probably slightly less than that of the binder in the field test but the results suggest that 80–100 or even 180–200 bitumen may also have failed cohesively under the severe conditions of the field test.

The test did show that the initial concerns about achieving sufficient cure to prevent ductile failure, pick-up and tracking of the binder were not justified. Qualitatively, the binder even immediately after construction was less tacky than that in the adjacent untreated flushed surface.

Figure 8.8 Chip loss after 24 hours trafficking

Figure 8.9 Test patch the day after construction showing chip loss through cohesive failure of the binder

8.1 Summary

The road test indicted that the prototype 2% epoxy binder used in this study might be too brittle as currently formulated. Undesirable side effects of accelerated curing, employed to ensure the road could be opened to traffic quickly and to avoid ductile failure and binder tracking, might have been partly responsible. The balance between a rapid curing rate to enable construction and ensure that potential benefits such as reduced flushing are achieved and the avoidance of an unduly brittle binder needs more detailed investigation.

9 Costs and benefits

Epoxy bitumen seals are still at the concept stage. The types of application and the possible benefits of epoxy bitumen seals are speculative at the present time and it is difficult to estimate the likely costs. Even allowing for these qualifications, it was considered worthwhile to make some approximate, ‘scoping’, net present value (NPV) calculations, to provide an indication of the lifetimes required of epoxy seals to generate cost benefits over conventional seals.

Two scenarios were considered:

1 The use of epoxy seals as a replacement for standard bitumens in routine sealing operations

2 The use of epoxy seals as an alternative to the rehabilitation of badly flushed sites (at which seal lives of less than the average life were being achieved) using an area wide treatment. The concept was that a ‘tough’ epoxy seal would ‘contain’ the flushing.

The NPV calculations presented in table 9.1 were made using the following assumptions:

- The cost of an average standard chip seal (including two-coat and polymer modified seals) was taken as \$7.5m^{-2} with an average application rate of 1.5Lm^{-2}. Calculations were also made for a lower seal cost scenario using \$5.0m^{-2}.
- The cost of bitumen was taken as \$1,100 per tonne.
- The average life for a standard seal was taken as eight years.
- The cost of epoxy bitumen was taken as \$8,272 per tonne (based on a price supplied by ChemCo Ltd for delivered container-sized lots in drums and assuming an exchange rate of 0.80 with the \$US). The figure would be lower for bulk shipments.
- The area wide treatment consists of a 100mm thick overlay of basecourse with 2% cement by volume and the whole surface milled and mixed to 250mm, graded, compacted and a first coat seal applied. The second coat seal is applied one year later.
- Annual maintenance costs (ie other than resealing) were assumed to be the same for both epoxy and conventional seal types and were not included in the calculation.
- Costs due to traffic delays during resealing or rehabilitation were not included in the calculations.
- Based on experience with epoxy bitumen OGPA, construction costs (labour, plant etc) were assumed to be the same for both seal types.
- Based on experience with epoxy bitumen OGPA, it was assumed that epoxy seals would not require any special pavement preparation.
- Inflation was not included in the calculations.
- A discount rate of 6% was used.
- An investment period of about 40 years was used.

Using the above assumptions the cost of an epoxy bitumen seal would be \$18.4m^{-2} compared with \$7.5m^{-2} for a standard seal.

For comparison a diluted (25% epoxy bitumen in standard bitumen) epoxy seal would cost \$11.6m^{-2} (diluted epoxy bitumen provides benefits in epoxy modified OGPA but was not investigated in this research project). An epoxy seal with a lower application rate (1.0Lm^{-2}), which given the strength of the material might be feasible, would cost about \$14.2m^{-2}.

Table 9.1 shows the NPV calculation for a standard seal resurfaced at eight-yearly intervals (scenario one). Under this scenario an epoxy seal costing \$18.4m^{-2} would need an average life of about 40 years to be cost neutral with an average standard seal costing \$7.5m^{-2}. Compared with a low-cost seal, epoxy seals would need lives of well over 40 years to produce cost benefits.

Table 9.1 Conventional seal net present values at different initial seal costs for the resealing scenario

Time period in years	Resealing NPV ($ per square metre)		
	Initial seal cost		
	Standard seal \$7.5m^{-2}	Standard seal \$5.0m^{-2}	Epoxy seal \$18.36m^{-2}
0	7.5	5.0	18.4
8	12.2	8.14	-
16	15.16	10.1	-
24	17.0	11.3	-
32	18.2	12.1	-
40	18.9	12.6	20.1

Table 9.2 shows the NPV calculation for the rehabilitation treatment (scenario two). The initial cost of the epoxy seal is lower than that of the rehabilitation and even with a very modest estimate of only a 10-year life, the epoxy seal would still produce benefits compared with the rehabilitation over an approximate 40-year period.

Table 9.2 Conventional seal net present values at different initial seal costs for the rehabilitation scenario

Time period in years	Rehabilitation NPV ($ per square metre)		Epoxy seal NPV ($ per square metre)
	Initial seal cost		
	Standard seal \$7.5m^{-2}	Standard seal \$5.0m^{-2}	Epoxy seal \$18.36m^{-2}
0	23.0	20.5	18.4
2	29.7	25.0	-
10	34.9	27.7	28.6
18	37.0	29.5	-
20	-	-	34.3
26	38.7	30.6	-
30	-	-	37.5
34	39.7	31.3	-
40	-	-	39.3
42	40.3	31.7	-

9.1 Summary

Based on material costs provided by Chemco Systems, epoxy seals may cost approximately 2.5 times that of a standard seal. This figure is only a rough estimate as binders designed for constructing epoxy seals are not commercially available and an accurate assessment of costs (and benefits) is impossible at this stage. The likely method of application of such seals would require only minimal changes in sprayer design so large capital investment or significant changes to practice would probably not be required.

The NPV calculations made above suggest that epoxy seals would require a more than 40-year life to provide cost benefits compared with those of standard bitumen seals. However, if a life of only about 10 years or more can be achieved, epoxy seals may well be cost-effective alternatives to rehabilitation as a means of dealing with badly flushed multiple seal layers.

10 Conclusions

Exploratory investigations were made to assess the potential performance and benefits associated with epoxy modified bitumen chip seals. The epoxy materials studied were prototype materials supplied by ChemCo Systems Ltd with added accelerator to increase the rate of cure.

10.1 Curing rates and field test

Initially epoxy bitumen has a very high penetration (>200) compared with conventional New Zealand sealing grade bitumens, and rapid curing (over a few hours) to a level comparable with normal binders was thought important to provide adequate strength for chip retention and prevent bitumen tracking. The curing rate was found to be more than adequate at realistic summer road temperatures. A test patch applied to SH73 near Darfield confirmed that the curing rate of the epoxy bitumen was sufficiently rapid to allow seal construction within the same time constraints as conventional seals. The test patch was constructed in cold winter conditions in August 2014 and a problem with chip loss through brittle failure of the bitumen was observed. This might have related to an inherent property of epoxy bitumen or could have been due to the use of an additive to accelerate curing (in general too rapid curing can have adverse effects on epoxy materials and increase brittleness). It should also be noted that cohesive energy measurements at 0.2ºC suggest that standard 80–100 or even 180–200 bitumens might have failed similarly under the cold conditions at the test site. The road test highlighted the need for additional work focusing on the low temperature properties of the epoxy bitumen especially as it cures.

10.2 Adhesion and resistance to water-induced stripping

The epoxy binders showed excellent adhesion and resistance to water stripping without the need to add adhesion agents. This is an important finding as commonly used amine-based adhesion agents would probably react with the epoxy resin and become ineffective and also reduce the ability of the epoxy resin to cross link.

10.3 Application as binders for high-friction surfacings

Although curing at a rate suitable for normal chip sealing operations, the epoxy bitumens did not achieve cohesive energy levels comparable to those of commercially available high-friction surfacing binders quickly enough to be useful.

10.4 Durability

Experiments to assess the durability and resistance to oxidation of the epoxy bitumen were unfortunately limited by the equipment available and timeframe of the project, and were inconclusive, but did not highlight any problem with the epoxy bitumen. The epoxy bitumen demonstrated a large increase in strength after accelerated ageing probably due to extensive curing rather than oxidation and reached a level comparable or exceeding that of the commercial high-friction surfacing binders tested.

10.5 Prevention of flushing

A major finding of this work was that (after at least five days curing at 35ºC) the binders were able to prevent chip embedment in a simulated soft, flushed seal. The low 'tack' of the cured binders also meant that they did not retain aggregate fines; an epoxy bitumen seal would be less likely to lose texture through the void volume filling with fines compared with conventional seals. Both of these observations indicate that epoxy bitumens may have significant practical benefits in reducing or eliminating flushing in chip seals.

11 Recommendations

- The results of this exploratory study demonstrated the potential for epoxy bitumens to resist flushing and this should be explored more thoroughly. Laboratory and field trial work is needed to examine the effect of important parameters such as temperature and higher tyre loadings on flushing resistance, in order to assess the practical benefits and costs more accurately.
- The low temperature behaviour of epoxy bitumen needs to be studied in more detail to investigate the causes of the apparent brittle behaviour observed in the field test. The materials used in this study were prototype formulations and changes may be needed to optimise low temperature flexibility.

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