Removing barriers to the use of crumb rubber in roads

November 2015

JP Wu, PR Herrington and K Neaylon
Opus Research
Opus International Consultants Ltd

NZ Transport Agency research report 578
Contracted research organisation – Opus International Consultants Ltd

ISBN 978-0-478-44533-6 (electronic)
ISSN 1173-3764 (electronic)

NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

Wu, JP, PR Herrington and K Neaylon (2015) Removing barriers to the use of crumb rubber in roads. *NZ Transport Agency research report 578.* 51pp.

Opus International Consultants Limited was contracted by the NZ Transport Agency in 2014 to carry out this research.

Keywords: asphalt rubber, bitumen, chipseal, crumb rubber, devulcanisation, emulsification, end-of-life tyres, polymer modified binders (PMB), viscosity

An important note for the reader

The NZ Transport Agency is a Crown entity established under the Land Transport Management Act 2003. The objective of the Agency is to undertake its functions in a way that contributes to an efficient, effective and safe land transport system in the public interest. Each year, the NZ Transport Agency funds innovative and relevant research that contributes to this objective.

The views expressed in research reports are the outcomes of the independent research, and should not be regarded as being the opinion or responsibility of the NZ Transport Agency. The material contained in the reports should not be construed in any way as policy adopted by the NZ Transport Agency or indeed any agency of the NZ Government. The reports may, however, be used by NZ Government agencies as a reference in the development of policy.

While research reports are believed to be correct at the time of their preparation, the NZ Transport Agency and agents involved in their preparation and publication do not accept any liability for use of the research. People using the research, whether directly or indirectly, should apply and rely on their own skill and judgement. They should not rely on the contents of the research reports in isolation from other sources of advice and information. If necessary, they should seek appropriate legal or other expert advice.

Acknowledgements

The authors would like to thank:

John Donbavand (NZ Transport Agency), Vanessa Browne (NZ Transport Agency), Glynn Holleran (Fulton Hogan), John Vercoe (Road Science), Sean Bearsley (Higgins), Deven Singh (Wellington City Council) for their participation in the project's Steering Group.

Bryan Pidwerbesky (Fulton Hogan) and John Starr (Downer) for peer review of the final report.

Steve Matthews and Andrew Melbourne (Rubber Solutions Asia Pacific Ltd.), Guadalupe Dickerson (Rubber Pavements Association), Adrian Jones and Matthew McInerney (Tyrecycle Australia), late Reiner Wenzel (Entyre NZ Ltd), Paul Prendergast (Z Energy NZ), Ryan Jansz (Boral Australia), Kelly Ray Sockwell (Phoenix Industries, LLC), Stuart Monteith and Dave Youngson (Pacific Rubber), John Lysenko (Fulton Hogan, Australia), Alan Merrie (EcoVersion) for their contributions of valuable information on this subject.

Abbreviations and acronyms

AASHTO	American Association of State Highway and Transportation Officials
AGPT	Austroads Guide to Pavement Technology
ARAC	asphalt rubber asphaltic concrete
ASTM	American Society for Testing and Materials
Austroads	Association of Australasian Road Transport and Traffic Agencies
DOT	Department of Transportation, United States
EPA	Environmental Protection Agency (US)
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration (US)
HMA	hot mix asphalt
ISTEA	Intermodal Surface Transportation Efficiency Act
MTO	Ministry of Transport Ontario
NIOSH	National Institute for Occupational Safety and Health (US)
PERS	poroelastic road surfaces
PMB	polymer modified binder
RAP	reclaimed asphalt pavement
RHMA	crumb rubber modified HMA
SAMI	stress alleviating membrane interlayer
SAMI-R	rubberised stress alleviating membrane interlayer
SBS	styrene-butadiene-styrene
WMA	warm mix asphalt

Contents

Executive summary

The purpose of this research was to identify the barriers to using tyre-derived crumb rubber in bitumen binder in New Zealand roading and the methods to remove these barriers to create market demand for New Zealand waste tyre-derived products.

Tyre-derived crumb rubber has become a common additive to bituminous binders around the world since the 1960s for addressing pavement performance issues as well as tackling the disposal problem of end-of-life tyres. While early New Zealand trials of crumb rubber in both hot mix asphalt and chipseal pavements resulted in mixed performances, technological advances and ongoing research and practices internationally have demonstrated that crumb rubber can be effectively incorporated into road surfacing. Although rubber in the form of natural rubber latex or styrene-butadiene-styrene (SBS) block copolymer has been used in New Zealand roads since the 1970s, crumb rubber has not been used to any extent in normal road pavement and surfacing maintenance or construction.

The objectives of this research project were to:

1. Identify the barriers to be overcome so that crumb rubber can be used as a sustainable and cost-effective material in New Zealand road construction and maintenance.
2. Consult with key stakeholders to propose changes required to overcome the barriers identified.
3. Assess the risks and cost implications of the proposed changes.
4. Devise an implementation plan.

As a result of stakeholder consultations and a comprehensive literature review, the following barriers were identified:

- **High initial costs:** The use of ambient ground tyre rubber in roads is typically viewed as more expensive than polymer modified binders (PMBs) in New Zealand due to the high initial cost of specialist equipment and other costs such as personnel training associated with implementation of a 'new' technology. Most of the specialist equipment is currently unavailable in New Zealand. This is particularly true for wet processed rubber modification where special blending processes and conditions are essential in order to produce a well-defined high-viscosity modified binder. This has led to the dominance of SBS polymer modification in the New Zealand market. The mobile blending technology also does not address key issues such as emulsification and the relatively high operating temperature, ie the use of hot cutback bitumen.
- **Economy of scale/market size:** Bitumen use in New Zealand is predominantly in chipseals and only a small percentage (<5%) of the total use is in PMBs. The use of modified binders is traditionally constrained by relatively higher cost and therefore limited to specialist applications such as ports, airport runways, and large roading projects where high cost can be justified by performance requirement of high stress/traffic volume roads and/or simply by the economy of scale. As crumb rubber binders are used in the same types of applications, then modified chipseal is potentially the greatest end use application for crumb rubber in New Zealand.
- **Security of supply:** There are approximately 60,000 tonnes of end-of-life tyres generated in New Zealand each year. Should end-of-life tyres be processed and incorporated into road pavements, based on the size of the current total bitumen market in New Zealand, there are in fact more than enough end-of-life tyres each year as a source of material for the production of binder modifier. In reality, the lack of enforcement of existing regulations, an estimated 70% of New Zealand's annual

end-of-life tyre waste stream is stockpiled or illegally dumped as it is more economical. This potentially leads to supply issues of end-of-life tyres for both crumb rubber manufacturers and end users.

- **Implications of industry's switch to emulsion:** The last barrier, which is a roading-specific issue, relates to the ability to use crumb rubber modified binder as an emulsion. Most of the New Zealand road network is surfaced with chipseals; for safety reasons the roading industry is considering moving towards a switch to bitumen emulsions (sprayed at 80–90^{0}C) from hot cutback bitumen (sprayed at about 160^{0}C) for chipseal construction. This imposes a major technical challenge to the use of crumb rubber modified binders, which due to the properties of vulcanised tyre rubber must be sprayed at over 180^{0}C. Even with warm mix additives, the application temperatures are still higher than what is typically achieved with bitumen emulsion. The need to apply crumb rubber modified binders at high temperatures for chipsealing, conflicts with the industry's move away from hot cutback bitumen binders. Devulcanised rubber is a potential solution to enable the use of crumb rubber in emulsion sealing.

These issues are not insurmountable. There are two key proposed changes which will effectively remove the barriers to crumb rubber use in road pavements in New Zealand:

1 Growing the PMB market

2 Devulcanisation of waste tyre rubber.

Growing the PMB market: Chipsealing is by far the biggest user of bitumen and potentially the greatest market for crumb rubber use. The properties and performance of crumb rubber modified binders are often compared with those of PMBs, which are already widely used internationally. Therefore, the logic behind growing the PMB market in New Zealand is that by increasing the use and awareness of the widely reported benefits of PMBs, opportunities are created for end-of-life tyre-derived rubber to be used as an alternative to virgin polymer in binder modification. As a result, end-of-life tyres can be considered a local source of polymer, adding value to the growing waste stream. This potentially reduces New Zealand roading industry's exposure to international prices (price fluctuation of imported virgin polymers), reduces other procurement risks associated with importation, and increases the performance of the chipseal. The growth of the local PMB demand could remove barriers to the use of tyre rubber in roads by increasing market size and securing a supply of polymer for binder modification.

Devulcanisation of waste tyre rubber: Devulcanised tyre rubber should be investigated as a solution to overcome the high capital cost of specialist crumb rubber equipment, the associated cost of personnel training and the emulsification of crumb rubber modified binder. The devulcanisation process breaks down the crosslinking that makes rubber tyres rigid and durable, so they interact with bitumen more intimately, creating a much more homogenous and low-viscosity modified binder compared with conventional crumb rubber modified binder. Devulcanised rubber modifiers have the potential to be incorporated into bitumen binders in the same manner as virgin PMBs such as SBS with similar properties. This is advantageous for emulsification technology which is well practised in New Zealand with unmodified and modified binders. In summary, devulcanised tyre rubber can be used with minimal changes required to the plant and procedures currently used in both chipseal and asphalt construction. This should address the technical issues associated with the use of tyre rubber in emulsion sealing as the industry is well versed in emulsifying PMBs in New Zealand.

Recommended implementation plan

Conventional crumb rubber modified bitumen technologies can be applied in New Zealand and although the initial cost increase could be significant, once they are established the cost would be expected to be comparable to polymer modified binders. The fact that crumb rubber cannot be emulsified is a barrier to its use but recent developments in devulcanisation technology may overcome this. Currently the market for crumb rubber is small, but this is because improvements provided by modifying chipseal binders have not previously been definitively proven; however, methods are now available to assess the potential enhancements. Implementation of the following recommendations would allow the use of tyre rubber modified bitumen essentially as a seamless substitute for SBS modified bitumen. In an ideal scenario, the proposed changes would be implemented in a chronological order as follows:

1 Expanded use of PMB over the network. Quantification of the performance benefits of currently used PMBs over unmodified binders must be investigated to demonstrate the whole-of-life cost benefits from the use of PMBs. These benefits can then be used by the transport sector to justify increased use of PMBs. This 'mandated' market growth is needed to increase the potential market for devulcanised crumb rubber modified binders (assuming satisfactory behaviour – see below), and justify investment by the transport sector in the technology. It is recommended a working group consisting of industry stakeholders be formed to adopt/develop a new specification for PMBs.

2 Validation of devulcanised rubber technology. Research must be done to establish that devulcanised tyre rubbers can be emulsified using standard equipment. The field performance of devulcanised rubber modified binders (with and without emulsification) needs to be verified by comparison with benchmarks set by the initial PMB study.

3 With a growing market for PMB/crumb rubber modified binders, the expected lower cost of devulcanised tyre rubber would encourage greater use of the technology and increased consumption of waste tyres.

Abstract

The purpose of this research was to identify the barriers to using tyre-derived crumb rubber in bitumen binder in New Zealand roading and the methods to remove these barriers to create market demand for New Zealand waste tyre-derived products. As a result of the comprehensive literature review and stakeholder consultations, it was found that the key barriers in New Zealand were high initial cost of specialist equipment, the relatively small market, security of supply and implications of the industry's switch to emulsion binders. Fortunately, with a growing appetite for better performance in roading infrastructure and continued technological advancement, a number of solutions were identified. These include growing the use of modified binders over the network and investigation into the use of devulcanised rubber. The combination of these proposed changes will effectively remove the barriers identified and allow tyre rubber to be incorporated into the New Zealand roading network cost effectively and enable this waste stream to be diverted away from landfills.

1 Introduction

The purpose of this research was to identify the barriers to using tyre-derived crumb rubber in bitumen binder in New Zealand roading and the methods to remove these barriers to create market demand for New Zealand waste tyre-derived products.

Tyre-derived crumb rubber has become a common additive to bituminous binders around the world since the 1960s for addressing pavement performance issues as well as tackling the disposal problem of end-of-life tyres. While early New Zealand trials of crumb rubber in both hot mix asphalt (HMA) and chipseal pavements resulted in mixed performances, technological advances and ongoing research and practices internationally have demonstrated that crumb rubber can be effectively incorporated into road surfacing. Although rubber in the form of natural rubber latex or styrene-butadiene-styrene (SBS) block copolymer has been used in New Zealand roads since the 1970s, crumb rubber has not been used to any extent in normal road pavement and surfacing maintenance or construction.

The objectives of this research project were to:

1 Identify the barriers to be overcome so that crumb rubber can be used as a sustainable and cost effective material in New Zealand road construction and maintenance.

2 Consult with key stakeholders to propose changes required to overcome the barriers identified.

3 Assess the risks and cost implications of the proposed changes.

4 Devise an implementation plan.

The report is structured in a way that the key barriers are summarised in chapter 2, followed by the proposed changes to remove these barriers in chapter 3, and supported by a comprehensive literature review in chapters 4 to 9.

2 Summary of key barriers

2.1 High initial costs

The use of ambient ground tyre rubber in roads is typically viewed as more expensive than polymer modified binders (PMBs) in New Zealand due to the high initial cost of specialist equipment and other costs such as personnel training associated with implementation of a 'new' technology. Most of the specialist equipment is currently unavailable in New Zealand. This is particularly true for wet processed rubber modification (see section 6.3) where special blending processes and conditions are essential in order to produce a well-defined high-viscosity modified binder.

A mobile blending unit from the US can be sold to New Zealand for about US$300,000 (the AR150M), (email communications, Phoenix Industries 2014). This blending plant is designed to fit in a standard 40-foot sea container to facilitate economical ocean shipping as well as easy inland transportation to and from job sites. This plant has a production capacity of 10–13 tonnes per hour of modified asphalt (ie bitumen) rubber binder with a minimum crumb rubber content of 15% by weight.

However, the reality is that even with the existing relatively wide uptake of crumb rubber modified binders in Australia, there are only a few of this type of mobile blending plants in Australia. Hence, it remains challenging to justify the cost of bringing such specialist equipment into New Zealand without a clear picture of the size of the market potential. The mobile blending technology also does not address key issues such as emulsification and the relatively high operating temperature, ie the use of hot cutback bitumen (see sections 2.4, 6.3 and 6.5). In addition, there is no government subsidy to incentivise the roading industry to use the material in New Zealand.

2.2 Economy of scale/market size

Bitumen use in New Zealand is predominantly in chipseals (~75%) and asphalt (~25%). However, only a small percentage (<5%) of the total use is in PMBs. The use of PMBs is traditionally constrained by relatively higher cost and therefore limited to specialist applications such as ports, airport runways, and large roading projects where high cost can be justified by performance requirement of high stress/traffic volume roads and/or simply by the economy of scale. As crumb rubber binders are used in the same types of applications, then without expanding the market for PMB use in general, it would be difficult for tyre rubber or end-of-life tyres to find its application in New Zealand.

There is one advantage of crumb rubber over virgin polymers and that is its relatively stable price. Ambient ground crumb rubber at 30 mesh (~500 microns) is sold at approximately NZ$750–$1,000 per tonne in New Zealand. In addition, there is potential for the cost price to reduce should the market demand increases.

2.3 Security of supply

On average, approximately 4 million units of tyres have entered the New Zealand market each year since 2008. Based on 2011 figures, there are 62,000 tonnes of end-of-life tyres generated in New Zealand each year (Tyrewise 2013). There are three different pathways for used tyres in New Zealand:

1 Landfill and disposal

2 Recycling or transformation

3 Reuse: exported for reuse, or retreaded (truck tyres only).

Should end-of-life tyres be processed and incorporated into road pavements, based on the size of the current total bitumen market in New Zealand, there are in fact more than enough end-of-life tyres each year as a source of material for the production of binder modifier.

Unfortunately, the current system for the monitoring, collecting and disposal of the waste stream is flawed. There is no driver nor enforcement for recycling and getting further value out of end-of-life tyres, which leads to collectors disposing of end-of-life tyres using the path of least resistance, ie exporting whole tyres or landfilling tyres in various forms (shredded, cut, bundled) as the cheapest options. Landfill disposal of end-of-life tyres costs between $89 per tonne in the Far North and $427 per tonne in Masterton (Tyrewise 2012a). In some instances where a council has set a high disposal fee, the volumes of end-of-life tyres being presented for disposal has dropped dramatically, raising questions as to the whereabouts of those end-of-life tyres.

There are plenty of examples of stockpiles of end-of-life tyres around the country which create additional hazards such as fire risks. Another commonly used and inexpensive disposal path in New Zealand is silage covers on farms.

There is some local capability to process end-of-life tyres into tyre-derived fuel, but for exports mainly. The value of tyre-derived fuel can also fluctuate sporadically due to variations in supply and demand, making this option unsustainable on a small, batch scale operations.

There are a number of pieces of existing legislation (Tyrewise 2012a) that potentially need more rigorous enforcement and/or consistency of application in order to create a more levelled environment for the industry to control the storage and disposal of waste tyres, including:

1 Litter Act 1979 – section 15

2 Resource Management Act 1991 – section 9.1

3 National Environmental Standards for Air Quality Regulations 2004 – clause 7

4 Local Government Act 2002 – part 8

5 Waste Minimisation Act 2008

In summary, because of the lack of specific regulation and limited enforcement of existing regulations, an estimated 70% of New Zealand's annual end-of-life tyre waste stream is unaccounted for (stockpiled or illegally dumped) causing issues with security of supply of end-of-life tyres for crumb rubber manufacturers.

For detailed analysis of the overall end-of-life tyre market in New Zealand and recommendations regarding regulatory measures towards the barriers in general, please refer to *Waste tyres economic research: report 3* which was published by the Ministry for the Environment (KPMG 2015).

2.4 Implications of industry's switch to emulsion

The last barrier, which is specifically a roading specific issue, relates to the ability to use crumb rubber modified binder as an emulsion. Most of the New Zealand road network is surfaced with low-cost chipseals, For safety reasons the roading industry is considering moving towards a switch to bitumen emulsions (sprayed at 80–90ºC) from hot cutback bitumen (sprayed at about 160ºC) for chipseal construction. This imposes a major technical challenge to the use of crumb rubber modified binders, which due to the properties of vulcanised tyre rubber must be sprayed at over 180ºC. While there are several patents on emulsification processes incorporating crumb rubber, the principle behind the technology requires costly, ultra-fine crumb rubber, typically finer than 40 mesh (~400 microns), in order to promote excellent digestion of the rubber to produce a modified binder with viscosity suitable for emulsification. The technologies have also not been widely demonstrated as yet.

Wet processed crumb rubber modified binders typically have to be used at temperatures above 180ºC, and even with warm mix additives the application temperatures are still higher than what is typically achieved with bitumen emulsion. The need to apply crumb rubber modified binders at high temperatures for chipsealing conflicts with the industry’s move away from hot cutback bitumen binders.

3 Proposed changes

There are two key changes required to effectively remove the barriers to crumb rubber use in road pavements:

1 Growing the PMB market

2 Devulcanisation of waste tyre rubber.

3.1 Growing the PMB market

The properties and performance of crumb rubber modified binders are often compared with those of PMBs. In Australia, crumb rubber is considered a credible alternative to virgin polymer for binder modification. Crumb rubber binders and PMBs are used more commonly in Australia due to the need to address fatigue cracking. Therefore, the logic behind growing the PMB market in New Zealand is that by increasing the use and awareness of the widely reported benefits of PMBs, opportunities are created for end-of-life tyre-derived rubber to be used as an alternative to virgin polymer in binder modification.

The performance benefits (summarised in section 5.3), of crumb rubber and virgin PMBs are very similar, which supports the proposed change to substitute PMBs such as SBS modified binder with crumb rubber modified binders as is already practised internationally. As a result, end-of-life tyres can be considered a local source of polymer, adding value to the growing waste stream. This not only reduces New Zealand roading industry's exposure to international prices (price fluctuation of imported virgin polymers) but also reduces other procurement risks associated with importation. The growth of the local PMB demand could remove barriers to the use of tyre rubber in roads such as:

- economy of scale/market size
- security of supply of virgin polymer as end-of-life tyres become an extra, local source of polymer.

Other potential indirect benefits of growing the PMB market and thus the use of tyre rubber as a bitumen modifier include:

- Tyre rubber is also a bitumen extender. Rubber crumb (when used without devulcanisation) can swell up to three to five times its original size due to the adsorption of components from the maltenes phase of the bitumen (Ibrahim et al 2013). This means that on a per volume basis, there is less bitumen required when modified with crumb rubber thus reducing the cost.
- Because of the performance enhancements achieved (especially the rheological properties), from the modification, lower quality (and potentially cheaper), bitumen may be imported into New Zealand and subsequently cost effectively modified, without compromising performance.

3.1.1 Costs and risks of increased use of crumb rubber binders

3.1.1.1 Supply versus demand

The supply of end-of-life tyres in New Zealand is more than sufficient to meet the demand resulting from a significant increase in the overall PMB market.

There are currently an estimated 62,000 tonnes of waste tyres disposed in New Zealand each year. Even with the worst case scenario where only tyres of certain composition are usable, eg truck tyres due to their high natural rubber content, there are still approximately 15,500 tonnes of truck tyres (25% of total) generated in New Zealand each year.

For a typical truck tyre that weighs 40kg on average, approximately 30kg of the total weight is rubber (natural and synthetic) and can be recycled. The remaining 10kg is normally fibre and steel reinforcement which are also recycled separately. Of the 15,500 tonnes, there are approximately 11,625 tonnes of rubber generated, excluding what are already disposed in landfills and stockpiles, available for recycling.

- Scenario 1: At a dosage rate of 15% by weight of bitumen (SBS is typically 4%), 11,625 tonnes of rubber will be able to serve a modified bitumen market of approximately 77,500 tonnes, which is approximately 39% of a 200kt total bitumen market.
- Scenario 2: At a dosage rate of 10%, then the entire truck tyre waste stream can supply ~58% of the total bitumen market.
- Scenario 3: At a dosage rate of 20%, then the entire truck tyre waste stream can supply ~29% of the total bitumen market.

Hence, even if the PMB grows from <5% to 20% of the total bitumen market, there are sufficient end-of-life tyres generated in the country each year to meet the demand. This is without considering the use of non-truck tyres.

Further investigation is required into the optimum dosage for tyre-derived rubber. However, based on international literature, the majority of wet-process crumb rubber modified binders consist of 15–20wt% crumb rubber.

The more rubber is incorporated in the modified binder without compromising the performance specifications, the more waste tyres are diverted away from landfill. Similarly the more rubber is used; there is potentially less bitumen and less virgin polymer needed to be imported into the country.

3.1.1.2 Costs

The adoption of a better performing material will impose a cost to the NZ Transport Agency (the Transport Agency) and other local roading authorities. However, it is important to note that while the initial cost of material may be higher, there is potentially an overall cost saving as a result of enhanced performance and extended lifecycle of the surfacings constructed.

In the State of North Carolina, chipseals made of polymer-modified emulsions applied on structural asphalt pavement were evaluated on high traffic volume roads (Corley-Lay and Wofford 2012). The polymer modification was found to enhance rutting resistance, especially at high temperatures, as well as aggregate retention – chip loss. Chip loss was reduced by 30%.

Although polymer modified chipseals in New Zealand cost about 20% more than unmodified chipseals, other preservation treatment options for higher-volume roads such as thin HMA overlays costs almost three times as much as unmodified chipseals. A lifecycle cost analysis also showed the polymer modification can be cost effective as long as the modified chipseal life is extended by an extra two years from the five-year lifecycle of a typical unmodified chipseal.

Using figures and estimates obtained from the literature, table 3.1 outlines the net present value of the initial seal cost using unmodified bitumen and PMB, with different expected life spans (from 5 to 12 years).

Table 3.1 Net present values at different seal costs from resealing scenarios

Time period in years	Initial Seal Cost										
	Standard		PMB								
	$7 per m2		$8.05 per m2			$9.1 per m2			$10.5 per m2		
	5 year life	8 year life	8 year life	10 year life	12 year life	8 year life	10 year life	12 year life	8 year life	10 year life	12 year life
0	7	7.5	8.05	8.05	8.05	9.1	9.1	9.1	10.5	10.5	10.5
5	12.23										
8		12.21	13.10			14.81			17.09		
10	19.06			12.55			14.18			16.36	
12					12.05			13.62			15.72
15	27.01										
16		17.01	18.26			20.64			23.81		
20	35.44			16.46			18.60			21.47	
24		21.21	22.77		15.03	25.74		16.99	29.70		19.60
25	43.69										

Note: Assumptions:

1 Discount rate of 6%.

2 Unmodified chipseal is $7 per m^2.

3 Polymer modified chipseal is 15, 30, and 50% more expensive at 8.05–10.5 per m^2.

4 Application rate of 1.5L per m^2.

5 Cost of bitumen was taken at $1,000 per tonne.

6 Inflation was not included in the calculation.

If a polymer modified chipseal is 50% more expensive than an unmodified chipseal, then for the PMB to be cost neutral, it has to extend the life of a standard, unmodified chipseal by four to six years depending on the initial lifespan of an unmodified seal.

If it is 30%, the required extension reduces to three to five years.

If it is 15%, the required extension reduces further to two to four years.

Information on the life extension in reality is limited due to the relatively small market in New Zealand. There are also many types of PMBs, making it more difficult to quantify the true performance benefits of polymer modified chipseals over unmodified chipseals without some form of standardisation and/or optimisation. Thus far benefits are largely based on anecdotal evidence in New Zealand. In Australia, long-term trials funded by Austroads (Austroads 2000; 2014a) are currently being assessed to study the performance of polymer modified chipseal against unmodified seals. In order to expand the PMB market in New Zealand, a complementary investigation is required to evaluate the performance benefits of polymer-modified chipseals over unmodified ones under New Zealand conditions.

3.1.1.3 Specifications

There is currently no specification for PMB material properties in New Zealand. In order to manage the consistency and quality, new specifications would have to be developed as a result of the proposed change. The Austroads *Specification framework for polymer modified binders AGPT/T190* (Austroads 2014b) covers a comprehensive suite of test methods and should be used as a basis for developing a New Zealand based specification. In AGPT/T190, there is also a specification for crumb rubber modified binders.

3.2 Devulcanisation of waste tyre rubber

Devulcanised tyre rubber should be investigated as a solution to overcome the following barriers:

1 High capital cost of specialist crumb rubber equipment and the associated cost of personnel training

2 Emulsification of crumb rubber modified binder.

The devulcanisation process, as summarised in the literature review (section 6.8.2), breaks down the crosslinking that makes rubber tyres rigid and durable. Devulcanised rubber can interact with bitumen more intimately, creating a much more homogenous and low viscosity modified binder compared with conventional crumb rubber modified binder. This is also advantageous for emulsification technology which is well practised in New Zealand with unmodified and modified binders. Conventional crumb rubber modified binder is high viscosity and difficult to emulsify. Devulcanisation effectively removes this barrier. While the devulcanised rubber may lose some of its elasticity, commercial devulcanistion processes for bitumen modification include a step to restore this property.

In summary, devulcanised tyre rubber can be used with minimal changes required to the plant and procedures currently used in both chipseal and asphalt construction. There are currently two companies gearing up to produce devulcanised tyre rubber in New Zealand: Entyre (Otaki) and EcoVersion (Kawerau). The devulcanisation technology used by each company is different and is based on proprietary technologies.

3.2.1 Costs and risks of using devulcanised tyre rubber

The only downside to the uptake of this new technology is the extra cost added to the crumb rubber by the process. Due to the extra processing steps needed to devulcanise the rubber crumb, it adds to the overall cost of the rubber modifier. However, it is offset by cost savings made from specialist equipment needed to handle conventional crumb rubber modified binders, which is no longer required.

30 mesh ambient ground crumb rubber is about $750–$1,000 per tonne, and devulcanised rubber modifier (in pellet form) is about $900–$1,500 per tonne. Compared with virgin polymer (eg SBS), which is about $4,000 per tonne and prone to international market price fluctuation and can have additional importation complications, using a locally sourced devulcanised rubber does become an economically viable option.

The other indirect benefit of devulcanised tyre rubber is that any emission concern (predominantly sulphurous gases from breaking the sulphur bond) is mitigated at the devulcanisation plant where gas scrubbers are put in place to trap sulphides.

Should this option be pursued, further independent evaluation of the devulcanised rubber modified binder needs to be carried out to compare it with the currently available SBS modified binder. This is to verify that similar performance properties can be obtained without the use of specialist equipment and processes. In addition, investigation into emulsification of the devulcanised rubber modified binder is another key to a successful uptake of tyre rubber in New Zealand roads.

3.3 Implementation plan

Conventional crumb rubber modified bitumen technologies are unattractive in New Zealand for cost (plant) and safety reasons (cannot be emulsified), and are unlikely to be widely adopted in New Zealand given the dominance of SBS polymer modification in the market. The following plan relies on the success of new devulcanised rubber technology that would allow use of tyre rubber modified bitumen to be used essentially as a seamless substitute for SBS modified bitumen. In an ideal scenario, the proposed changes would be implemented in a chronological order as follows:

1 **Expanded use of PMB over the network.** Quantification of the performance benefits of currently used PMBs over unmodified binders must be investigated to demonstrate the whole-of-life cost benefits from use of PMBs. These benefits can then be used by the transport sector to justify increased use of PMBs. This ‘mandated’ market growth is needed to increase the potential market for devulcanised crumb rubber modified binders (assuming satisfactory behaviour, see below), and justify

investment by the sector in the technology. It is recommended a working group consisting of industry stakeholders be formed to adopt/develop a new specification for PMBs.

2 **Validation of devulcanised rubber technology**. Research must be done to establish that devulcanised tyre rubbers can be emulsified using standard equipment. The field performance of devulcanised rubber modified binders (with and without emulsification) needs to be verified by comparison with benchmarks set by the initial PMB study.

With a growing market for PMB/crumb rubber modified binders, the expected lower cost of devulcanised tyre rubber would encourage greater use of the technology and increased consumption of waste tyres.

4 Introduction to the literature review

Chapters 4 to 9 comprise the literature review.

The purpose of the literature review was to examine international practice with regard to the use of crumb rubber in road surfacings and identify possible constraints or other issues that may have a bearing on the adoption of crumb rubber surfacing technology in New Zealand.

Tyre-derived crumb rubber is a finely ground (<0.6mm) product derived from waste tyre rubber. It has become a common additive to bituminous binders in many parts of the world since the 1970s to address pavement performance issues as well as to tackle the disposal problem of end-of-life tyres. International experience has shown that crumb rubber can be effectively incorporated into road surfacings both in asphalt mixes and in chipseals.

4.1 Previous New Zealand research

Anecdotal evidence suggests that sporadic efforts to use crumb rubber modified bitumen, at least in chipseals, have been made in New Zealand since the 1960s. However the history and outcomes of these attempts have not been documented. It was recorded that addition of crumb rubber directly into the pug-mill had been used in New Zealand on a proprietary recreational asphalt surface (Patrick 1983).

Patrick et al (1996) conducted a study 20 years ago that concentrated on the potential use crumb rubber waste tyres had as an additive to the bitumen used in constructing New Zealand surfacings. High initial cost was seen as a major obstacle for crumb rubber when compared with synthetic polymers (such as SBS) which was seen as a lower risk alternative. Approximately 20–25% of crumb rubber was estimated to achieve the same level of elasticity as 4% SBS. Hence, the recommendation at the time was to restrict crumb rubber use to special situations where modification was cost effective due to enhanced performance and a longer life cycle. Subsequently a small trial of crumb rubber addition to asphalt (using the dry process) was conducted with mixed results (Patrick et al 2006). Since that work no evidence of further trials or application of crumb rubber in road surfacings in New Zealand has been identified.

A literature review was conducted for Transit New Zealand in 2006 (Williamson 2006). Among the key conclusions were:

- SBS modified bitumen provided the same benefits as wet process crumb rubber modified binders but at lower cost.
- Dry process asphalt mixes did not appear to confer performance advantages on asphalt mix.
- Recyclability of crumb rubber asphalt mix would probably not be a barrier to its use in New Zealand.
- Wet process crumb rubber modified binders could be accommodated under New Zealand asphalt specifications in the same way as SBS binders, but the dry process would be excluded (without special permission from Transit New Zealand) as the crumb rubber would not meet the aggregate performance requirements.
- Air discharge limits under the RMA might exclude use of the wet process.

5 Crumb rubber in roads

5.1 Waste utilisation

From an environmental standpoint, use of crumb rubber diverts the used-tyre waste stream away from landfills. Road construction is one of the few applications that can potentially use large volumes of the material. There are other recycling technologies such as pyrolysis to produce tyre-derived fuels, but attempts to apply these technologies in New Zealand have been unsuccessful (Tyrewise 2012b; Dana Peterson, pers comm 2014).

5.2 Crumb rubber modified road surfacings

In the USA, crumb rubber modified binders are known as asphalt rubber or rubberised asphalt. Based on the American Society for Testing and Materials (ASTM) (2013) D8-13b specification, asphalt rubber is defined as a blend of asphalt cement, reclaimed tyre rubber and certain additives, in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles. Asphalt rubber is also referred to as 'wet process – high viscosity'. Rubberised asphalt is another crumb rubber modified bitumen product where the rubber component is normally less than 15%. This includes rubber modified binders and 'wet process – no agitation' or terminal blends, which will be discussed in more detail in section 5.3.3.

5.3 Performance

Properties and performance of tyre rubber modified binders are often compared with those of PMBs. The following subsections highlight the areas where the use of PMBs can be advantageous over unmodified binders.

5.3.1 Reduced chip loss, reduced binder rise and bleeding/tracking

Unmodified binders can become brittle in low-temperature areas, posing issues for chipseals, such as poor aggregate retention or chip adhesion. This can occur both during construction as well as in service. Polymer modification reduces temperature susceptibility, provides increased adhesion to the existing surface, increases aggregate retention and flexibility, and allows the roadway to be opened to traffic earlier (Zaniewski and Mamlouk 1996).

In high temperature areas, polymers are also considered to be beneficial in minimising bleeding and enhancing the durability of the chipseal, and are recommended for high traffic volume roads and late season work (Shuler 1990; Wegman 1991). Similar performance benefits, in particularly excellent chip adhesion, were reported by Patrick (2000) from a PMB emulsion trial in New Zealand in the mid-1990s.

5.3.2 Improved fatigue resistance and skid resistance

PMBs are frequently used for constructing stress alleviating membrane and stress alleviating membrane interlayer (SAMI) to address fatigue damage to pavements and surfacing. Lu et al (2013) reported that performance improvements are normally found with respect to fatigue resistance, particularly with modified binders with SBS copolymer.

In high stress and high curvature areas, the improved elasticity and strength of polymer modified pavements can endure higher traffic induced stresses, especially high shear force generated by traffic braking and on curved road surfaces. This indirectly assists skid resistance of the modified pavements.

5.3.3 Improved resistance to rutting and reflective cracking

A comprehensive review of different types of PMBs by Zhu et al (2014) highlighted the increased resistance to permanent deformation such as rutting at high temperatures. Polymer modification also results in better elastic recovery and higher cracking resistance, particularly at low temperatures.

The potential performance benefits of crumb rubber modified binders are very similar to those of PMBs in general. There is a large body of work dealing with the performance of crumb rubber modified road surfacings (see for example, Caltrans 2005b; 2006; Miró et al 2009; SABITA 2009; VicRoads 1994; VicRoads 2004). A detailed analysis of this work was beyond the scope of the current project but there is considerable evidence that crumb rubber modification confers performance benefits compared with standard materials, at least with respect to asphalt mixes. The extent of the benefits derived depends on many factors including the amount of crumb rubber used, the method by which the crumb rubber is incorporated, and the rubber properties and particle size distribution.

In general terms the benefits can be summarised as:

- improved rutting resistance in asphalts from more elastic binders with higher softening points
- less temperature sensitive binders improve high temperature rutting resistance without adversely affecting low temperature properties
- higher binder films possible in asphalt mixes improve durability (oxidation resistance) without binder drain-down
- improved resistance to fatigue due to the elastic nature of the binder
- resistance to reflective cracking when used as an asphalt interlayer membrane
- reduced pavement noise (primarily tyre noise) due to the use of crumb rubber in open- and gap-graded mixes (Caltrans 2006; Hicks et al 2012b; Zhu and Carlson 2001).

Potential benefits often claimed in the literature for chipseal surfacings include improved chip retention, resistance to reflective cracking and reduced likelihood of bleeding and tracking of bitumen at high road temperatures.

6 Technology developments

6.1 Historic problems in using crumb rubber modified binders

Crumb rubber was first used in the US in the 1960s. However, there was never any appropriate code of practice for the roading authorities to follow. The lack of usage guides plagued efforts to use crumb rubber more widely around the world prior to the 1990s and was one of the main causes of the failure of the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) in the US. This Act was an attempt by the US Government to mandate the use of crumb rubber in asphalt pavements. The act was introduced with very little technological assistance from the federal government. Despite the presence of a regulated market, each state government was left to organise their own resources to develop and improve crumb rubber processes. Patents which were effective at the time made it difficult for any collaborative advancement in the technologies.

Common issues with using crumb rubber include:

- The need for high processing temperatures which often leads to potentially harmful emissions and other environmental concerns (this is addressed in chapter 7).
- Segregation of rubber particles from highly viscous crumb rubber binders is a potential threat to the quality of the wet process binder. Many practitioners have experienced separation of the crumb rubber and the bitumen binder into two or more phases (Epps 1994).

Inadequate compaction of asphalt is a common occurrence across various countries in the early developmental stage of using crumb rubber in roads. There have been issues with asphalt compaction in colder climates, due to the unfamiliarity of working with high viscosity binders in the climates concerned.

Crumb rubber is now used widely and successfully in some countries, however, particularly in chipseals in Australia (VicRoads 1994; Austroads 2009) and South Africa (SABITA 2009; 2012) and in asphalt mixes in the US and Canada. Authorities in California, Texas, Arizona and Florida in the US and in Ontario, Canada have worked continuously with crumb rubber modified binders since the 1990s and have developed a large body of experience that has been published in comprehensive user guides (Caltrans 2005b; 2006; Hicks et al 2012b). Some of the critical aspects of crumb rubber use are highlighted in the following sections.

6.2 Composition and production of crumb rubber

The preferred composition for crumb rubber is one with higher natural rubber content, such as is normally found in truck tyres. Natural rubber digests and disperses relatively quickly and thickens the bitumen phase which helps to promote interaction with other rubber compounds in the crumb rubber. Natural rubber has also been found to enhance adhesion of aggregates in chip seals (Caltrans 2005b; Artamendi and Khalid 2006). The natural rubber component can be increased by adding non-tyre derived natural rubber.

Table 6.1 Typical tyre composition

	Passenger car tyre (wt%)	Truck tyre (wt%)
Natural rubber	14%	27%
Synthetic rubber	27%	14%
Carbon black	28%	28%
Steel	15%	16%
Fabric, fillers, etc	16%	15%

Source: Jansz (2012)

As crumb rubber is derived from a waste stream the composition of the rubber can vary between different classes of tyres and manufacturers and the resulting material properties can also vary once incorporated with bitumen binders and aggregates. Good quality control is necessary to maintain a consistent crumb rubber product.

There are various processes available to produce crumb rubber. Waste tyres are typically shredded to pieces (40cm^2 and smaller) and the steel belts and fibres separated from the rubber prior to granulation or grinding. The final crumb rubber materials are defined as either ambient or cryogenically processed.

- **Ambient processing** consists of grinding the waste tyre rubber at room temperature. This provides irregularly shaped, torn particles with relatively large surface areas to promote interaction with the bitumen binder.
- **Cryogenic processing** cools the rubber below its embrittlement (glass transition) temperature with liquid nitrogen and shatters it in a hammer mill into smooth particles with a relatively small surface area compared with the ambient temperature ground product.

Sometimes, the cryogenic process is used prior to ambient grinding to reduce particle size. Studies have confirmed that ambient grinding is preferred as it produces rubber crumbs with a higher surface area which helps with digestion and bonding (Lee et al 2008; Caltrans 2005b; 2006; Hicks et al 2012b). Only ambient ground crumb rubber is permitted for chip seal operations in South Africa (Lo Presti 2013).

A more recent process involves use of high pressure (55,000psi or 380MPa) water cutting heads to produce a rubber crumb. The particles have a high surface area similar to those from ambient grinding (Lo Presti 2013). Particle sizes for crumb rubber are generally less than 2.36mm (1.18mm in South Africa) and mainly in the 0.3–1.18mm range.

6.3 Processes for incorporating crumb rubber into road surfacings

Currently, there are three distinct processes by which crumb rubber can be incorporated into road surfacings. Each process has its own benefits and shortfalls. It is important to note that the most suitable type of process may depend on the chosen application.

6.3.1 Dry process

A dry process is any method that includes crumb rubber as a substitute for 1–3% by weight of the aggregate in paving mixture, not as part of the binder. The crumb rubber acts as a rubber ‘aggregate’ in the paving mixture. Therefore, the binder is not considered to be modified. This method applies only to the production of crumb rubber modified asphalt mixes. The rubber ‘aggregate’ is included with the dry heated aggregate and mixed thoroughly before the bitumen binder is added. The mixture is then compacted at a temperature between 143 and 150ºC (Hicks 2012b).

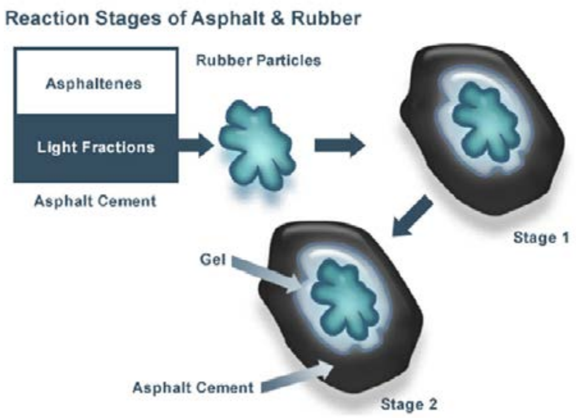
Such processes are not constrained by binder storage time (and phase separation). Based on extensive studies in North America, the dry process is most appropriate in an open- or gap-grade mix design. Appropriate adjustment must be made during mix design to counter for the lower specific gravity of the crumb rubber compared with the aggregate it replaces.

The potential shortfall of this process is the inferior bonding between the rubber and the binder due to limited interaction during mixing. This may result in limited performance improvement from the crumb rubber, which is a reason for limited use of this process. It is also necessary, to prevent damaging the rubber and producing fumes, that the crumb rubber is introduced to the plant in such a way it does not come into direct contact with any heating flames. Plants equipped with a recycling ring for recycling asphalt mix would be suitable for example.

6.3.2 Wet process – high viscosity

The wet process in general is used to modify binders with crumb rubber before being incorporated into either asphalt mix or spray applications such as chipseals. The main advantage of this process compared with the dry process is much greater interaction between the crumb rubber and the bitumen is possible, and extensive modification of the bitumen achieved. Oils from the bitumen are absorbed into, swell and partially disperse the outer surface of the crumb rubber particles as shown in figure 6.1. Due to the high viscosity of the resulting blend this method normally requires modification to bitumen handling equipment (see section 6.5.1).

Figure 6.1 Reaction stages of bitumen binder and crumb rubber



Source: Jansz (2012)

Based on California guidelines (Caltrans 2006), crumb rubber modified binders that maintain or exceed the minimum rotational viscosity threshold of 1,500cP (or 1.5Pa.s) at 190ºC should be classed as 'wet process – high viscosity' binders. These binders require continuous agitation to keep the gel-like crumb rubber particles evenly distributed. Wet process – high viscosity binders typically require at least 15% crumb rubber by mass to achieve the threshold viscosity. Concentrations of 20% are typical for wet process binders. Special spray nozzles (see section 6.6.1) are also needed to prevent clogging during application when constructing chipseals. The crumb rubber and bitumen are blended, usually with high shear mixing, at 175–225^{0}C for up to an hour after which the mix is transferred to a storage tank. This tank must also be stirred to prevent separation of the crumb rubber. Extender oils may also be added to the blend at about 2.5–6% by mass. Storage at high temperatures (>165⁰C) gradually degrades the product and the viscosity decreases. South African guidelines are to limit storage times to less than four hours at the application temperature (Asphalt Academy 2007).

6.3.3 Wet process – no agitation (terminal blends)

This type of process is also known as 'terminal blend', and is gaining popularity in the US because of the improved workability of the modified binders. It is a form of wet process where crumb rubber is blended with hot bitumen binder at the refinery or at an asphalt storage and distribution terminal and transported to the HMA mixing plant or job site for use. While this type of modified binder does not require subsequent agitation to keep the crumb rubber particles evenly dispersed, it does require high-speed, high shear mixing to digest and partially devulcanise the fine rubber particles (complete devulcanisation is not desirable as much of the elasticity of the crumb rubber would be lost). Normally, crumb rubber particles finer than the 300 microns (Caltrans 2006) or 600 microns (Hicks et al 2012b) sieve size are used to modify the bitumen binder. The combination of relatively small particle size compared with that typical of the traditional wet process, high shear mixing and 200–300⁰C temperatures at elevated pressures ensures the rubber can be digested quickly and kept dispersed by normal storage tank circulation rather than special augers/paddles. In the past, the rubber contents for such blends have been no more than 10% by mass of binder with viscosities less than 1,500cP at 190⁰C (which does not meet the ASTM D8 13b (ASTM 2013) definition of a high viscosity binder). However, there are now products which include 15% or more crumb rubber. In general though the degree of modification achieved is less than in the conventional wet process and the viscosities of terminal blend products are lower (Lo Presti 2013).

The specific advantage of this type of modified binder is that it is possible to use such modified binders at lower temperatures than the high viscosity type and that the blends are stable as long as the crumb rubber is fully digested (Hicks et al 2012b). Various proprietary processes claim to enhance storage stability and homogenisation still further through various mechanisms, for example the addition of sulphur or air blowing the blends to cross link the rubber to the bitumen. Similarly, another process involves pre-treatment of the crumb rubber particles with hydrogen peroxide to introduce reactive sites that enable crosslinking to the bitumen (Lo Presti 2013).

Figure 6.2 Spraying of PG76- 22TR (terminal blend)

Source: CP2C (2014)

Figure 6.3 Application of hot chip in California

Source: CP2C (2014)

In summary, wet processes are more commonly used over the dry process because of the enhanced digestion and chemical interaction between the binder and rubber, thus creating a more homogeneous modified binder. Terminal blends are gaining popularity because of the superior quality, in terms of workability, homogeneity and storage stability.

6.4 Specifications

Internationally, a number of specifications for crumb rubber modified bitumen or PMB that would include crumb rubber modified material have been developed. These include ASTM D8-13b (ASTM 2013), ASTM D6114/D6114M-09 (ASTM 2009) and the specification framework for PMBs (Austroads 2014b) in Australia, in which properties such as minimum softening point, torsional recovery, rubber content and maximum viscosity are specified. The US PG grading system would also accommodate crumb rubber modified bitumen.

There is currently no material specification or guidelines for the use of crumb rubber modified binders in New Zealand. This presents a potential obstacle to roading contractors in New Zealand as construction of crumb rubber modified surfacings can be more challenging than when using standard materials.

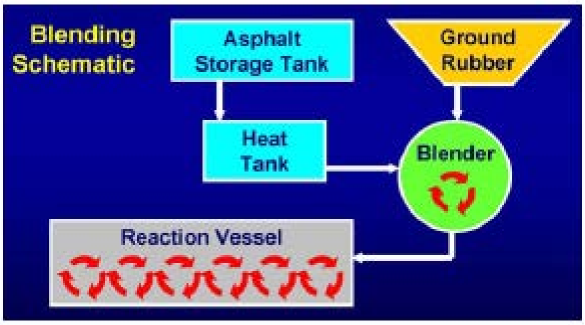
Development of a material specification and usage guidelines is considered essential to foster uptake of crumb rubber technology in New Zealand.

6.5 Crumb rubber binder production

6.5.1 Mixing equipment requirement

For the wet processes, binder production methods are essentially the same for both hot mix and chipseal applications. The following schematic shows the basic principle, which applies more or less at a plant as well as for field production. The components (bitumen binder and crumb rubber) are metered into the high shear blender. The blending unit thoroughly mixes the binder, crumb rubber modifier and other additives such as extender oil. Extender oil is typically a non-volatile, naphthenic process oil that helps swell the rubber particles and aids in digestion. The blend is then pumped into a heated reaction vessel where the interaction of the crumb rubber particles and binder proceeds. For terminal blends, the fully digested crumb rubber binder can go directly into a storage tank or tanker.

Figure 6.4 Schematic diagram of the blending process where crumb rubber is incorporated



Source: Caltrans (2006)

The quality of the crumb rubber modified binder depends on the proportioning, temperature, agitation and digestion time, all of which should be accurately monitored and controlled. Tanks for the initial storage and blending should be heated to temperatures of at least 190ºC and well insulated. The equipment should include retort heaters or heat exchangers for heating, and insulated transfer lines to minimise heat loss between processing units. Different guidelines have indicated various maximum operating temperatures of around 200ºC. The reasons for not overheating the crumb rubber modified bitumen is the risk of emission and odour, and some studies have found that prolonged heating can significantly reduce the viscosity of the modified binder and inherited properties of crumb rubber may be lost.

Modified binders (except for terminal blends), for spray applications are normally produced close to the job site, which minimises the risk of segregation. For remote sites, commercially available mobile blending/digesting facilities are potential solutions. The illustration below is an example of a mobile system where continuous production of crumb rubber modified binders can be produced close to the job site. Note the additional technology to contain 'blue smoke', which is a result of overheating.

Figure 6.5 Example of a mobile crumb rubber modified bitumen plant in Australia

Source: Jansz (2012)

6.5.2 Storage and transport

In terms of storage and transporting modified bitumen, the general rule of thumb is to have good temperature management and avoid heating crumb rubber modified binders above 200ºC. During storage or transport, continual circulation/stirring is essential to ensure homogeneity and the temperature should be maintained at 185–195ºC. When re-heating crumb rubber modified binders, heating should be at a maximum of 10ºC per hour with slow circulation (Strategic Alliance Reference Group 2009).

6.6 Applications of crumb rubber modified binders in chipsealing

Chipsealing with crumb rubber modified bitumen has been practised in Australia particularly Victoria, New South Wales and Western Australia since the 1970s (VicRoads 1994) and in South Africa since the 1980s (SABITA 1998).

In Australia two grades of crumb rubber with different gradations are used in chipsealing applications. All crumb rubber must pass the 2.36mm sieve (in South Africa all must pass the 1.18mm sieve) and all particles must be less than 3mm (Austroads 2014b). Most crumb rubber binders for sprayed seal work are produced by the traditional wet process, without extender oils and with up to 25% crumb rubber. The properties of crumb rubber binders for chipsealing in Australia are specified in terms of softening point and elastic recovery according to Austroads AGPT/T190 (Austroads 2014b).

6.6.1 Spraying

For chipsealing operations, crumb rubber modified binders are produced using one of the wet processes. Controlling the viscosity of the modified binder by managing temperature is important, but distributors with large spray nozzles must be used to prevent clogging due to undigested rubber particles. Pumps on the bitumen distributors must also be appropriate for the high viscosity of crumb rubber binders. Terminal blend type material is easier to work with and is less prone to streaking.

Based on the *Technical commentary on part 226 – application of sprayed bituminous surfacing* for South Australia (Neaylon 2009), crumb rubber and high bitumen content emulsions should be sprayed using B6 Copley nozzles. The latest Austroads and AAPA document AP-PWT33-14 (Austroads and AAPA 2014) provides the following selection guidelines:

Table 6.2 Nozzle selection guideline

Intermediate nozzles			End nozzles			Typical uses
Copley designation	Austroads designation	Rated output (L/min)	Copley designation	Austroads designation	Rated output (L/min)	
S2	*(Note 1)*	9	ES2	*(Note 1)*	18	Enrichment, rejuvenation and other uses requiring very light application rates
A4	AN 18	18	EA4	EAN 18	36	General spraying applications for bitumen, cutback bitumen and PMBs
			EA4 (W) *(Note 2)*	EAN 18 W *(Note 2)*	18	
B6	*(Note 1)*	27	EB6	*(Note 1)*	54	Spraying high bitumen content emulsions
B8	*(Note 1)*	36	*(Note 3)*	*(Note 3)*	–	Spraying hot crumb rubber bitumen binders

Notes:

1. Austroads designations are not currently applied to these sizes and Copley designations are still used.
2. The modified end nozzle, developed in WA, provides half the fan width and output of an EAN 18 – see also notes on spraying width, below.
3. There are no specific end nozzles manufactured for B8 applications. EB6 end nozzles may be used with both B6 and B8 intermediate nozzles.

Source: Austroads and AAPA (2014)

General guidelines (based on Australian (VicRoads 1994) and South African practice (Judd et al 2008) for sealing with crumb rubber modified binders are set out below:

- Ensure the pavement temperature is at least 20°C and rising, prior to commencement of spraying.
- Transfer temperature should be 190–195°C using normal tanker-sprayer transfer procedure. A larger in-line strainer mesh (especially when B6 or B8 nozzles are used) is recommended. Minimum spraying temperature for crumb rubber modified binder is 190°C. Recommended temperature is 195°C.
- Generally, 2–3% kerosene (industrial power kerosene or jet fuel A1) is required to prevent streaking and ensure even distribution of binder through the nozzles. Up to 6% cutter is recommended in areas where the pavement temperature is below 25°C at the time of spraying or where the site experiences frosty winter conditions.
- Use of pre-coated aggregate is highly recommended and adhesion agent is also recommended to ensure minimal chip loss.

In general, similar to laying conventional road surfacings, good temperature management is critical. With crumb rubber modified binders and mixes, the operating window is likely to be narrower due to the higher temperatures required to keep it workable.

6.6.2 Crumb rubber emulsions for chip sealing

The roading industry in New Zealand favours a switch from hot cutback bituminous binders to bitumen emulsions for health and safety as well as logistical reasons. This does introduce a potential barrier to the use of crumb rubber. The high temperatures required for handling these binders and their high viscosity makes emulsification much more difficult than using standard binders.

Fortunately, there are growing examples where crumb rubber has been successfully incorporated into emulsified binders. The principle behind one technology is to add a solvent-based dispersion of crumb rubber of high concentration (40–50%) into a bitumen emulsion by simple blending (Holleran et al 1997; Holleran and Reed 2000).

Terminal blends, being of lower-viscosity can be emulsified directly and thus used as conventional bitumen emulsions (Pacific Emulsions Inc 2009). The caveat is that the percentage of crumb rubber used is no more than 5–10%. This may result in crumb rubber modified surfacings falling short of the expected performance benefits. More recently, the terminal blends have been developed which contain more than 15% crumb rubber (up to 20% in some Caltrans specifications). It is clear that it is possible to emulsify crumb rubber modified binders, but the technology is still in development.

An alternative method for emulsifying crumb rubber modified binder is by devulcanising the crumb rubber prior to binder modification. The devulcanisation process (see section 6.8.2) removes the sulphur crosslinks and enables crumb rubber to be incorporated into bitumen binder in similar manner as virgin polymers, resulting in a homogenous binder with a significantly reduced high-temperature viscosity suitable for emulsification (Subhy et al 2015; Zanzotto and Svec 1996).

6.7 Warm mix technologies or warm mix asphalt

Crumb rubber modified bitumen have also been used in warm mix asphalt applications (WMA) in the USA (FHWA 2014). The lower temperatures required for these processes may reduce emissions when using crumb rubber. There are currently four main approaches taken to produce WMA.

1 Inorganic chemical additives – predominantly crystalline hydrated alumina-silicates, such as synthetic zeolite (eg Aspha-Min, Advera) which is added during mixing to create a foaming effect in the binder.

2 Asphalt foaming systems – these typically involve first pre-coating the aggregate with a soft binder which allows for a lower mixing and compaction temperature, and then using a harder binder that is foamed to improve workability, eg WAM-Foam.

3 Organic additives – typically paraffin-based compounds, eg Sasobit and Asphaltan B.

4 Emulsion systems – using bitumen emulsions with additional chemical additives (eg Evotherm).

While warm mix technologies are relatively new, they are considered to be acceptable for use provided they meet equivalent performance requirements to those of HMA. They have promising futures in terms of energy saving and air quality management. Numerous case studies have shown that the technologies do work as far as producing satisfactory HMA at reduced temperatures.

Case studies of warm mix technologies used with crumb rubber modified chip seals (Hicks et al 2010; 2012a; Cheng et al 2012) have shown that numerous trials using warm mix technologies and terminal blends were conducted in the early 2000s. The initial results were promising. The main recommendations were continuation of monitoring and evaluation of the pavement performance to know for certain that the finished pavement still performed the same, if not better.

Behl et al (2013) conducted laboratory studies using the Evotherm technology to lower the working temperature of a terminal blend crumb rubber modified bitumen, containing 10–12% of tyre rubber by weight of bitumen. The study successfully lowered the mixing temperature to 120–130ºC with 0.5% of the WMA additives by weight of bitumen. The modified ‘warm mix’ performed well against the conventional hot mix.

WMA systems may in some cases allow the manufacture of crumb rubber modified asphalt at lower temperatures than normal and so potentially reduce emissions but very little research has been conducted in this area.

Warm mix technologies were also used to pre-treat tyre-derived rubber in an attempt to reduce the high-temperature viscosity as a way of reducing the operating temperature range and improving the storage stability of crumb rubber modified binders (Subhy et al 2015).

6.8 Other technologies

6.8.1 Poroelastic road surfaces (PERS)

This concept was first developed and used in Sweden in an attempt to produce a low-noise road surfacing (Biligiri et al 2013). The principle is similar to that of porous asphalt (>20% air voids) but >20% of the aggregate is replaced by crumb rubber of 1–4mm and it uses polyurethane as the binder instead of bitumen. The elastic nature and the high porosity help to create a low-noise surface, and aggregates in the mix improve the friction of the surface. This is potentially an alternative application for crumb rubber in car parks where skid resistance is not as critical as on high-speed roads.

6.8.2 Devulcanisation

According to the literature research, the breaking of bonds in the three-dimensional matrix of vulcanised rubber can be accomplished by several methods. There are processes that use radiation energy, microwave energy and ultrasonic energy (Zanzotto and Svec 1996). Chemical and thermo-chemical processes to devulcanise or partially devulcanise crumb rubber (Memon and Franco 2006). There are also thermo-mechanical devulvanisation processes which remove the sulphur and cross-linking without the use of chemicals, high pressure and elevated temperature (Zanzotto and Svec 1996).

The processes are more or less selective in breaking the sulphur and carbon bonds. The thermal and thermo-mechanical processes seem to be the most practical. The properties of a devulcanised material are substantially different from those of the original crumb rubber resulting in different properties for the modified binder.

Devulcanisation leads to a rubber modified binder with a much lower high-temperature viscosity and thus allowing it to be used with dense graded asphalt mixes where the film thickness needs to be low. This also helps to overcome the two main issues of conventional crumb rubber modified binders:

1 The high cost of specialist equipment to work with high viscosity modified binder

2 The risk of segregation of partially digested rubber in the high viscosity binder during storage and transport.

However, this is currently a more costly process (about 60% more expensive than a conventional crumb rubber modification). The cost–benefit of this process needs to be evaluated over the lifecycle of the modified pavement and surfacing.

Zanzotto and Svec (1996) commented that if end-of-life tyres are to be used in large quantities for binder, the economy of the devulcanisation process has to be such that:

- Rubber binder should have improved properties to justify the increased cost associated with the manufacturing process.
- Rubber modified binder should be cheaper than PMBs. Otherwise, the cost will be prohibitive for massic use and it will not be competitive with existing products that use virgin polymers.

- The devulcanisation process and the incorporation of the devulcanised rubber will have to be relatively simple and rugged so that it can be used without excessive capital investment.
- It must be environmentally friendly.
- The final product will have to be useable by equipment and technologies presently employed in road pavement and surfacing.

6.9 Non-surfacing roading applications

1 Similar to the principle of PERS and open-/gap-graded porous asphalt, crumb rubber may have a role in non-surfacing roading applications such as drainage where resistance to traffic loading is not as important. Vila et al (2012) experimented with using crumb rubber as a drainage layer in green roofs. In this paper, crumb rubber was used instead of the porous stone materials currently used in some commercial solutions (such as expanded clay and pumice). Preliminary result was encouraging and further research and development was recommended.

2 Humphrey and Eaton (1995) found by road trials that a layer of waste tyre chips provided effective insulation to limit frost penetration beneath a gravel-surfaced rural road. Good drainage property was also observed. Similar observation was reported by Frascoia and Cauley (1995) in a separate study.

3 As part of a strategic recycling programme, Pennsylvania Department of Transportation (PennDOT 2011) conducted a trial adding crumb rubber to a four-inch basecourse and two-inch friction course. The asphalt mix was modified with 0.5% (by total weight) crumb rubber using a dry process. However, no performance data was reported. More recently, Florida Department of Transportation report (FDOT 2014) conducted a significant amount of research on ways to re-use waste materials including glass, waste tyres, and reclaimed asphalt and concrete pavements. FDOT reported that crumb rubber does not make a good stabilising agent for subgrade soils. However, the authors concluded that the use of shredded rubber in sand sub-bases may be feasible as the increased rubber content improved drainage without affecting the properties of the sand such as California bearing ratio.

4 Safety barriers made of waste tyre rubbers and other materials. There is currently a European Union funded project on demonstrating and validating a generation of eco-friendly safety barriers made from recycled waste tyres, plastics and concrete. www.lifeproject-newjersey.com/

5 Railway sleepers or railway ties may be moulded from crumb rubber (US Patent 1993) and other plastics to replace those made by timber or concrete.

7 Environmental impacts

While incorporating crumb rubber in roads may seem to be the perfect solution for repurposing waste tyres, there have been ongoing concerns over the potential increase in hazardous emissions during production and its effects on exposed workers, leaching during service, and recyclability of the end-of-life crumb rubber modified surfacings. The following section summarises the latest findings.

7.1 Emission and worker exposure concerns

In 1991, the US Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA) which required each state to use a minimum quantity of crumb rubber modified HMA in federally funded roads. The mandate generated momentum in the development of crumb rubber surfacings across the US but it also created strong opposition and serious concerns over fume emissions and other environmental and human health issues, along with cost and other potential implications. As a result of these concerns, a temporary moratorium was immediately put in place on the ISTEA mandate until those issues could be satisfactorily resolved.

The US federal government funded comprehensive emissions testing programmes of asphalt and crumb rubber modified asphalt fumes at seven sites across the US (Hanley and Miller 1996; Stout and Carlson 2003). Extensive studies on fume emissions from crumb rubber bitumen use were carried out by various US states Department of Transportation (DOTs) to provide detailed information on the health concerns compared with conventional processes. While initial studies indicated the emissions caused by using tyre rubber in asphalt were no greater than those from conventional asphalt, variations in the conditions of a hot mix operation sometimes confounded the effect of crumb rubber on emission rates (Crockford et al 1995). In many cases increases in plant emissions were due to the elevated operating temperatures rather than the presence of crumb rubber.

Roschen (2002) conducted stack emission tests at two asphalt concrete mixing facilities in California in 2001. Emissions during the production of crumb rubber asphalt mixes were compared with the production of conventional mixes under the same plant conditions. The report concluded that the measured emissions of particulate and specified toxic compounds during the production of crumb rubber asphalt were not significantly greater, if greater at all, than the emissions measured during the production of conventional asphalt. The emission rates were consistently lower than those specified in the US Environmental Protection Agency (EPA) *Compilation of air pollutant emission factors AP-42* (EPA 1995). As a result, the existing production plants in the area investigated were permitted to produce crumb rubber asphalt mix.

In most cases and in subsequent studies, for all samples and all mixes used, the levels of exposure to hazardous compounds were significantly below exposure levels established by the National Institute for Occupational Safety and Health (NIOSH) and the US Occupational Safety and Health Administration (OSHA) (Gunkel 1994). However, a later NIOSH report (Burr et al 2001) highlighted that there was still a lack of worker exposure studies to complement the numerous stack emission studies.

In summary, although no definitive results were obtained indicating that crumb rubber asphalt exposures are more hazardous than exposures from conventional asphalt production, NIOSH remains cautious and suggests based on the trend of this report that crumb rubber emission exposures are potentially more hazardous. The confidence intervals generally show that worker exposures can be considerably higher on crumb rubber modifier paving days and that some of these differences were statistically significant. Also, in general, the frequency of symptoms reported by workers was greater on the crumb rubber paving days.

These were often related to the distinct odour from heating crumb rubber binder at elevated temperatures. While the measured concentration from various emission studies does not exceed acceptable limits, the odour may still be an issue for the general public.

With regards to odour management, there are commercially available technologies. For instance, Ecosorb (OMI 2014) by OMI Industries is a chemical absorption method that works with asphalt. There is also information on odour control systems available from the Ministry for the Environment (MfE 2003).

7.2 Leaching concerns

Another area of concern is potentially hazardous compounds from the crumb rubber making their way into water sources by leaching of crumb rubber surfacings. While studies have demonstrated that trace metals, volatile organics and semi-volatile organics may be leached from milled crumb rubber asphalt, the levels are too low to be environmentally significant or dangerous under the US guidelines (Crockford et al 1995). It also must be noted that the tests were done on milled surfacings. These represent the worst case scenario as the surface area available for leaching is much greater than in a compacted asphalt layer.

Devulcanisation may be a solution to reduce the ecotoxicity problem by removing the chemicals prone to leaching before the crumbs are put into use (Myhre 2005).

8 Implications for recycling

Only a limited number of cases have been reported, but crumb rubber modified asphalts have been successfully recycled in the US. Caltrans (2005a) evaluated and reported a list of recycling options for crumb rubber modified pavements. In the order of highest feasibility, they are full depth pavement reclamation, hot plant recycling, cold in-place recycling and hot in-place recycling. Full depth reclamation is already being used for flexible pavement rehabilitation in California. It appears that crumb rubber modified materials can be readily incorporated in the basecourse with improved properties.

Hot plant recycling is where reclaimed crumb rubber modified material is recycled using a HMA plant. This processing route has huge potential for successful development and implementation given what is already been implemented for a conventional reclaimed asphalt pavement (RAP). The City of Los Angeles recycled a 12-year-old crumb rubber modified asphalt pavement on Olympic Blvd (Youssef and Hovasapian 1995). The pavement was milled and stockpiled at a nearby asphalt plant. The asphalt rubber grindings were added to virgin rock and extender oil so that the grindings composed 15% of the final mix. At another location, the grindings were put through a microwave process where nearly 100% of the output was composed of recycled asphalt rubber. They also performed an air quality impact of grinding, transporting and processing the asphalt rubber. The results of the testing showed that the recycled asphalt rubber reclaimed from Olympic Blvd met specifications and passed all tests and was recyclable using either microwave technology or conventional mixed design technology. The air quality testing found employee exposure to air contaminants well below the OSHA permissible exposure limits and in most cases, below the detection limit.

Both cold and hot in-place recycling options require further research and development. In cold in-place recycling, there were issues with the stability of the recycled mixes as a result of cold compaction. Caltrans was developing emulsion binders to resolve these issues. Similarly, in hot in-place recycling, there were issues with emission from extender oils as well as the use of rejuvenating agents. Recommendations from Caltrans were to focus on full depth reclamation and hot plant recycling while continuing to develop solutions for both cold and hot in-place recycling.

For the recycled crumb rubber mixture, volatile organic compound emissions were lower than the range for standard HMA. The report pointed out that air quality did not seem to be any more of a severe problem than it was with conventional asphalt. Due to odour, cold or very low heat, milling was preferred over hot milling when recycling the crumb rubber pavements. Any hot in-place recycling could only be done with equipment trains having effective emission control systems on them. Standard plants with effective emission control devices appeared to be adequate when incorporating up to 30% crumb rubber RAP in the mixture (Crockford et al 1995). It is also important to note that while traditional recycling of crumb rubber modified RAP requires higher production temperatures (>160ºC), it is possible to incorporate lower quantities of crumb rubber modified RAP (30%) at temperatures similar to conventional hot mixes.

More recently, Shen et al (2006) successfully conducted experiments to incorporate 15% crumb rubber modified RAP into asphalt mixture with the plant recycling process. The results from rutting tests and indirect tensile strength tests of the recycled mixture were comparable to those of the control mixture. It was noted that further research is required for incorporating higher percentages of crumb rubber as it may impact on the workability of the RAP mixture.

As the use of RAP is becoming more widespread in New Zealand, it is critical that temperature management is addressed when dealing with recycling crumb rubber modified pavements to minimise the risk of increased emissions. The use of warm mix technologies is an effective solution to reduce mixing and compaction temperatures (SCDOT 2010). In the case of modified pavements using devulcanised rubber, the implications for processing the RAP should be no different from that of RAP originating from polymer modified pavements.

In conclusion, there are certainly many examples abroad which the New Zealand industry can learn from. Over the past few decades, plenty of technologies have been developed to improve recycling of crumb rubber modified materials. The key to successful uptake in New Zealand is to investigate technology appropriate for the New Zealand market to ensure recycling of crumb rubber modified RAP can be implemented effectively and economically.

9 Costs

9.1 Cost-related issues

9.1.1 Supply

In New Zealand, approximately five million tyres are imported each year. It is estimated that 70% by weight of waste tyres go to some form of landfill (Tyrewise 2013). About 62,000 tonnes of waste tyres are generated in New Zealand annually, 25% of which (15,500 tonnes) are truck tyres and suitable for use in roading applications as a bitumen modifier. There is currently no market for crumb rubber use in roads in New Zealand and no strict monitoring of the flow of tyres in the country as a product or waste stream, which makes it difficult to maintain a secure supply of crumb rubber.

In Australia, where 16% of 48 million tyres are recycled annually, an estimated 30 million litres of crumb rubber-modified bitumen are sprayed on Australian roads each year (Jansz 2012). This is helped by the fact that many Australia state binder specifications have allowed the use of crumb rubber seals. As of July 2014, Australia has launched a voluntary Tyre Product Stewardship Scheme, which takes a levy of 25 cents on every new tyre sold in Australia (ACCC 2013). This will help fund and enhance the type of market that several groups are advocating to create in New Zealand.

The Tyrewise reports (Tyrewise 2012a, b and c; 2013) highlighted that New Zealand is currently missing supportive legislation that bans landfill of tyres and shapes the market system so there is a clear supply and demand balance within the life cycle of tyres. The Tyrewise working group have recommended, a mandatory participation scheme with priority waste stream/product status for waste tyres that should help create a market system, as demonstrated by a similar approach taken in the US.

By 1998, 48 states in the US had implemented waste tyre legislation or regulations to monitor the flow of waste tyres. Many states banned the practice of tyre disposal in landfills. Fees related to tyre sales or vehicle registrations were established to help fund waste tyre pile, clean-up efforts and to incentivise end-users to divert the flow of waste tyres from piles. Some states offer grants or direct reimbursement to tyre processors based on the product output.

With respect to roading applications for waste tyres, there are only four states (California, Texas, Arizona and Florida) in the US actively using crumb rubber in their roads. These states persisted with developing the practice and have incentives in place to encourage demand. For example in California, grants are given to roading contractors for construction jobs involving crumb rubber use (CalRecycle 2010).

In New Zealand, the Tyrewise project suggested a scheme in which fees on loose tyres would be collected from brand owners (preferably via Customs) and fees on fitted tyres collected via the Transport Agency on behalf of vehicle importers. The collected fee would be paid to a non-profit product stewardship organisation that would fund the collection of waste tyres from the public. The funds accumulated would be paid as incentives to registered scheme participants. The flaw in this scheme is that the roading contractors and bitumen suppliers are not part of the lifecycle of tyres, so they have no obligation or incentive to use crumb rubber under such a scheme.

9.1.2 Material costs

The cost of crumb rubber can vary significantly based on the quality of the product, which is determined by the processing techniques used. The cost can also increase significantly with decreasing size. The finer the mesh size, the more processing steps and thus costs are added to the final product.

It is important to note that 'quality' in the present context refers to the consistency of the overall product composition and particle size not the chemical purity of the crumb rubber. It is not essential to have 100% pure rubber for the crumb rubber to work in roads. In fact, it is advantageous to have carbon black (Brown and Bouncher 1990) as a reinforcing agent.

Another factor affecting cost is the volume of crumb rubber produced. The market for crumb rubber in New Zealand is currently very small and there are only a few waste tyre recyclers currently producing crumb rubber:

Pacific Rubber Ltd Located in Takanini, Auckland, does not produce 30 mesh (which is a grade used in Australia), but is in position to add it into the production line, which operates by mechanical grinding at ambient conditions.

Entyre NZ Ltd Based in the Clean Technology Park (Otaki), Entyre is currently building a recycling plant based on a chemical devulcanisation technology capable of handling 40% of the annual waste tyre stream. Its granulation processes are operated at ambient temperatures. The company's future is currently unknown as founder passed away late 2014.

Rubber Solutions Ltd Located in Upper Hutt, Rubber Solutions main operation is re-treading truck tyres. Currently 30 mesh crumb rubber using the ambient process is produced mainly for export to Australia.

EcoVersion EcoVersion is building a devulcanisation plant in New Zealand using proprietary technology developed by Maxlink Recycling in China. The thermo-mechanical devulcanisation process will be operational by 2016.

The supply of crumb rubber (and the number of suppliers) would presumably increase if a market in roading was established in New Zealand.

Currently ground crumb rubber costs NZ$700–750 per tonne (as of 2014) compared with bitumen at about $795 per tonne (as of April 2015). The price of devulcanised rubber varies from NZ$900 to NZ$1,500 per tonne (as of 2015). A recent presentation by Australian contractor, Boral, reported the cost of importing raw materials as A$800 for crumb rubber versus A$4,000 per ton of polymers (Jansz 2012).

9.1.3 Equipment and production costs

The initial cost of any technology uptake will always be high. This is unavoidable as capital investment is often key to implementation of a new process. Cost can be minimised by careful selection of what is required.

The plant requirements for use of crumb rubber are in general similar but not identical to use of SBS PMB. The phase stability of modern SBS-bitumen materials is superior to that of crumb rubber modified binders and odour is generally not a problem which is not the case with crumb rubber materials. For asphalt plants, there may be extra costs associated with the installation of specialised blending equipment and emission controls. For chipsealing, sprayers may need to be modified by use of more powerful pumps (due to the high viscosity of crumb rubber modified bitumen) and use of different spray nozzles. Unless the job sites are close to a blending plant where the modified binder is produced, then phase separation may be a problem. It may be necessary to have a mobile blending unit available at the job site.

Production costs are also potentially higher than conventional bitumen per unit ton until economies of scale are in place. While the necessary plant is readily available and the design and construction of crumb rubber modified surfacings is well established technology, the relatively lower volume in the New Zealand market presents an obstacle for the roading contractors to justify the initial costs. Nevertheless, the expiration of many patents on processing technologies in the late 1990s and early 2000s, has had the effect of driving the costs down in the US. In 1999, the price differential between conventional and crumb rubber HMA was about US$10.00 per ton in the US. In California, crumb rubber modified chipseal is priced at US$2 per square yard with an estimated treatment life of eight years and US$1 per square yard for conventional chipseal (Caltrans 2006).

9.2 Life cycle cost analysis

Although the initial cost of crumb rubber modified bitumen construction may be higher than that of conventional materials this may be offset by improved performance of crumb rubber surfacings in terms of fatigue resistance and durability. Caltrans, for instance, has done a thickness equivalency design guide for conventional dense graded asphalt concrete and crumb rubber modified hot mixes. The guide indicated that the initial cost for crumb rubber modified hot mixes is actually lower than conventional HMA due to the lower thickness required to achieve the same performance level (Caltrans 2006).

Crumb rubber modified binders are in general cost effective when used as thin, gap- or open-graded surface courses or overlays of 30–60mm compacted thickness, chipseals and interlayer applications (Caltrans 2006).

Jung et al (2002) conducted a life cycle cost analysis study comparing agency and user costs of conventional and asphalt-rubber hot mixes in Arizona. An analysis period of 25 years was chosen because it reflects the long-term cost effect as one or more rehabilitation should be undertaken, assuming the pavement life is around 10 years. The cost prediction was based on historical data from the first 11 years of the pavement’s life, which provided some assurance of the validity of the analysis.

The unit cost of an asphalt-rubber pavement in the US is normally 1.5 to 2 times more than conventional asphalt pavement. However, the total initial cost is much less for the asphalt-rubber pavement due to the difference in the thickness of each layer (as constructed). Costs were divided into agency costs and user costs. Agency costs consist of an initial construction cost (at year 0), rehabilitation and maintenance costs which typically increase over time. There may be other costs such as preliminary engineering. User costs include travel time delay costs, vehicle operating costs, accident costs and discomfort costs. User costs are often difficult to collect and quantify accurately. In addition, as mentioned in section 9.1, the four US states DOTs subsidise the use of crumb rubber in pavements, effectively making it more economical and appealing for contractors.

The pavements in the study are shown in table 9.1 below. In this particular case (a four-mile long, eight-yard wide section in Arizona), the initial cost for the conventional pavement design is almost twice as much as the asphalt-rubber pavement (to achieve equivalent structural strength).

Table 9.1 Illustrating a reduced construction cost of asphalt rubber pavement when the thickness is taken into account

Asphalt concrete	**Thickness (in)**	**Length (yard)**	**Width (yard)**	**Cost ($US) per sq yard per inch**	**Total cost ($US)**
Aggregate base	4	7,040	8	0.55	123,904
Bitumen treated base	6	7,040	8	1	337,920
Asphalt concrete	11	7,040	8	1.7	1,053,184
Sum					**1,515,008**

Asphalt concrete	Thickness (in)	Length (yard)	Width (yard)	Cost ($US) per sq yard per inch	Total cost ($US)
Asphalt rubber asphalt concrete (ARAC)					
Aggregate base	8	7,040	8	0.55	247,808
Asphalt concrete	3	7,040	8	1.7	287,232
ARAC	2	7,040	8	2.4	270,336
ARAC friction course	0.5	7,040	8	2.5	70,400
Sum ($US)					**875,776**

Source: Jung et al (2002)

The cost effectiveness of asphalt-rubber modified asphalt concrete is particularly good because of the reduction in thickness which brings the initial construction cost down dramatically even though the unit cost for the modified asphalt concrete is high. The net present value calculation over a 25-year period and at a discount rate of 4% is shown in table 9.2.

Table 9.2 Difference in maintenance costs and user costs over 25 years

	AC		ARAC		Difference (AC –ARAC)	
Year	**MC ($)**	**UC ($US 1,000)**	**MC ($US)**	**UC ($US 1,000)**	**MC ($US)**	**UC ($US 1,000)**
0	1,515,008		875,776		639,232	
5	1,844	12,296	1,317	12,325	527	-29
10	7,477	12,705	4,295	12,288	3,182	417
15	10,471	13,288	5,853	12,890	4,618	398
20	11,998	13,981	6,471	13,172	5,527	809
25	12,649	14,800	6,683	13,565	5,966	1,235

Year 0: initial construction cost, AC: asphalt concrete; MC: maintenance cost; UC: user cost

Source: Jung et al (2002)

The summary of costs in table 9.2 highlights that after year 10, both maintenance and user costs become significantly higher for the conventional pavement as its deterioration becomes more serious.

In another cost–benefit analysis study in California, Shatnawi (2013) compared four rehabilitation treatments each designed with an expected 20-year life based on retardation of reflective cracking. The four strategies were:

1 105mm HMA overlay

2 Crumb rubber modified stress alleviating membrane interlayers (SAMI-R) followed by 60mm HMA

3 60mm crumb rubber modified HMA (RHMA)

4 SAMI-R followed by 30mm RHMA

The cost effectiveness of using asphalt rubber modified SAMI in rehabilitating existing flexible pavements was demonstrated to be significantly greater than conventional HMA treatments. Net present value calculations for a 4% discount rate are shown in table 9.3.

Table 9.3 Cost differences between four rehabilitation strategies

Strategy description	Agency cost ($US1000)	User cost ($US1000)	Total cost ($US1000)
1 105mm HMA	2,500.28	1,852.30	4,352.58
2 SAMI-R + 60mm HMA	2,358.33	1,569.15	3,927.48
3 60mm RHMA	1,669.93	957.58	2,627.51
4 SAMI-R + 30mm RHMA	1,706.96	818.13	2,525.09

Source: Shatnawi (2013)

10 Conclusions

The purpose of this review was to bring to light information related to the use of crumb rubber in road surfacing applications that have a bearing on potential use of the material in New Zealand. A number of observations can be made in summary:

10.1 International experience

Crumb rubber has been successfully used in asphalt and chipseal surfacings internationally for many decades, particularly in asphalt mixes in the US and as a chipseal binder in Australia and South Africa. Plant, equipment and extensive guidance on the use of crumb rubber in asphalt and chipseal surfacings is readily available internationally and could be readily applied or adapted to crumb rubber use in New Zealand.

10.2 Specifications

There are numerous international specifications governing the properties of crumb rubber modified bitumen and asphalt mixes. If necessary these could be readily adapted for use in New Zealand (there is no Transport Agency specification covering crumb rubber or any other form of PMB) even if only in the form of guidelines as to the expected physical properties to be achieved. With the exception of the dry process (which is relatively little used) there appear to be no specification barriers to the use of crumb rubber binders in New Zealand; contractually they could be treated as any other proprietary PMB.

10.3 Technology

Two main processes dominate crumb rubber applications in road surfacings, the ‘dry’ process in which crumb rubber is added as 1 to 3% (by weight) of the aggregate fraction in the asphalt mix, and the ‘wet’ process. Not all asphalt plants in New Zealand would be suitable for use of the dry process. In the wet process crumb rubber is mixed with conventional bitumen and an oil and digested at around 200^0C. Typically 10–20% by mass (most commonly about 15%) of crumb rubber is used in the modified binder either in asphalt mix or as a chipseal binder. In the latter case the binder is sprayed at about 190^0C though lower temperatures have been used with the addition of warm mix technologies. The use of crumb rubber bitumen emulsions is still in the developmental stage. This is a key consideration for crumb rubber applications in chipsealing in New Zealand as in general the industry has agreed that a move to a lower temperature, wholly emulsion-based sealing is desirable for health and safety reasons.

Based on the literature review, wet processes have the best track record in terms of performance and commendation from various leading authorities. It is logical to further investigate the benefits of terminal blends against high viscosity crumb rubber modified binders.

10.4 Performance enhancement

Extensive laboratory studies and field experience have shown that crumb rubber modification enhances the rutting and fatigue cracking resistance of asphalt mixes compared with mixes made with conventional bitumen. Other (less well documented) advantages include improved noise reduction and drainage when used in open grade mix designs.

The performance benefits when crumb rubber is used in chip sealing applications are largely anecdotal. Improved resistance to reflected cracking, chip retention and reduce bleeding at high temperatures are generally cited as advantages for crumb rubber modified binders but there is little documented evidence from controlled trials to support these claims. In New Zealand, chipsealing offers the greatest potential for consumption of large volumes of crumb rubber but it is essential there is clear evidence of the predicted benefits actually being achieved.

10.5 Costs and supply

The US experience shows that per unit of material crumb rubber modified asphalt costs 1.4–2 times that of standard mix (in place) although the use of crumb rubber is longstanding, widespread and large volumes are used. Costs in New Zealand may be significantly higher especially in the early stages of adoption. The initial cost of a crumb rubber asphalt surfacing can be lower than that of conventional mix due to savings being made through, where possible, use of thinner layer thicknesses that achieve the same level of performance. This is possible because of the enhanced binder properties conferred by the rubber modification. In other cases the initial cost of crumb rubber modified asphalt may be higher than that of a conventional surfacing but savings accrue through a longer lifecycle (as is the case with SBS polymer modified asphalts). Based on the Australian experience costs of crumb rubber chipseals are typically very similar to chipseals with binders modified by synthetic polymers (PMBs).

Costs of the raw crumb rubber product will vary according to the volumes involved. There are at least three companies producing crumb rubber in New Zealand but the volumes produced are relatively small. The manufacturing processes involved are relatively simple and inexpensive, and expansion of production could be rapidly achieved if there was demand from the roading industry. Figures quoted by one supplier were $700–750 per tonne (compared with bitumen at around $1,000 per tonne).

10.6 Environmental concerns

Several environmental studies in the US have demonstrated that the emissions from crumb rubber asphalt mix production and paving operations are not significantly different from conventional processes and the detectable levels are normally within limits set by US Government agency guidelines. California has some of the strictest environmental regulations, and crumb rubber is widely used and developed in this state. From New Zealand's point of view, there is insufficient evidence from an environmental viewpoint to prohibit the use of crumb rubber in New Zealand roads. In addition, it is important to note that much of the environmental concerns can be minimised by available technologies, for example, warm mix technologies, which lower the application temperature of the crumb rubber modified binders and thus reduce the emission and potentially odour as well. A 'best practice' must also be followed so that proper measures, such as emission and temperature controls, are taken.

The same notion applies to recycling of crumb rubber modified materials. While there are no significant technology barriers associated with recycling crumb rubber modified RAP, further investigation is needed by the New Zealand industry to make sure crumb rubber modified RAP can be implemented cost effectively.

The most difficult obstacle here is overcoming public perception of the distinct odour associated with heated rubber. Many mixing plants in New Zealand are situated in areas where there is a growing presence of residential dwellings because of the changing resource consents over time. The roading contractors have adopted to the changes and modified the plants to meet the environmental requirements. Similarly, there are technologies available to control emission and odour associated with crumb rubber use. Emissions are likely to be affected by plant design and operation so that if used in New Zealand a more thorough investigation of potential emissions is desirable.

11 Recommendations

Conventional crumb rubber modified bitumen technologies can be applied in New Zealand and although the initial cost increase could be significant, once they are established the cost would be expected to be comparable to polymer modified binders. The fact that crumb rubber cannot be emulsified is a barrier to its use but recent developments in devulcanisation technology may overcome this. Currently the market for crumb rubber is small, but this is because improvements provided by modifying chipseal binders have not previously been definitively proven; however, methods are now available to assess the potential enhancements. Implementation of the following recommendations would allow the use of tyre rubber modified bitumen essentially as a seamless substitute for SBS modified bitumen. In an ideal scenario, the proposed changes would be implemented in a chronological order as follows:

1 **Expanded use of PMB over the network.** Quantification of the performance benefits of currently used PMBs over unmodified binders must be investigated to demonstrate the whole-of-life cost benefits from use of PMBs. These benefits can then be used by the transport sector to justify increased use of PMBs. This ‘mandated’ market growth is needed to increase the potential market for devulcanised crumb rubber modified binders, and justify investment by the sector in the technology. It is recommended that a working group consisting of industry stakeholders be formed to adopt/develop a new specification for PMBs.

2 **Validation of devulcanised rubber technology**. Research must be done to establish that devulcanised tyre rubbers can be emulsified using standard equipment. The field performance of devulcanised rubber modified binders (with and without emulsification) needs to be verified by comparison with benchmarks set by the initial PMB study.

3 **Environmental considerations.** From an environmental point of view, it is recommended that a ‘best practice’ is followed so that proper measures, such as emission and temperature controls, are taken. The potential issue of the distinct odour emanating from the hot bitumen containing crumb rubber needs to be considered. While there are no significant technology barriers associated with recycling crumb rubber modified RAP, further investigation is needed by the New Zealand industry to make sure crumb rubber modified RAP can be implemented cost effectively.

12 References

Asphalt Academy (2007) *Technical guideline: the use of modified bituminous binders in road construction.* TG1. 2nd ed.. Pretoria: Asphalt Academy. 112pp.

AASHTO (2010) *AASHTO M320-10 Standard specification for performance-grade asphalt binder*. American Association of State and Highway Transportation Officials.

ACCC press release (2013) *ACCC approves National Tyre Stewardship Program*. Accessed 27 November 2014. www.accc.gov.au/media-release/accc-approves-national-tyre-stewardship-program

ASTM (2009) *ASTM D6114/D6114M Standard specification for asphalt-rubber binde*r. ASTM International.

ASTM (2013) *ASTM D8-13b Standard terminology relating to materials for roads and pavements*. ASTM International.

Artamendi, I and HA Khalid (2006) Diffusion kinetics of bitumen into waste tyre rubber. *Journal of the Association of Asphalt Paving Technologists 75:* 133–164.

Austroads (1999) The use of recycled crumb rubber. *APRG technical note TN10.* Austroads Pavement Research Group.

Austroads (2000) Polymer modified binder sprayed seal trials – summary report. *Austroads technical report AP-T05*. 23pp.

Austroads (2009) *Guide to pavement technology part 4E: recycled materials*. Sydney: Austroads.

Austroads (2014a) Inspection of sprayed seal trials. *Austroads technical report AP-T277-14.* 74pp.

Austroads (2014b) Specification framework for polymer modified binders. *Austroads test method AGPT/T190.*

Austroads and AAPA (2014) Sprayed sealing – selection of spraying nozzles. *Pavement work tips AP-PWT33-14.* 2pp.

Ball, GFA (2010) Environmental and financial costs and benefits of warm asphalts. *NZ Transport Agency research report 404*. 42pp.

Behl, A, G Kumar and G Sharma (2013) Performance of low energy crumb rubber modified bituminous mixes. *2nd Conference of Transportation Research Group of India (2nd CTRG)*, *Procedia – Social and Behavioural Sciences 104*: 49–58

Biligiri, KP, B Kalman and A Samuelsson (2013) Understanding the fundamental material properties of low-noise poroelastic road surfaces. *International Journal of Pavement Engineering 14,* no.1: 12–23.

Brown, SF and JL Bouncher (1990) Asphalt modification. *Proceedings of the 1990 Conference on Highway Research: Sharing the Benefits,* London, 29–31 October 1990: 181–200.

Burr, G, A Tepper, A Feng, L Olsen and A Miller (2001) Crumb-rubber modified asphalt paving: occupational exposures and acute health effects. *NIOSH health hazard evaluation report HETA #2001-0536-2864.* 51pp.

CalRecycle (2010) *Rubberized pavement grant program, city of Clovis.* Accessed 10 November 2014. www.calrecycle.ca.gov/Grants/ModelProject/TRPModel.pdf

Caltrans (2005) *Use of scrap tire rubber – state of the technology and best practices.* California: Department of Transportation. 117pp.

Caltrans (2005a) *Feasibility of recycling rubber-modified paving materials.* California Department of Transportation. 22pp.

Caltrans (2006) *Asphalt rubber usage guide.* Revised. California Department of Transportation. 71pp.

Carlson, DD and H Zhu (1999) Asphalt-rubber: an anchor to crumb rubber markets. *3rd Joint UNCTAD/IRSG Workshop on Rubber and the Environment, International Rubber Forum*, Veracruz, Mexico.

Cheng, D, L Lane and RG Hicks (2012) Improvements in asphalt rubber chip seal application with warm-mix technology, maintenance management. Transportation Research Board. *Transportation research circular E-C163*: 13–23.

Corley-Lay, J and D Wofford (2012) Chip seals for improved pavement preservation – North Carolina's approach. *TR news 282*, September–October 2012, p41–43.

CP2C (2014) *Pavement preservation treatment database*. Accessed 6 November 2014. www.csuchico.edu/cp2c/PPTG/PPTDB.shtml

Crockford, WW, D Makunike, RR Davison, T Scullion and TC Billiter (1995) Recycling crumb rubber modified asphalt pavements. *Report FHWA/TX-95/1333-1F*. Texas Transportation Institute. 180pp.

Epps, JA (1994) Uses of recycled rubber tires in highways. *National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 198.* 170pp.

Environmental Protection Agency (EPA) (1993) *A study of the use of recycled paving material.* Report to Congress EPA/600/R-93/095. Washington, DC: EPA. 50pp.

Environmental Protection Agency (EPA) (1995) *Compilation of air pollutant emission factors AP–42.* 5th ed. 2038pp.

Florida Department of Transportation (FDOT) (2014) *Ground tire rubber as a stabilizer for subgrade soils – final report*. Florida Department of Transportation contract number: BDK81 977-03. 159pp.

Federal Highway Administration (FHWA) (2014) *Warm mix asphalt technologies and research*. Accessed 5 November 2014. www.fhwa.dot.gov/pavement/asphalt/wma.cfm

Frascoia, RI and RF Cauley (1995) Tire chips in the base course of a local road. *Transportation Research Board Conference Proceedings 6*: 47–52.

Goetz, MR (1994) *Review of studies conducted to evaluate environmental concerns of crumb rubber modified asphalt.* Asphalt Institute. 68pp.

Gunkel, KO'C (1994) *Evaluation of exhaust gas emissions and worker exposure from asphalt rubber binders in hot mix asphalt mixtures.* Part I and Part II. Report for Michigan Department of Transportation. 135pp.

Hanley, KW and AK Miller (1996) Health hazard evaluation report: Granite Construction Company, Sacramento, California. *NIOSH HETA 94-0408-2564*. 54pp.

Hicks, R.G., Epps, J.A. (2000) *Life cycle costs for asphalt-rubber paving materials*. World of Asphalt Pavements, 1st International Conference, Sydney, Australia, 2000. pp69-88

Hicks, RG, D Cheng and L Lane (2012a) *Evaluation of warm mix asphalt technologies with asphalt rubber and terminal blends*. Report for California Department of Resources Recycling and Recovery. 11pp.

Hicks, RG, S Tighe and D Cheng (2012b) *Rubber modified asphalt technical manual*. Prepared for Ontario Tire Stewardship. 177pp.

Hicks, RG, D Cheng, T Duffy and T Teesdale (2010) Evaluation of rubberized asphalt terminal blends and a preliminary study on warm mix technologies with asphalt rubber. *California Pavement Preservation Center report CP2C-2010-104.* California, USA. 19pp.

Holleran, G and JR Reed (2000) Emulsification of asphalt rubber blends. *Proceedings of Asphalt Rubber 2000,* Portugal, chapter 4, paper 0402.

Holleran, G, JR Reed and J Van Kirk (1997) Use of crumb rubber in slurry and microsurfacing and chipseals, *Proceedings of 10th AAPA International Flexible Pavements Conference*, Perth, Australia, 16–20 November 1997, volume 1, session 2, no.2.

Humphrey, DN and RA Eaton (1995) Field performance of tire chips as subgrade insulation for rural roads. *Transportation Research Board Conference Proceedings 6*: 77–86.

Ibrahim, MR, HY Katman, MR Karim, S Koting and NS Mashaan (2013) A review on the effect of crumb rubber addition to the rheology of crumb rubber modified bitumen. *Advances in Materials Science and Engineering 2013, article ID 748579.* Hindawi Publishing Corporation. 8pp.

Jain, PK, AK Jain and C Kamaraj (2008) Pavement preservation utilizing cost effective crumb rubber modified bitumen seals – a pilot study. *23rd ARRB Conference – Research Partnering with Practitioners: Proceedings*, Adelaide, Australia 2008.

Jansz, R (2012) *Crumb rubber production and New Developments in Australia.* Accessed 3 December 2014. http://arrb.com.au/admin/file/content13/c6/Jansz_Crumb%20rubber%202012%2010%20[Compatibility%20Mode].pdf

Judd, D, K Jooste, J Hattingh, D Sadler and J Muller (2008) The use and performance of bitumen rubber in spray seals in RSA. *1st Sprayed Sealing Conference – Cost Effective High Performance Surfacings*, Adelaide, South Australia, 27–29 July 2008. 17pp.

Jung, J-K, KE Kaloush and GB Way (2002) Life cycle cost analysis: conventional versus asphalt-rubber pavements. Rubber Pavements Association report. 23pp.

KPMG (2015) *Waste tyres economic research: report 3 –intervention options to promote investment in on-shore waste tyres recycling*. Wellington: Ministry for the Environment.

Lee, S-J, CK Akisetty, SN Amirkhanian (2008) The effect of crumb rubber modifier on the performance properties of rubberized binders in HMA pavements. *Construction and Building Materials 22:* 1368–1376.

Lo Presti, D (2013) Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review. *Construction and Building Materials 49:* 863–881.

Lu, X, H Soenen, S Heyrman and P Redelius (2013) Durability of polymer modified binders in asphalt pavements. *The XXVIII International Baltic Road Conference*, Vilnius, Lithuania, 26–28 August 2013. 10pp.

Memon, GM and C Franco (nd) *Chemically modified crumb rubber asphalt (CMCRA).* Accessed 1 December 2014. www.vegvesen.no/_attachment/110548/binary/192715?fast_title=Paper%3A+Chemically+Modified+Crumb+Rubber+Asphalt+%28CMCRA%29

MfE (2003) Good practice guide for assessing and managing odour in New Zealand. *Air quality report 36.* Ministry for the Environment, New Zealand. 67pp.

Miró, R, F Pérez-Jiménez, AH Martínez, O Reyes-Ortiz, SE Paje and M Bueno (2009) Effect of crumb rubber bituminous mixes on functional characteristics of road pavements. *Transportation Research Record: Journal of the Transportation Research Board 2126*: 83–90.

Myhre, M (2005) Devulcanization by chemical and thermomechanical means. Pp401–428 in *Rubber recycling.* SK De, AI Isayev, K Khait (Eds). Boca Raton, Florida: Taylor & Francis Group.

Neaylon, K (2009) *Technical commentary on part 226 – application of sprayed bituminous surfacing*. Government of South Australia, Department of Planning, Transport and Infrastructure. 16pp.

OMI (2014) *Odor management for asphalt applications*. Accessed 14 November 2014. http://odormanagement.com/markets-served/asphalt/

Patrick, JE (1983) Rubber in bitumen. *Central Laboratories report 6-82/2*. Wellington: Ministry of Works and Development.

Patrick, JE (2000) Polymer-modified bitumen emulsions as chipseal binder in high stress areas on New Zealand roads. *Transfund New Zealand research report 162.* 28pp.

Patrick, JE and TC Logan (1996) Use of tyre rubber in bituminous pavements in New Zealand. *Transit New Zealand research report 62.* 65pp.

Patrick, JE, SJ Reilly and GK Cook (2006) Trials of recycled asphalt and rubber materials in hot mix asphalt for New Zealand roads. *Land Transport New Zealand research report 309.* 31pp.

Pacific Emulsions Inc (2009) *TRMSS, tyre rubber modified slurry seal*. Accessed 1 December 2014. www.rubberslurry.com/index-3.html

PennDOT (2011) *Strategic recycling program*. Accessed 3 December2014. www.industrialresourcescouncil.org/Portals/7/Presentations/IMC2012/PennDOT%20Specification%20Survey.pdf

REAAA (2010) *Bitumen supply and performance*. REAAA New Zealand, 17–23 November 2010. Accessed 13 October 2014. www.reaaa.co.nz/publication/bitumen-properties-and-supply-by-allan-tuck-higgins-bitumen/wppa_open/

Roschen, T (2002) *Results of Stack Emission Testing Asphalt Rubber and Conventional Asphalt Concrete.* Letter to Public Works Agency, Department of Transportation, County of Sacramento, CA. www.asphaltrubber.org/ari/Emissions/SAC_County_Emission_Cover_Letter.pdf

SABITA (1998) Technical guidelines: construction of bitumen rubber seals. *SABITA manual 1*. Roggebaai, South Africa. 16pp.

SABITA (2009) Guidelines for the design, manufacture and construction of bitumen rubber asphalt wearing courses. *SABITA manual 19.* 2nd ed.

SABITA (2012) Revision of SABITA manual 19 – Bitumen rubber asphalt. Presented by L-J Ebels. *23rd Road Pavements Forum, 9 May 2012.*

SCDOT (2010) Crumb rubber-modiifed warm-mix asphalt study. *Factsheet DHEC OR-0910 10/10*. South Carolina: Department of Health and Environmental Control, The Asphalt Rubber Technology Service (ARTS) 2pp.

Shatnawi, S (2013) *Life-cycle cost analysis of flexible pavement systems rehabilitated with the use of asphalt rubber interlayers*. Accessed 9 October 2014. www.ra-foundation.org/wp-content/uploads/2013/02/006-PAP_053.pdf

Shen, J, S Amirkhanian, S-J Lee and B Putman (2006) Recycling of laboratory-prepared reclaimed asphalt pavement mixtures containing crumb rubber-modified binders in hot-mix asphalt. *Transportation Research Record: Journal of the Transportation Research Board 1962*: 71–78.

Shuler, S (1990) Chip seals for high traffic pavements. *Transportation Research Record 1259: Journal of the Transportation Research Board*: 24–34.

Strategic Alliance Reference Group (2009) Crumb rubber sprayed seal binder. Presentation, Queensland Government-APPA-SAMI, 17 June 2009. Accessed 1 December 2014. www.aapaqtmr.org/SARG20090617/SARG20090617-00plus.pdf

Stout, D and DD Carlson (2003) Stack emissions with asphalt rubber. A synthesis of studies. *Proceedings of the Asphalt Rubber Conference 2003*, Brasilia, Brazil, 2–4 December 2003.

Subhy, A, D Lo Presti and G Airey (2015) An investigation on using pre-treated tyre rubber as a replacement of synthetic polymers for bitumen modification. *Road Materials and Pavement Design 04/2015*. DOI: 10.1080/14680629.2015.1030826.

Tyrewise (2012a) *Scoping report 1: Investigation into the collection of disposal of used tyres in New Zealand and internationally.* Tyrewise Working Group. 49pp.

Tyrewise (2012b) *Scoping report 2: Investigation into alternative uses for end of life tyres in New Zealand and internationally.* Tyrewise Working Group. 60pp.

Tyrewise (2012c) *Scoping report 3: Feasible product stewardship options for end of life tyres in New Zealand.* Tyrewise Working Group. 59pp.

Tyrewise (2013) *Report 7: Tyrewise summary report.* Tyrewise Working Group. 31pp.

US Patent (1993) *US 5238734A Railroad ties made of recycled tire fragments*. Published 24 August 1993 – current fee status: lapsed.

VicRoads (1994) *Scrap rubber bitumen guide.* Main Roads Western Australia: Roads and Traffic Authority. 27pp.

VicRoads (2004) Bituminous sprayed surfacing manual. *Technical bulletin 45.* Melbourne: Vicroads. 434pp.

Vila, A, G Pérez, C Solé, AI Fernándezb and LF Cabeza (2012) Use of rubber crumbs as drainage layer in experimental green roofs. *Building and Environment 48:* 101–106

Way, GB (1979) Prevention of reflection cracking Minnetonka-East. *Arizona Department of Transportation report 1979 GWI.* 49pp.

Wegman, S (1991) Design and construction of seal coats. Final report, Mendota Heights: Minnesota Department of Transportation: 34pp.

Williamson, P (2006) Use of reclaimed tyre rubber in asphalt. *Transit New Zealand technical memorandum: TNZ TM 6001 v1.* 15pp.

Youssef, Z and PK Hovasapian (1995) *Olympic Boulevard asphalt rubber recycling project*. City of Los Angeles: Department of Public Works. 17pp. www.asphaltrubber.org/ARTIC/Reports/RPA_A1315.pdf

Zaniewski, JP and MS Mamlouk (1996) *Preventive maintenance effectiveness – preventive maintenance treatments*. Participant's handbook, FHWA-SA-96-027. Washington DC: Federal Highway Administration. 204pp.

Zanzotto, L and O Svec (1996) *Utilization of recycled tire rubber in asphalt pavements.* Transportation Association of Canada, 162pp.

Zhu, H and DD Carlson (2001) A spray based crumb rubber technology in highway noise reduction application. *Journal of Solid Waste Technology and Management 27*, no.1: 27–33.

Zhu, J, B Birgisson and N Kringos (2014) Polymer modification of bitumen: advances and challenges. *European Polymer Journal 54*: 18–38.