Epoxy-modified porous asphalt

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- David Alabaster of the New Zealand Transport Agency
- John Bors and Robert Gaul of Chemco Ltd
- Igor Kvatch of Opus International Consultants.

Abbreviations and acronyms

CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
EMOGPA	epoxy-modified open-graded porous asphalt
NZTA	New Zealand Transport Agency
OECD	Organisation for Economic Cooperation and Development

Contents

Executive summary

This research forms part of a larger collaborative research programme conducted under the auspices of the OECD/ECMT (European Conference of Ministers of Transport) Joint Transport Research Centre, which is focused on the economic evaluation of long-life pavements.

The aim of the research was to investigate the potential of epoxy-modified asphalt as a low-maintenance long-life (>30 years) surfacing material. The NZ Transport Agency's (NZTA) contribution to the research focused on the potential benefits of epoxy-modified open-graded porous asphalt (EMOGPA).

EMOGPA appears to offer the potential for a significant improvement in life for open-graded surfacings. EMOGPA uses the same mix designs as conventional open-graded porous asphalt (OGPA), but the bitumen component is replaced with a bituminous binder incorporating a reactive epoxy resin and curing agent. Over time, this binder cures to a hard, slightly rubbery consistency.

Research outline

The purpose of this research was to further investigate the curing behaviour and durability properties of EMOGPA, and to undertake the construction of a full-scale road trial and monitor its performance. The effect of oxidation on EMOGPA specimens was studied by measuring changes in moduli and abrasion resistance (the Cantabro Test). In addition to using a 'standard' 20% air void mix design, the potential application of EMOGPA in 30% mixes was also examined. During the course of this project, additional work, separately funded by the NZ Transport Agency, was undertaken to examine the effects of diluting the epoxy binder composition as a way of reducing costs – the results of these 'dilution experiments' have also been reported here, for completeness. Finally, a road trial was constructed in Christchurch in December 2007 and monitored over the first two years.

Materials

The epoxy bitumen used (supplied courtesy of ChemCo Systems Ltd, California) is a two-part product that is blended just before use. Part A (used at 14.6% by weight) consists of an epoxy resin formed from epichlorhydrin and bisphenol-A. Part B type V (85.4%) consists of a fatty acid curing agent, in an approximately 70 penetration grade bitumen. The product is free from solvents. OGPA specimens (20% or 30% air voids, 5% binder) were compacted by Marshall Hammer (75 blows per side).

Durability

Although the moduli of both materials increased with oxidation time, that of the EMOGPA was much more pronounced, reaching 12,000MPa after 171 days at 85°C, compared with 7800MPa for the control. This time period results in oxidation equivalent to about 20 years in the field (80 days is equivalent to 12 years in the field). The greater hardening of the EMOGPA appears to be largely attributable to gradual curing, rather than to oxidation. Despite the very high modulus, the Cantabro Test results showed that oxidation had no significant effect on the abrasion resistance of the EMOGPA. After 171days the EMOGPA mass loss was within error of the initial value, whereas that of the control had increased by 1.8 times. Similarly the fatigue life of oxidised EMOGPA was markedly greater (more than 25 times) that of the control.

Dilution experiments

Dilution of the epoxy binder to 25% or 50% of the mix binder composition, using standard bitumen, gave an OGPA mix with properties inferior to that of the undiluted material, but still markedly superior to conventional OGPA in terms of abrasion resistance after oxidation. Cantabro Test losses for the 25% and 50% mixes increased only 1.4 times after 171 days oxidation. The fatigue life of the oxidised 25% and 50% EMOGPA mixes were equivalent to that of the control.

Road trial

Trial sections of 20% and 30% air void EMOGPA, and a control (80–100 penetration grade bitumen) 20% air void OGPA, was laid on State Highway 1 in Christchurch on December 7 2007. The site carried more than 15,000 vehicles per day.

A turbulent-mass continuous-mix drum plant was used to manufacture the EMOGPA. An in-line blending system was used to introduce the epoxy binder. Epoxy component A, heated to 85°C, entered the line carrying component B (120°C) about 4m from the point of discharge into the drum to provide premixing of the two components. Manufacture of the epoxy mixture was found to be straightforward and completed without difficulty, except for the unanticipated drain-down of the 30% EMOGPA, which resulted in a low (4%) binder content.

Construction and compaction was by a tandem steel-wheel vibratory roller. The total time from the commencement of the manufacture of the first epoxy mixture to the commencement of construction was 45−60 minutes. There was some concern over the epoxy curing before compaction could be completed, so to increase the working-time, the period for which the mix was held at high temperature was kept to a minimum. As a result, the binder viscosity was actually *lower* than desirable – there was some initial ‘pick-up’ on the roller (especially of the 30% air void material), and the road surface had to be cooled with water before traffic was allowed on it that afternoon. Other than this, the behaviour and appearance of the EMOGPAs was indistinguishable from that of the control material. No unusual fuming or smell was noted and the trial sections were opened to traffic that afternoon.

Monitoring of the site up until March 2010 showed no significant difference between the sections in terms of rutting or skid resistance. The permeability of the 30% air void EMOGPA site was substantially better than that of the 20% sections, but unexpectedly, traffic noise levels on all three were similar.

Conclusions

Durability

The results reported here confirm earlier research showing the oxidation resistance of EMOGPA. The material appears to be essentially unaffected (in terms of abrasion loss), even after oxidation equivalent to about 20 years in the field. Although the modulus continues to increase, this does not lead to increased abrasion loss, as is the case with standard OGPA, nor does it lead to reduced fatigue life, which was found to be at least 25 times that of the control.

Dilution experiments

Dilution of the epoxy binder to 25% or 50% of the binder composition, using standard bitumen, gives an OGPA mix with properties inferior to that of the undiluted material, but still markedly superior to conventional OGPA in terms of abrasion resistance after oxidation. Although the moduli of the diluted materials were higher than that of the control after oxidation, the fatigue life was not reduced.

It should be noted that the usefulness of this approach may depend on the selection of the appropriate bitumen to ensure compatibility with the epoxy components, and may not be successful with all bitumens.

Cost

The cost of EMOGPA is likely to be in the order of 2.3 times that of standard OGPA (in place). The costs of an OGPA using 25% or 50% epoxy bitumen as binder are estimated to be 1.3 or 1.6 times that of conventional OGPA.

Lifetime estimate

Extrapolation of abrasion data (the Cantabro Test) from heavily oxidised specimens (up to ~20years in the field) predicts an estimated field life of 144 years for EMOGPA. Similarly, extrapolation of the data for the 50% epoxy OGPA predicts a lifetime of 93 years (the 25% dilution would also be about the same).

Consistent with the above estimates, fatigue testing of highly oxidised samples indicates an improvement in lifetime, compared to the control, of over 25 times for the 100% EMOGPA mix, although the 25% and 50% EMOGPA materials showed no significant improvement. The results show that despite the high moduli reached by even the diluted EMOGPA, the material is not excessively brittle and likely to crack prematurely (at least at the strain levels tested).

Field trial

The field trial of 20% and 30% air void EMOGPA that was laid in Christchurch in December 2007 was, at the time of writing, still performing satisfactorily. The trial is only three years old and needs ongoing monitoring to assess durability behaviour, but it has successfully demonstrated that the full-scale manufacture and construction of an EMOGPA surface can be accomplished with standard plant and equipment, and with only very minor changes to practice. The latter refers to the need to control the time that the EMOGPA is maintained at high temperatures, to ensure that the epoxy binder is not under-or over-cured at compaction.

Abstract

Investigations into the cohesive properties and oxidation resistance of an acid-cured, epoxy-modified open-graded porous asphalt (EMOGPA) were undertaken, and an associated field trial constructed on State Highway 1 in Christchurch in December 2007.

Open-graded porous asphalt (OGPA) specimens were treated in an oven at 85°C for up to 171 days, resulting in oxidation equivalent to approximately 20 years in the field. The modulus (25°C) of the oxidised epoxy mixture (12,000MPa) was also much higher than that of the control OGPA (7800MPa). Results from the Cantabro Test at 10°C indicated that the cohesive properties of the oxidised epoxy OGPA were markedly superior to those of conventional OGPA. On the basis of the Cantabro test results, lifetimes of up 144 years were estimated for an increase in cost of up to 2.3 times that of conventional OGPA. Similarly, the fatigue life of oxidised EMOGPA was found to be more than 25 times that of the control. Epoxy bitumen diluted with up to 75% standard 80–100 penetration grade bitumen had an estimated life of up 93 years for 1.3 to 1.6 times the cost of conventional OGPA. The fatigue life of the oxidised 25% and 50% EMOGPA mixes were similar to that of the control.

The field trial demonstrated that full-scale manufacture and surfacing construction with epoxy OGPA could be easily undertaken without any significant modification to plant or the necessary operating procedures. Epoxy OGPA sections with 20% and 30% air voids were constructed. Monitoring of the trial site for 27 months showed no difference in performance compared with the control section.

1 Introduction

1.1 Background

This research forms part of a larger collaborative research programme conducted under the auspices of the OECD/ECMT (European Conference of Ministers of Transport) Joint Transport Research Centre, which is focused on the economic evaluation of long-life pavements (OECD 2008).

The aim of the research was to investigate the performance of epoxy-modified asphalt (of various designs) and an especially formulated thin cementitious material. These surfacing materials offer the possibility of very long lifetimes (>30 years) with essentially no maintenance required. Key roading research organisations and agencies from a number of countries participated in the programme, including:

- Transport Research Laboratory, UK Highways Agency, UK
- Turner-Fairbank Highway Research Center, USA
- Laboratoire Central des Ponts et Chaussées, France
- Undesanstalt für Straßenwesen (BAST), Germany
- Danish Road Institute, Denmark
- Road and Bridge Research Institute, Poland
- State Road Scientific Research Institute, Ukraine.

The NZ Transport Agency's contribution to the research focused on the potential benefits of epoxy-modified open-graded porous asphalt (EMOGPA). In 2007, laboratory investigations into the cohesive properties of open-graded porous asphalt (OGPA) that was manufactured using epoxy-modified bitumen were undertaken, and an associated accelerated loading test was carried out at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to demonstrate the technology. Results of this work have been reported in earlier publications (Alabaster et al 2008, Herrington et al 2007).

Although the safety and noise-reduction properties of OGPA are well documented, binder oxidation is a major problem and is the principal factor governing the ultimate life of porous asphalt. Because of the very open nature of the material, oxidation and consequent binder embrittlement is more rapid than in conventional mixes. Oxidation ultimately leads to failure of the mix through loss of material from the surface (ravelling or fretting) under traffic-shearing stresses. The result is a rough, uneven riding surface. In New Zealand, the short average lifetime of 10–11 years (Bartley Consultants 1999) for porous asphalts (in many cases only seven or eight years), compared with that of dense mixes (about 16 years), adversely affects their benefit–cost ratios and thus inhibits the more widespread use of this safe and environmentally friendly surfacing.

Judging by the results of an earlier study (Herrington et al 2007), EMOGPA appears to offer the potential for a significant improvement in life for open-graded surfacings. EMOGPAs use the same mix designs as conventional OGPA, but the bitumen component is replaced with a bituminous binder incorporating a reactive epoxy resin and curing agent. Over time, this binder cures to a hard, slightly rubbery consistency. Extensive investigations of the physical properties of epoxy-modified bitumens and curing behaviour have been reported previously (Cubek et al 2009, Ludwig 2008, Elliot et al 2008, OECD 2008, Herrington and Alabaster 2008, Youcheff et al 2006). Epoxy-modified dense-graded asphalts have been used for over 40 years in specialist bridge-decking applications. A discussion of the literature is given in Herrington and Alabaster (2008).

1.2 Research aims and outline

The purpose of this research was to further investigate the curing behaviour and durability properties of EMOGPA, and to undertake the construction of a full-scale road trial and monitor its performance. OGPA usually fails through oxidation (ageing) of the binder, leading to loss of aggregate through surface abrasion (fretting). The primary advantage of EMOGPA appears, from earlier research, to be its resistance to oxidation and so this property was the focus of this research. The effect of oxidation on EMOGPA specimens was studied by measuring changes in moduli and abrasion resistance (the Cantabro Test). Resistance to fatigue cracking was also measured. In addition to using a 'standard' 20% air void mix design, the potential application of EMOGPA in 30% mixes was also examined. Such mixes are usually manufactured using polymer-modified bitumen. Epoxy modification may help prevent surface abrasion of this very open mix, given the high moduli obtained after curing.

During the course of this project, additional work, separately funded by the NZTA, was undertaken to examine the effects of diluting the epoxy binder composition as a way of reducing costs – the results of these 'dilution experiments' are also reported here, for completeness.

Finally, a road trial was constructed in Christchurch in December 2007 and monitored to follow changes in surface condition and noise over the first two years. Ongoing monitoring of the site is planned and will be reported on separately.

2 Materials and methods

2.1 Materials

For the main laboratory study, greywacke aggregates were obtained from Pound Road Quarry in Christchurch (courtesy of Fulton Hogan Ltd). These same materials were used in the construction of the field trial. Greywacke aggregates for the 171-day dilution studies (see section 4) were obtained from Winstones Ltd (Belmont Quarry) in Wellington.

The epoxy bitumen (supplied courtesy of ChemCo Systems Ltd, California) is a two-part product that is blended just before use. Part A (used at 14.6% by weight) consists of an epoxy resin formed from epichlorhydrin and bisphenol-A. Part B type V (85.4%) consists of a fatty acid curing agent in an approximately 70 penetration grade bitumen. The product is free from solvents.

The bitumen used for all control mixtures was an 80–100 penetration grade bitumen, manufactured from Middle Eastern crudes, comprising both air-blown and butane-precipitated material, and conforming to the NZTA M/1:2007 specification. This bitumen is commonly used in OGPA surfacings in New Zealand.

2.2 Mixture design and manufacture

In the main study, both 20% and 30% air void mixes were used (table 2.1: mixes 1 and 2). The aggregate grading of the 20% mix conformed to the NZTA P/11 OGPA specification (NZTA 2007). Only 20% air void mixes were used in the dilution experiments. The aggregates and grading used in the 171-day experiments (see section 4.3) were slightly different to those used in the main study and the 40-day dilution study (owing to problems with aggregate supply), but also conformed to NZTA P/11.

Table 2.1 Mix designs for laboratory work

Mix	Passing (%) sieve size (mm)					Bitumen content (%)	Air voids % (± 95% CL)
	13.2	9.5	4.75	2.36	0.075		
1. 20% air void OGPA and EMOGPA	100	95.4	32.2	18.6	2.5	5.0	20.8 ± 0.3
2. 30% air void OGPA and EMOGPA	100	92.3	8.1	2.3	0.3	5.0	28.6 ± 0.4
3. 20% air void OGPA and EMOGPA (dilution experiments)	99.8	95.0	22.6	16.8	3.2	5.5	21.1 ± 0.2

For all mixes, 100mm diameter specimens were prepared by compaction (75 blows per side) in a Marshall Hammer, according to ASTM D6926 (ASTM 2004). The average air voids of the specimens used, measured according to ASTM D3203–05 (ASTM 2005) are given in table 2.1. The control mixtures were manufactured at a temperature of 125°C. In accordance with the literature supplied by ChemCo Systems Ltd, the epoxy bitumen mixtures were made with parts A and B heated to 90°C and 125°C respectively, and blended just before addition to the aggregate, held at 125°C. The epoxy bitumen mixtures were held at 125°C for 45 minutes before compaction.

2.3 Test methods

2.3.1 Indirect tensile modulus (ITM) measurements

ITM measurements were conducted on a 5kN test frame (Model UTM-5, IPC Australia Ltd) at 25°C, according to AS 2891.13.1(Standards Australia 1995a). This procedure employs a recovered horizontal strain of 50 microstrain (με), a rise time (90%) of 0.04 seconds and a pulse repetition of 3.0 seconds. A Poisson's ratio of 0.35 was assumed. The moduli of 'zero' time specimens (ie uncured or unoxidised) were measured within 24–48 hours after manufacture. At least four hours were allowed for specimens to stabilise at the test temperature. Unless otherwise stated, the ITM results presented were the mean of at least six, and up to 42, replicates. In cases where three or fewer specimens were tested, the error quoted is the average of the 95% confidence limits of the latter experiments (± 17%).

2.3.2 Indirect tensile fatigue test

Fatigue measurements were made on compacted mix specimens at 25°C using the method given by Read and Collop (1997). A loading time (pulse width) of 110ms, followed by a rest period of 1390ms, was used. The load used for each specimen was chosen so as to produce an initial tensile strain of 100 ± 20με. Failure was deemed to occur when the vertical deformation reached 9mm.

2.3.3 Cantabro Test – cohesion measurements

Mixture abrasion resistance and cohesion was measured using the Cantabro Test. The test procedure and detailed specifications for the equipment are given in APRG 18 (1999), which is in turn based on the Los Angeles abrasion test described in AS 1141.234 (Standards Australia 1995b). In this test, cylinders of compacted mix (100mm diameter and 50–70mm high) are brought to a temperature of 25 ± 0.5°C in an incubator and then tumbled in a steel drum (maintained at 25 ± 3°C) for 300 revolutions at 30rpm. The mass of aggregate lost from the specimen through abrasion is recorded as a percentage of the original mass.

Measurements of 'zero' time specimens (ie uncured or unoxidised) were made within 24–48 hours of manufacture. At least four hours (usually overnight) were allowed for specimens to stabilise at the test temperature. The test machine was enclosed in a large cabinet through which temperature-controlled air from a refrigeration/heating unit was circulated.

The Cantabro Test results presented are the mean percentage losses of 5–10 replicates.

2.3.4 Bitumen extraction and viscosity measurement

Bitumen from oxidised control specimens was extracted using dichloromethane. A roughly triangular segment was broken away from a compacted control OGPA specimen and placed in a beaker. Sufficient dichloromethane (A.R. grade) to just cover the sample was added and left, with occasional stirring, for one hour, covered and in the dark.

The solution was decanted into a centrifuge tube and the aggregate washed with 2x 10ml fresh dichloromethane. The combined solution was centrifuged for 20 minutes at 2000rpm (939g) and filtered under vacuum (water pump) through Whatman grade 1 and GFC filters (grade 1 paper on the bottom).

Approximately equal portions of the solution were poured onto polished 245 x 340mm stainless steel plates. Stainless steel was used instead of glass to reduce the possibility of selective surface adsorption of polar species. A wide-bladed spatula was used to spread the solution, allowing the solvent to evaporate and leave a thin film of bitumen. After three or four minutes the bitumen was scraped off with a single-sided razor blade. The last traces of solvent were removed by heating the combined bitumen scrapings (about 1–3g) at 100°C for 600 minutes under >29.9inHg vacuum. The samples were stored in a freezer at -18°C.

The viscosity of the extracted bitumen was measured at 60°C on a Carrimed 500CSL rheometer using a cone and plate geometry.

The extraction procedure has been shown previously to have no significant effect on the measured viscosity (Herrington et al 2005, Herrington et al 2007).

2.3.5 Oxidation

Compacted mix specimens were oxidised by heating in a forced draft oven at 85 ± 1°C. The sides of specimens were wrapped in a silicone release paper to prevent slumping and were supported on solid steel trays. The position of the specimens in the oven was interchanged to minimise effects due to temperature variations. The specimens were inverted approximately weekly to minimise bitumen drainage, although some minor drainage was observed. Specimens were removed for testing and then replaced in the oven (obviously with the exception of those used in the Cantabro Test).

3 Laboratory studies on durability

3.1 Oxidation

Control and EMOGPA 20% air void specimens were oxidised at 85°C as described above. The viscosity (η) at 60°C of bitumen extracted from oxidised control specimens was used to estimate an approximate equivalent field age (T) using equation 3.1 (Herrington et al 2005):

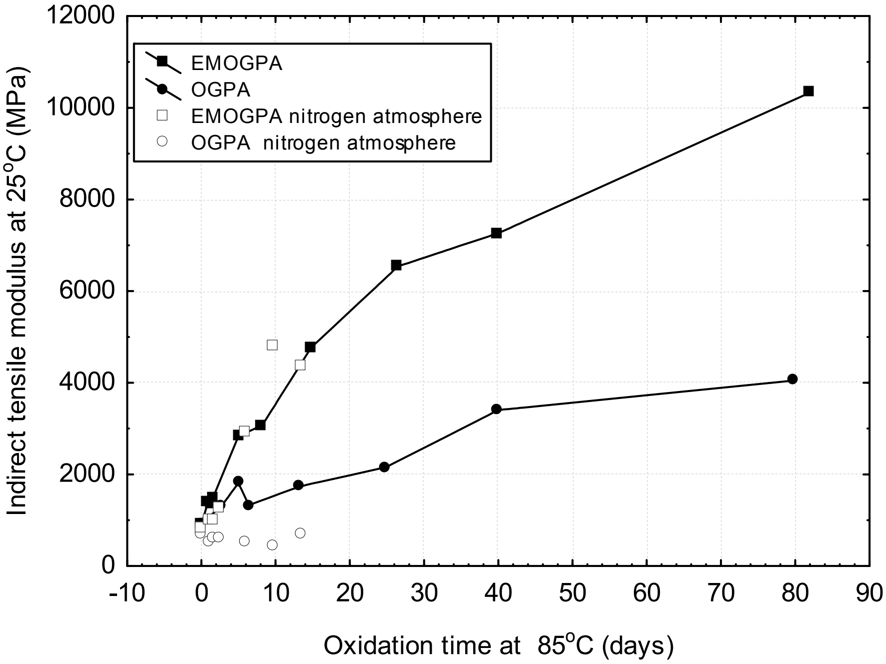
$$T = (\mathrm{Log}\ \eta - 2.72) / 0.20\ T \qquad \text{(Equation 3.1)}$$

Note that this relationship is based on a limited number of field cores less than 10 years old, and is only approximate. The viscosity measurement of bitumen extracted from control specimens after oxidation shows that a 40-day test period is approximately equivalent to seven or eight years in the field; 80 days is equivalent to approximately 12 years.

The change in moduli with oxidation time up to 80 days is shown in figure 3.1. Although the moduli of both materials increase with time, the increase for the EMOGPA is much more pronounced, consistent with earlier findings (Herrington et al 2007). Data for 20% air void specimens – with a slightly different mix design (table 2.1 but similar zero time modulus of ~900MPa) – are discussed in section 4.3. After 171 days the modulus had reached 12,000MPa, compared with 7800MPa for the control, indicating that curing/oxidation would continue for well in excess of 12 years in the field.

In the control, the increase is due to oxidation and hardening of the bitumen. In the EMOGPA, the increase is due to a combination of oxidation (mainly of the bitumen phase) and curing (cross-linking) of the epoxy polymer. In earlier work, infrared spectra of curing epoxy bitumen under a nitrogen atmosphere showed that reaction involving the epoxy ring function and those involving ester formation were essentially complete after only 26 hours (Herrington and Alabaster 2008). Evidently other curing reactions continue to take place, as the moduli obviously continue to increase well beyond this time. Also shown in figure 3.1 is data for (single) specimens of OGPA and EMOGPA cured in an inert nitrogen atmosphere at 85°C for up to 14 days. Whereas the control specimen modulus shows no change, that of the EMOGPA parallels the increase observed in air, indicating that curing, rather than oxidation, is the dominant phenomenon.

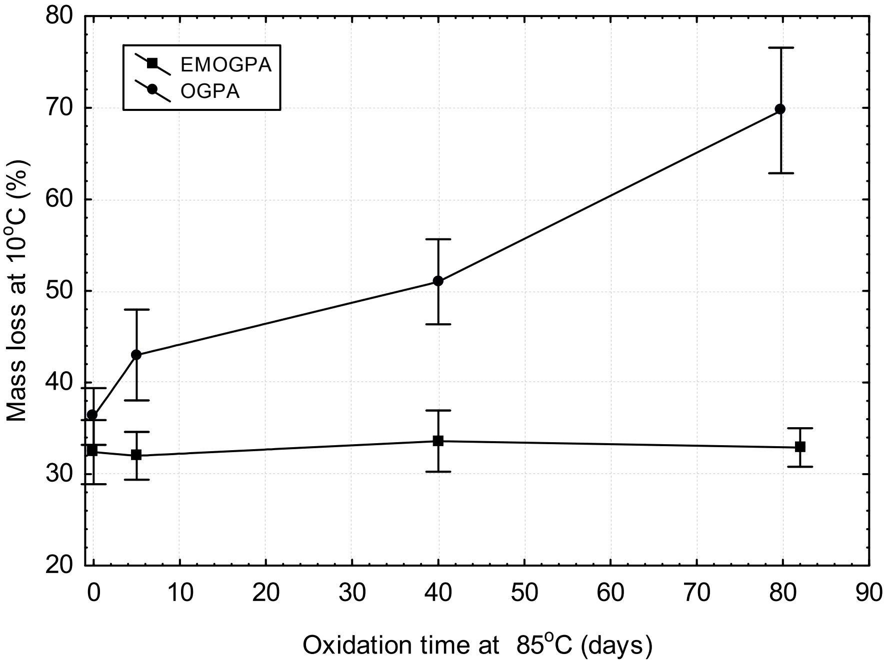
Figure 3.1 Effect of oxidation at 85°C on the IDT modulus at 25°C (± 17% see section 2.3.1)



3.2 Abrasion resistance

Cantabro Test data for oxidised OGPA and EMOGPA specimens are shown on the next page in figure 3.2. Tests were carried out at 10°C (rather than the usual 25°C) as the lower temperature provides a more stringent test of the materials. Cantabro Test losses for the EMOGPA were unchanged (within error) even after 80 days oxidation. These results confirmed previous work using EMOGPA (Herrington et al 2007). In that case, specimens were treated for up to 38 days at 85°C in air. Cantabro Test losses were found to be lower for both the control and for EMOGPA, but that of the control increased by a factor of 1.4 (the same as that found here after 40 days), whereas losses of the EMOGPA were constant. In that earlier work, the same behaviour was observed for tests carried out at 25°C.

Figure 3.2 Effect of oxidation at 85°C on the Cantabro Test mass loss at 10°C (± 95% confidence limits)



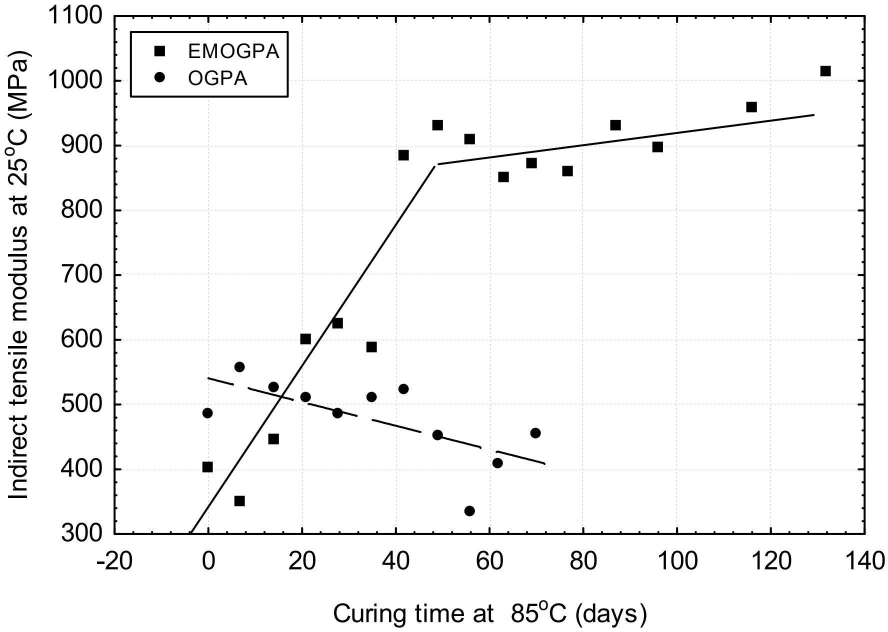
3.3 30% air void mix

Given the high abrasion resistance observed for EMOGPA, it was reasoned that 30% EMOGPA may offer advantages compared with standard 30% OGPAs. These types of mixes are relatively little used and require the use of polymer-modified binders to prevent binder drain-down and, supposedly, abrasion resistance. A 30% air void EMOGPA would provide a potentially very long-lived material that would maintain noise and drainage properties for longer than the usual 20% air void mixes

Both control and EMOGPA specimens of 30% mix were found to be very fragile and difficult to handle at high temperatures, which precluded oven treatment at 85°C. Curing experiments were carried out at 25°C to determine the likely rate of hardening in the field (figure 3.3). The data shows the 30% EMOGPA did increase in modulus, but the level reached (~1000MPa) was still low, even after 140 days. The control specimens remained unchanged (the slight downward trend was probably simply due to experimental error). Further data on curing behaviour at ambient temperatures, for both 20 and 30% air void specimens prepared as part of the field trial, is discussed in section 6.4.

No further testing was carried out on the 30% mixes because of the difficulty in handling the specimens, but it was decided that the mix deserved further evaluation in the field trial.

Figure 3.3 Effect of curing at 25°C on the IT modulus at 25°C (30% air void specimens)



4 Dilution experiments

4.1 Epoxy bitumen cost

Epoxy bitumen from Chemco Systems Ltd of San Francisco costs approximately $9300/tonne ($US5600) for a container load (approximately 15 tonne) delivered to Lyttelton, New Zealand (Bors 2009). Other suppliers may be able to provide a cheaper equivalent product, but as this was not investigated in the present study, the Chemco figures have been used for the purpose of the following discussion.

Assuming a cost of $130/tonne for conventional OGPA (at the plant) plus 5% bitumen content at $800/tonne, the resulting cost of the epoxy OGPA is $555/tonne. Some small setup costs may be incurred initially, but no significant plant alterations or changes in construction practice or equipment are needed (see section 5). Nevertheless, epoxy OGPA is likely to cost approximately 4.5 times as much as conventional material at the plant. This cost is significantly reduced if construction costs are included, as shown in table 4.1. Figures in the table are typical costs supplied by a major contracting firm for construction of OGPA in urban areas.

Table 4.1 EMOGPA comparative cost

Activity	EMOGPA ($/m^2)	OGPA ($/m^2)
Milling and removing old surfacing (30mm depth)	5.48	5.48
Constructing waterproof chipseal layer	3.00	3.00
Constructing wearing course (30mm layer in place, 5% binder content)	36.70	11.00
Total	**45.18**	**19.48**

The figures include addition of an adhesion agent to the standard OGPA bitumen and compacted OGPA density of 2.015 tonnes/m^3. When construction costs are included, EMOGPA is only approximately 2.3 times the cost of a comparable OGPA surfacing. One possible option for reducing the cost is to dilute the epoxy bitumen with standard bitumen. It was hypothesised that the lower-cost diluted material may still retain significantly improved properties compared with conventional OGPA. The costs (per square metre in place) of an OGPA using 25% or 50% epoxy bitumen as binder would be only 1.3 or 1.6 times, respectively, that of conventional OGPA.

Experiments were carried out using two 20% air void mix designs: the one used in the field trial and work described earlier in table 2.1, and another mix using a different aggregate source (mixes 1 and 3 in table 2.1 respectively). Specimens were prepared as above, except that in some instances the epoxy bitumen was diluted with varying proportions of the standard 80–100 penetration grade used in the control mixes. This was achieved by mixing components A and B of the epoxy bitumen, and then adding the desired weight of 80–100 penetration grade bitumen and mixing for 1–2 minutes (all at 125°C). The blends were used immediately to prepare OGPA specimens. The concentration of the resulting blends was expressed in terms of the percent w/w of epoxy binder. For example the 50% EMOGPA blend consisted of:

- 14.6g of epoxy binder part A
- 85.4g of part B
- 100g of 80–100 penetration grade bitumen.

Specimens were oxidised at 85°C and tested as described earlier in section 2.

4.2 Oxidation for 40 days

EMOGPA specimens with 20% air voids and varying proportions of epoxy binder were prepared according to the mix design in table 2.1 (mix 1). Figures 4.1 and 4.2 show the effect of oven treatment at 85°C on the mix modulus and abrasion resistance respectively. Budget constraints prevented tests being carried out on all the mixes at each ageing interval.

Experiments were carried out for up to 40 days. Viscosity measurements of bitumen extracted from control specimens showed that the 40-day test period was approximately equivalent to 7–8 years in the field (see section 3.2).

Figure 4.1 shows that after five days, losses from the epoxy materials were lower than those of the control, but the 25%, 50% and 100% epoxy binder mixes could not be distinguished. After 40 days both 25% and 50% mixes showed significantly lower losses than the control, but still could not be distinguished from the 100% mix.

Figure 4.1 Diluted epoxy binders – effect of oxidation at 85°C for 40 days on the Cantabro Test mass loss at10°C (± 95% confidence limits)

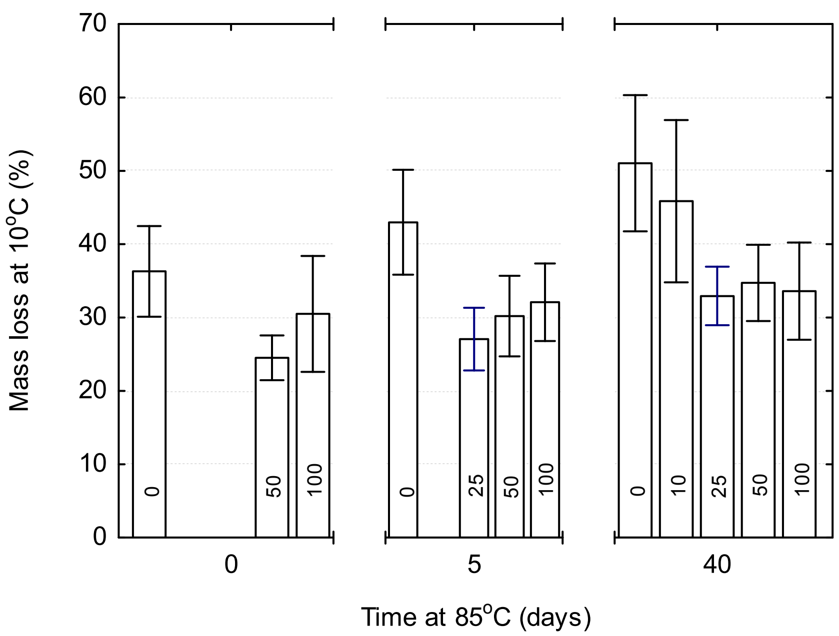


Figure 4.2 Diluted epoxy binders – effect of oxidation at 85°C for 40 days on the IT modulus at 25°C (± 95% confidence limits)

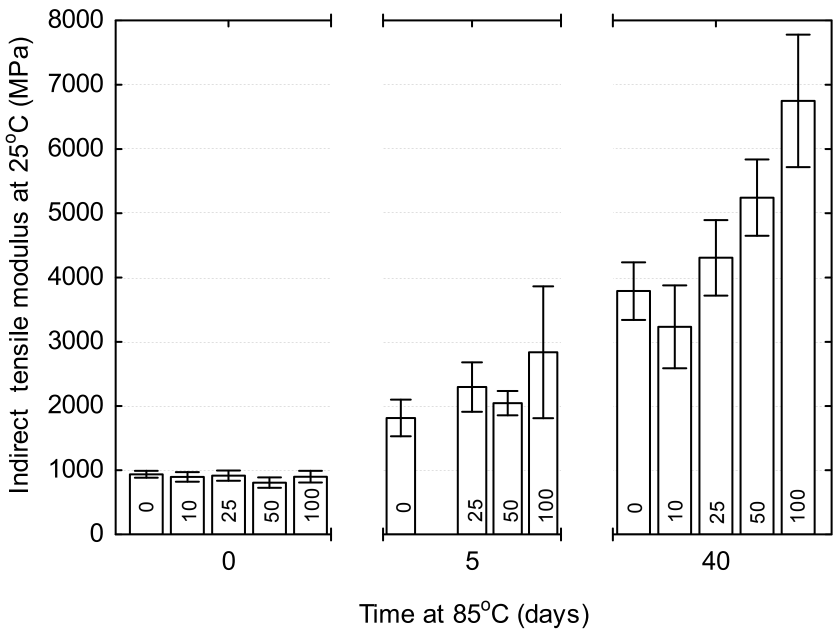


Figure 4.2 shows the effect of dilution was to reduce the modulus of the mix compared with the 100% specimens, the effect becoming more apparent as the ageing time increased and the epoxy material cured. After 40 days the 10% and 25% mixes were not significantly different from the control, but the 50% mix showed a substantial increase.

4.3 Oxidation for 171 days

Because of the findings detailed in section 4.2, further experiments were carried out using 25% and 50% dilutions but for a much longer period (171 days at 85°C). There was insufficient field data to accurately calculate a field age for the 171-day experiment using equation 3.1, but an extrapolation estimate based on the 40- and 80-day data indicates an approximate age of well over 20 years.

As the Pound Road Quarry had closed, these experiments were carried out using a different aggregate and mix design (though with 20% air voids) as given in table 2.1 (mix 3). The results are shown in figures 4.3 and 4.4.

The moduli results (figure 4.4) showed a steady increase from control to 100% EMOGPA and mirrored the 40-day data. After 171 days the difference in mass loss (figure 4.3) between the 100% and control specimens was much more apparent than at 40 days. There was also a noticeable difference between the 100% and 25% and 50% EMOGPA materials. As in the 40-day experiments, there was still little difference in mass loss between the 25% and 50% EMOGPA.

Figure 4.3 Effect of oxidation at 85°C for 171 days on the Cantabro Test mass loss at 10°C for diluted epoxy binders (± 95% confidence limits)

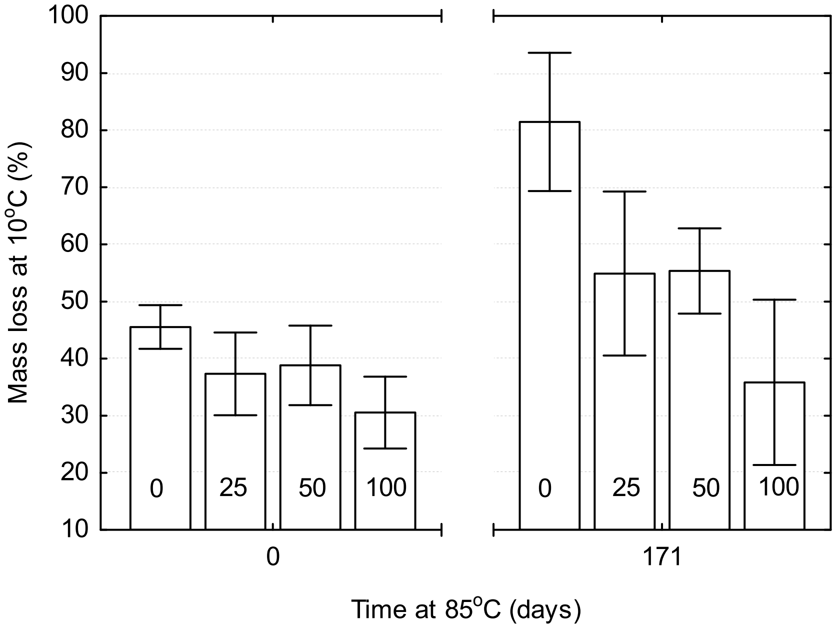
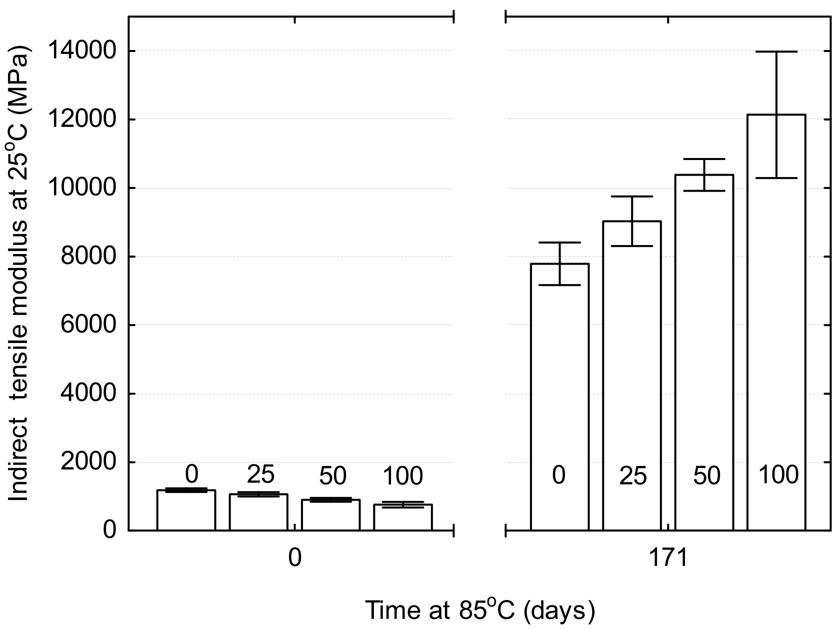


Figure 4.4 Effect of oxidation at 85°C for 171 days on the IT modulus at 25°C for diluted epoxy binders (± 95% confidence limits)



Indirect tensile fatigue test results are given in table 4.2. Because relatively few specimens were available (6–7 of each type) the results were obtained using only a single strain level (100με). This strain was the highest obtainable, given the high modulus of the oxidised specimens and the limitations of the equipment available.

The results showed considerable scatter. This is not uncommon with fatigue measurements, but it may also reflect artefacts from physical deformation that may have occurred during the long oxidation period.

In contrast to the modulus and Cantabro test results, the control, 25% and 50% EMOGPA materials were found to have similar fatigue lives. However, the 100% EMOGPA fatigue life was at least 25 times greater than that of the control (several specimens had not failed even after 500,000 cycles, when testing had to be abandoned because of time constraints).

The results of both the 40- and 171-day experiments suggest that dilution by up to 75% (25% epoxy binder) will produce an OGPA that, although having inferior properties to the 100% mix, is still substantially better than the control in terms of abrasion resistance, and at least equivalent to the control in terms of fatigue-cracking resistance.

Table 4.2 Fatigue life at 25°C

Mix	Cycles to failure at 100 ± 20$\mu\varepsilon$ (± 95% confidence limits)
Control	8700 ± 5500
25% EMOGPA	12,600 ± 12,200
50% EMOGPA	10,300 ± 12,300
100% EMOGPA	223,000[a]

a) Lower bound of real result – see text.

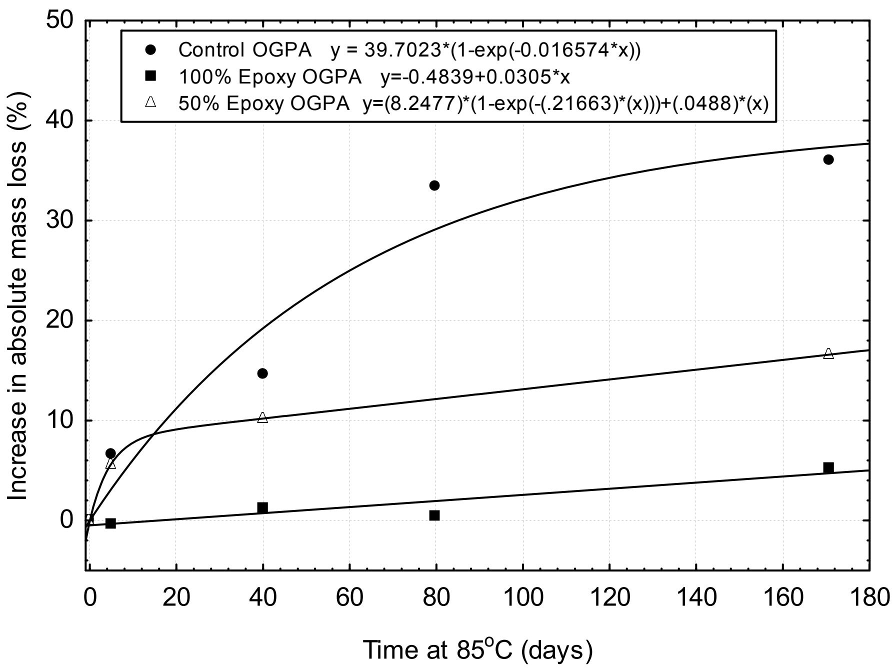
5 Lifetime estimate for EMOGPA

The lifetime of EMOGPA under typical New Zealand conditions is unknown. Internationally, the major application of the material is as a dense mix for bridge decking. Examples of lives in excess of 20 years under extremely high traffic loadings are documented (Gaul 1996).

As Cantabro Test data relate to the abrasion resistance of the mix, and surface fretting is the major failure mode for OGPA, the Cantabro Test data in sections 3 and 4 were combined to make an estimate of the potential lifetime of epoxy OGPA.

Because the same mix design was not used for all specimens, the increase in percentage mass loss from the respective zero time data were plotted, rather than using absolute percentage mass loss. The results are shown in figure 5.1.

Figure 5.1 Effect of oxidation at 85°C on the increase in Cantabro Test mass loss



At 80 days, the control OGPA mass loss increase from the combined data was 29%, corresponding to a field age of about 12 years. This age can be taken as a generous estimate of the maximum life for OGPA surfacings in New Zealand, and the mass loss increase at that age can be taken as a failure criterion. If the data for the EMOGPA in figure 5.1 is extrapolated, an estimate of the time taken to reach a 29% mass loss increase is 966 days (ie 12 times that of the control), and the estimated field life is 144 years! Similarly, extrapolation of the data for the 50% epoxy OGPA predicts a lifetime of 93 years (the 25% dilution would also be about the same).

Consistent with the above estimates, fatigue testing of highly oxidised samples (171 days) indicates an improvement in lifetime, compared with the control, of over 25 times for the 100% EMOGPA mix. In contrast, the 25% and 50% EMOGPA materials showed no significant improvement in fatigue life compared with the control. The fatigue life improvement observed for the 100% EMOGPA mix may be less pronounced if fresh mixes were compared (as the control material is more susceptible to oxidation). Elliot et al (2008), for example, found that the fatigue lives of (unaged) dense epoxy mixes were only up to 15 times greater than that of conventional materials. However, the results presented here do clearly show that the high-EMOGPA moduli did not result in a brittle material that was likely to crack prematurely (at least at the strain levels tested).

6 Road trial

6.1 Design

The road trial was laid on the outer north-bound lane of Main North Road (part of State Highway 1) at Belfast in Christchurch on 5th December 2007. The trial site consisted of three sections. A standard PA 14 open-graded porous asphalt (OGPA), meeting NZTA Specification P/11 (2007), was used as a control, and a 20% air void epoxy OGPA and a 30% high void epoxy were laid. The 30% void epoxy represented an attempt to match the highest voids content achieved with polymer-modified conventional OGPAs – such 30% air void mixes have been noted as having particularly good acoustic performance.

The site had an unbound granular pavement carrying 15,850 vehicles per day heading north, with 6% heavy commercial vehicles. The three sections were contiguous, each 60m long, 5m wide and 30–35mm thick. Looking north, the order of the sections was 20% EMOGPA, 30% EMOGPA and 20% control OGPA. The trial site was in the outer of the two lanes heading from the city, where an existing OGPA laid in 1992 was being replaced because of fretting. The inner lane was laid using standard 20% OGPA. Falling Weight Deflectometer (FWD) testing suggested that the site was structurally sound. The existing OGPA surface of the site was milled out and a grade 5 (10mm) chipseal was constructed over the remaining thin asphaltic-concrete surfacing.

6.2 Materials

The epoxy bitumen used was as described earlier in section 2. The mix designs (grading, aggregate source and binder content) were also nominally the same as those used in the laboratory work reported above (table 2.1, mixes 1 and 2). Compaction of 100mm diameter specimens for testing was by Marshall Hammer (75 blows per side) and carried out at the Fulton Hogan Ltd laboratory in Christchurch. Production testing of the mixes gave the results shown in table 6.1.

Table 6.1 Field trial mix gradings

Mix	Passing (%) sieve size (mm)					Bitumen content (%)	Air voids (%)
	13.2	9.5	4.75	2.36	0.075		
1. 20% air void OGPA	100	94	31	19	2	5.0	17.3
2. 20% air void EMOGPA	100	94	24	15	3	5.3	20.6
3. 30% air void EMOGPA	100	94	8	3	1	4.0	31.3

The target bitumen content in each case was 5%; however, production testing for bitumen contents gave 5.0%, 5.3% and 4.0% respectively. The low binder content of the 30% air void site was due to significant binder drain-down that occurred in the asphalt plant but had not been apparent in laboratory-scale work.

6.3 Manufacture and construction

A turbulent-mass continuous-mix drum plant was used to manufacture the EMOGPA. An in-line blending system was used to introduce the epoxy binder. Epoxy component A, heated to 85°C, entered the line carrying component B (120°C) about 4m from the point of discharge into the drum to provide premixing of the two components. Ordinary positive displacement gear pumps fitted with electronic mass flow metres were used. The flow meters reported to the plant control system controlling the pumps.

The epoxy mixtures were manufactured first; the first 4–5 tonnes of the control mixture that followed was run through and then discarded, in order to clean the plant. When the manufacture of the asphalt was complete, the pumps and lines used to introduce the epoxy bitumen components were disconnected from the plant and drained and flushed with bitumen and kerosene. Manufacture of the epoxy mixture was found to be straightforward and completed without difficulty, except for the unanticipated drain-down of the 30% EMOGPA.

Construction and compaction by a standard tandem steel-wheel vibratory roller required about 20–30 minutes for each section. Temperatures during compaction were 55–70°C for the epoxy mixtures. The total time from the commencement of the manufacture of the first epoxy mixture to the commencement of construction was 45–60 minutes. The mix was manufactured at a temperature of 117°C and 122°C for the 30% and 20% sites respectively.

There were some problems in compacting the epoxy OGPA, particularly the 30% material, because of concern that the epoxy might cure before compaction occurred. Although the initial viscosity of the epoxy binder is somewhat lower than that of 80–100 bitumen at the same temperature, when excessive curing occurs, the epoxy bitumen becomes 'dry' and is not adhesive. To increase the working-time, the period for which the mix was held at high temperature was kept to a minimum. Although this time was similar to that used in the laboratory work (45 minutes), a longer mixing time at high temperature in the plant, or a higher plant temperature, would have been desirable to increase the viscosity of the binder. As a result, there was some initial 'pick-up' on the roller, and the road surface had to be cooled with water before traffic was allowed on it that afternoon. The mix at the 30% site was still 'lively' some three hours after compaction was complete. Other than this, the behaviour and appearance of the EMOGPAs was indistinguishable from that of the control material. No unusual fuming or smell was noted, as was also the case in the earlier CAPTIF trial (Herrington et al 2007). Figures 6.1–6.4 show aspects of the trial construction. The trial sections were opened to traffic that afternoon.

Figure 6.1 General view of the site

Figure 6.2 Start of the 20% EMOGPA section

Figure 6.3 Compaction of the 20% EMOGPA section

Figure 6.4 Traffic damage to the 30% epoxy OGPA section (plucked chip is visible outside the wheel tracks)

6.4 Curing of the EMOGPA

The rate of curing of the EMOGPA was monitored by measuring the indirect tensile modulus of 100mm diameter cylindrical blocks (in triplicate) prepared at the time of construction and placed outside at the Fulton Hogan Ltd laboratory (Pound Road, Christchurch), close to the trial site. These blocks were wrapped in silicone release paper to help prevent deformation of the blocks, and were tested periodically to determine the increase in modulus.

Data for the 20% void EMOGPA (shown in figure 6.5) suggested that it had cured rapidly over the first 30 days and the modulus was still increasing slowly beyond that. The control modulus increased over the first summer but changed little after that. The 30% void EMOGPA modulus appeared to be unchanged. The very open structure and low bitumen content meant these samples were very fragile, and it is not certain that they were representative of the in-situ material. The results for the 30% EMOGPA were also in contrast to those of the 25°C curing experiments carried out on laboratory-prepared mix (see section 3.3), where a small increase was observed over 140 days at 25°C. This could have been because the average road temperature was below 25°C, or more likely, the lower binder content (4%) compared with the 5% of the laboratory mixes.

The curing rate of the isolated blocks was likely to have been lower than that of the material on the road, where the greater mass could have acted to produce higher overall average temperatures. Road temperatures were not measured directly; however, air temperature data from a weather station near the site (Christchurch Airport) is given in table 6.2.

Figure 6.5 Curing of field trial specimens (error bars represent the average 95% confidence limits for a large number of measurements made on similar materials)

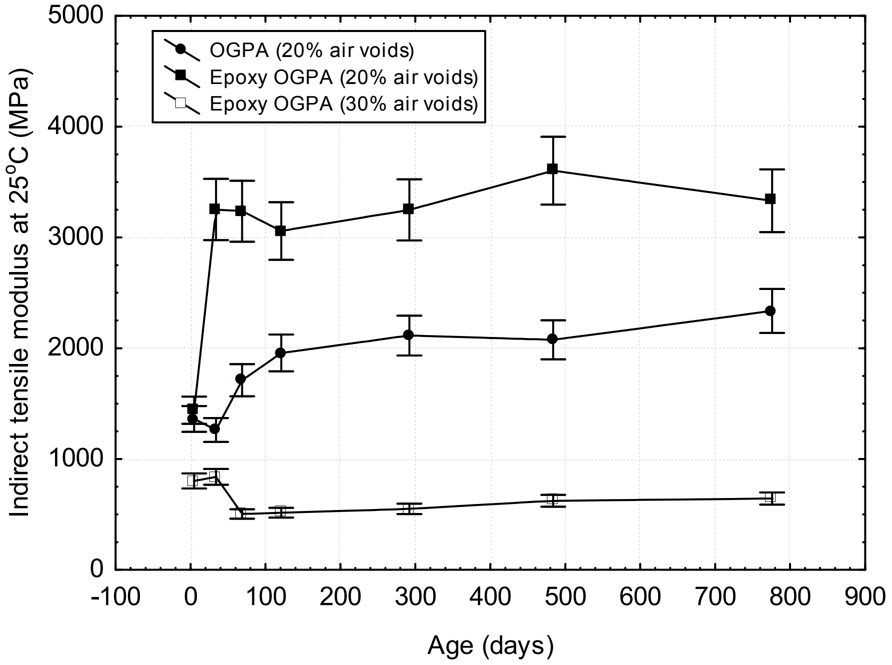


Table 6.2 Air temperatures near to trial site (December 2007–March 2010)

Temperature	Temperature (°C)
Average daily maximum	17.5
Average daily minimum	6.6

6.5 Performance under trafficking

The sites were monitored visually and vehicle noise was measured over three years. Measurements were also made for rutting, skid resistance and water permeability every 10m, both inside and outside the wheel tracks (except for rutting). The general appearance of the site after three years is shown in figures 6.6 and 6.7.

The surfaces were found to be in good condition, with the exception of small patches at the end of each of the EMOGPA sections (eg see the lower edge of figure 5.5), where some ravelling had occurred. These patches corresponded to locations where the paving machine sat for long periods waiting for new material to lay, which appears to have caused damaged. Discolouration in these patches was apparent immediately after construction.

Figure 6.6 Start of 30% air void EMOGPA section, looking towards 20% air void OGPA section

Figure 6.7 Start of 20% air void EMOGPA section, looking towards 30% air void EMOGPA section

6.5.1 Rutting

The 2m straight-edge rutting results in table 6.3 show minimal rutting. The results suggest that the epoxy sections were at least as strong as the control in early life, even without significant curing.

Table 6.3 Rutting

Section	Mean rut depth (mm) ± 95% CL		
	January 2008	January 2009	March 2010
Control	4 ± 1	3 ± 1	4 ± 2
20% EMOGPA	2 ± 1	2 ± 1	1 ± 1
30% EMOGPA	4 ± 1	2 ± 1	3 ± 1

6.5.2 Skid resistance

Skid resistance, measured using the British Pendulum Tester (according to NZTA draft method T/2:2000), was comparable for all sites (see table 6.4), demonstrating that the epoxy surface was not inherently more slippery than conventional OGPA. The results showed that skid resistance in the wheel tracks had dropped slightly compared with untrafficked areas, but the effect was comparable for all three sections. The skid resistance of all sites appeared to have increased after one year, which may have been due to wear of bitumen from the aggregate surface. However, comparison of skid resistance measurements made over such long periods may be unreliable and can be strongly influenced by, for example, weather over the days or weeks preceding the measurement. It is planned to obtain high-speed SCRIM data on the sites to confirm the skid resistance results.

Table 6.4 Skid resistance (British Pendulum Number)

Section	Mean British Pendulum Number ± 95% CL					
	January 2008		January 2009		March 2010	
	Wheel tracks	Outside wheel tracks	Wheel tracks	Outside wheel tracks	Wheel tracks	Outside wheel tracks
Control	53 ± 2	51 ± 2	59 ± 2	63 ± 3	50 ± 2	55 ± 5
20% EMOGPA	50 ± 2	45 ± 5	52 ± 2	56 ± 3	48 ± 2	56 ± 6
30% EMOGPA	53 ± 2	49 ± 3	57 ± 2	61 ± 3	49 ± 2	57 ± 3

6.5.3 Water permeability

The results from field water-drainage tests (using an in-house method based on ASTM D4867) detailed in table 6.5 show that drainage times had increased, with the exception of the 30% void material, which showed relatively little change and was the most free-draining of the three sites. Data for 2010 for the control and 20% EMOGPA sites was an underestimate, as several readings were, in each case, greater than 100 seconds. Measuring longer drainage times was not practicable with the method that was used.

Table 6.5 Water permeability

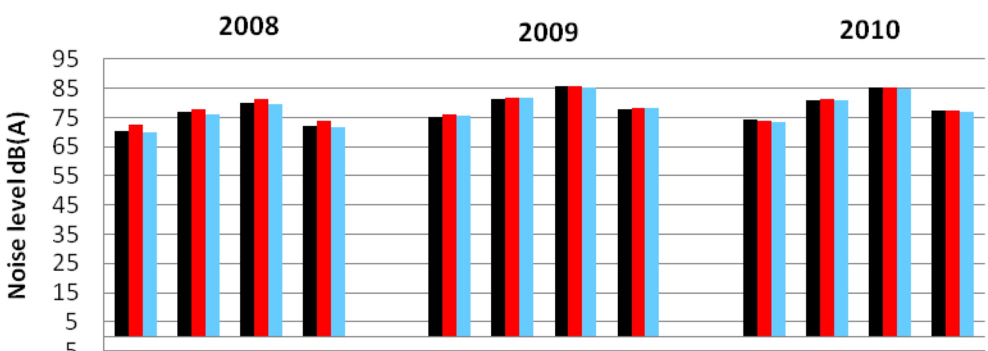
Section	Mean water permeability (seconds) ± 95% CL					
	January 2008		January 2009		March 2010	
	Wheel tracks	Outside wheel tracks	Wheel tracks	Outside wheel tracks	Wheel tracks	Outside wheel tracks
Control	22 ± 13	20 ± 14	33 ± 13	34 ± 28	>65[a]	>41[a]
20% EMOGPA	17 ± 5	12 ± 7	36 ± 19	23 ± 6	>64[a]	>75[a]
30% EMOGPA	14 ± 7	5 ± 2	15 ± 6	6 ± 3	23 ± 7	21 ± 12

a) Lower bound of real result – see text.

6.5.4 Noise

The results of noise measurements are shown in figure 6.6. These show that all three sites generated similar levels of tyre noise. Surprisingly, the 30% void epoxy OGPA did not produce a noticeably quieter surface. This may have been because of the problems associated with 'pick-up' of the material on the roller during compaction and early trafficking, which may have lead to more surface texture than would normally be expected, and hence higher noise levels that cancelled out the benefits of the higher percentage voids.

Figure 6.6 Mean noise levels for cars, dual-axle and multi-axle trucks – SPBI =Statistical Pass By Index (according to ISO 11819-1)



	car	dual	multi	SPBI	car	dual	multi	SPBI	car	dual	multi	SPBI
Control	70.2	76.7	80	71.9	75.2	81.4	85.6	77.9	74.1	80.9	85.4	77.2
Epoxy 30%	72.4	77.8	81.4	73.7	76.2	81.8	85.6	78.4	73.8	81.2	85.4	77.2
Epoxy 20%	70.1	76.2	79.7	71.6	75.7	81.8	85.4	78.1	73.3	81.0	85.0	76.8

The noise level had increased for all sites, consistent with the reduced water permeability measurements. It had rained heavily the night before the January 2009 measurements were taken, and although the surface was dry, water may have still been present in the voids and affected the result. More measurements are needed to properly assess trends.

7 Conclusions

7.1 Durability

The results reported here confirm earlier research showing the oxidation resistance of EMOGPA. The material appears to be essentially unaffected (in terms of abrasion loss), even after oxidation equivalent to 20 years in the field. Although the modulus continues to increase, this does not lead to increased abrasion loss, as is the case with standard OGPA, nor does it lead to reduced fatigue life, which was found to be at least 25 times that of the control.

7.2 Cost

The cost of EMOGPA is likely to be in the order of 2.3 times that of standard OGPA (in place). Dilution of the epoxy binder with bitumen, by 50% or 75%, gives an OGPA mix with properties inferior to that of the undiluted material, but still markedly superior to conventional OGPA in terms of abrasion resistance after oxidation. These findings suggest that these materials would have improved lifetimes compared with the control, and further investigation is warranted. The usefulness of this approach, however, may depend on the selection of the appropriate bitumen to ensure compatibility with the epoxy components, and may not be successful with all bitumens. The costs (in place) of an OGPA using 25% or 50% epoxy bitumen as binder are estimated to be 1.3 or 1.6 times that of conventional OGPA (compared to 2.3 times for 100% EMOGPA).

7.3 Lifetime estimate

Extrapolation of abrasion data (the Cantabro Test) from heavily oxidised specimens (up to ~20years in the field) predicts an estimated field life of 144 years for EMOGPA. Similarly, extrapolation of the data for the 50% epoxy OGPA predicts a lifetime of 93 years (the 25% dilution would also be about the same).

Consistent with the above estimates, fatigue testing of highly oxidised samples indicates an improvement in lifetime, compared to the control, of over 25 times for the 100% EMOGPA mix, although the 25% and 50% EMOGPA materials showed no significant improvement. The results show that despite the high moduli reached by even the diluted EMOGPA, the material is not excessively brittle and likely to crack prematurely (at least at the strain levels tested).

7.4 Field trial

The field trial of 20% and 30% air void EMOGPA that was laid in Christchurch in December 2007 was, at the time of writing, still performing satisfactorily. The trial needs ongoing monitoring to assess durability behaviour, but it has successfully demonstrated that the full-scale manufacture and construction of an EMOGPA surfacing can be accomplished with standard plant and equipment, and with only very minor changes to practice. The latter refers to the need to control the time that the EMOGPA is maintained at high temperatures, to ensure that the epoxy binder is not under- or over-cured at compaction.

8 References

Alabaster, D, P Herrington and J Waters (2008) Long life open-graded porous asphalt. In *Third International Conference on Accelerated Pavement Testing*, Madrid, October 2008.

APRG (Austroads Pavement Reference Group) (1999) Selection and design of asphalt mixes: Australian provisional guide. *APRG report 18*. Sydney: Austroads.

ASTM (American Society for Testing and Materials) (2004) Standard practice for preparation of bituminous specimens using Marshall apparatus. *ASTM D6926-04*.

ASTM (American Society for Testing and Materials) (2005) Standard test method for percent air voids in compacted dense and open bituminous paving mixtures. *ASTM D3203-05*.

Bartley Consultants Ltd (1999) Survey of New Zealand roading authorities regarding pavement engineering issues. *Transfund research report 143*.

Bors, J (2009) Personal communication, Chemco Systems Ltd, May 2009.

Cubuk, M, M Guru and M Kursat Cubuk (2009) Improvement of bitumen performance with epoxy resin. *Fuel*, *88*: 1324–1328.

Elliot RC, I Widyatmoko, J Chandler, A Badr and WG Lloyd (2008) Laboratory and pilot scale assessment of long life surfacing for high-traffic roads. Paper 300-005 in *Proceedings of the 4th Eurasphalt & Eurobitume Congress*, 21–23 May 2008, Copenhagen.

Gaul, R (1996) Epoxy asphalt concrete – a polymer concrete with 25 years experience. *Properties and uses of polymers in concrete*. J Fontana, A Kaeding and P Krauss (Eds). *American Concrete Institute Publication SP:166,* no.13: 233–251.

Herrington, P, D Alabaster, G Arnold, S Cook, A Fussell and S Reilly (2007) Epoxy modified open-graded porous asphalt*. Land Transport New Zealand research report 321*. 27pp.

Herrington, P and D Alabaster (2008) Epoxy modified open-graded porous asphalt. *Road Materials and Pavement Design 9*, no.3: 481–497.

Herrington, P, G Ball and S Cook (2006) Bitumen durability. *Land Transport New Zealand research report 291*. 42pp.

Herrington P, S Reilly and S Cook (2005) Porous asphalt durability test. *Transfund New Zealand research report 265*. 32pp.

Ludwig, S (2008) Design and development of asphalt long-life pavements. Paper 402-093 in *Proceedings of the 4th Eurasphalt & Eurobitume Congress*, 21–23 May 2008, Copenhagen.

NZTA (2000) Standard test procedure for measurement of skid resistance using the British Pendulum Tester. Draft NZTA T/2:2000.

NZTA (2007) Specification for open-graded porous asphalt (OGPA). *NZTA P/11:2007*.

OECD (2008) Long-life surfaces for busy roads. Paris: OECD Transport Research Centre. 185pp.

Read, J and A Collop (1997) Practical fatigue characterisation of bituminous paving mixtures. *Journal of the Association of Asphalt Paving Technologists 66*: 74–108.

Standards Australia (1995a) Methods of sampling and testing asphalt – determination of the resilient modulus of asphalt – indirect tensile method. *AS 2891.13.1:1995.*

Standards Australia (1995b) Methods for sampling and testing aggregates – Los Angeles value. *AS 1141.23*:*1995.*

Youtcheff, J, N Gibson, A Shenoy and G Al-Khateeb (2006) The evaluation of epoxy asphalt mixtures. In *Proceedings of the 51st Annual Conference of the Canadian Technical Asphalt,* Charlottetown, Prince Edward Island, Canada, November 2006.