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Crumb Rubber Review - 2020 Update

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Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for Waka Kotahi NZ Transport Agency ('**Client**') in relation to a review of crumb rubber applications in road surfacing materials ('**Purpose**') and in accordance with the IPA contract with the Client dated 26 March 2020. The findings in this Report are based on and subject to the assumptions specified in the Report. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose, or any use or reliance on the Report by any third party.

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Introduction

The use of crumb rubber from end-of-life tyres (ELT) in road pavement and surfacing construction has been the subject of industry-led research and ongoing discussion for some time. Crumb rubber is used extensively in surfacing construction in Australia and internationally, but not in New Zealand.

A report in 2015 (Wu et al. 2015) highlighted four key barriers to the uptake of crumb rubber in surfacing construction in New Zealand:

1. Capital cost – The high capital cost of the plant needed to process and then use crumb rubber modified bitumen and asphalt is a barrier to uptake.

2. Economy of scale – The market size in New Zealand is currently too small to support sustainable crumb rubber processing and use in surfacing construction.

3. Security of supply – Despite an abundance of ELTs, due to economics and a lack of coordination, obstacles remain for consistent collection and processing of crumb rubber in New Zealand.

4. Bitumen emulsions – Industry and Waka Kotahi NZ Transport Agency (Waka Kotahi) are considering a switch to bitumen emulsions for chip sealing for safety reasons. This would make the use of crumb rubber modified binders effectively impractical in chip sealing, the single largest surfacing activity.

Since the 2015 research report, the Ministry for the Environment (MfE) has made significant effort, via the Waste Minimisation Fund, to fund projects that seek solutions to the problems associated with the ELTs waste stream. Projects have been conducted by consultants, Crown Research Institutes, roading contractors, recyclers, waste processors, and other private entities. Most recently, MfE has funded projects to set up tyre recycling/processing plants to improve the country's capacity to process collected tyres. Unfortunately, this has not resulted in an uptake in the use of crumb rubber in roading in New Zealand, based on current information.

The purpose of this project is to assess the current relevance of the barriers to the use of crumb rubber identified in 2015, identify new ones that may have arisen since then, and determine specific actions and recommendations that can be taken by Waka Kotahi to facilitate the use crumb rubber modified materials by the New Zealand roading industry.

1 New Zealand Crumb Rubber Supply

1.1 Use of crumb rubber in road construction

Crumb rubber can be used in several roading applications, as detailed below.

1.1.1 Chip seals

Crumb rubber can be used in chip seals by adding it into the bituminous sealing binder up to about 20% by weight. This is typically done by breaking and digesting the crumb rubber in a high shear mixer, which tears the crumb rubber apart into even smaller fragments. The fragments are then swollen and/or partially dissolved by the bitumen at elevated temperatures.

The final product is a crumb rubber modified binder which has improved elasticity and rheological properties similar to that of a polymer modified binder (PMB). The crumb rubber modified binder can be sprayed for chip seals or used in asphalt production (see 1.1.2).

More recently, it has been shown that crumb rubber can also be used in chip seals as an aggregate replacement. However, unless benefits such as noise reduction can be demonstrated, the economic viability of this approach is questionable due to the costs associated with recycling and processing ELT rubber into an aggregate substitute, making it significantly more costly than natural aggregate.

Devulcanised rubber has also been demonstrated internationally to have applications in road surfacings. Devulcanised rubber is essentially crumb rubber, but is chemically / thermally / mechanically broken down (into a structure where the sulphur crosslinks are broken). Devulcanised rubber is an essential feedstock for tyre manufacture, and previous studies have shown that the devulcanisation process makes the rubber more workable in bitumen modification, and that it can be used in existing plant equipment in New Zealand without requiring excessively high processing temperatures. This was demonstrated through a feasibility project (MfE Deed 21298) recently funded by the MfE and Waka Kotahi. (Wu 2016, 2018, Wu and van den Kerkhof 2018a, 2018b)

1.1.2 Asphalt

Crumb rubber can be used in asphalt in two ways: a dry or wet process. The dry process involves a direct substitution of a certain proportion of the aggregate mix with crumb rubber. While there may be an indirect performance benefit from the inclusion of rubber in the asphalt mix, the value proposition here is also questionable because the cost of the crumb rubber exceeds that of the aggregate that it is replacing.

On the other hand, the wet process uses the same process used for chip seal binder modification, where the crumb rubber is partially dissolved in bitumen and thus modifies the inherent properties of the base bitumen. This is considered more effective in terms of performance enhancement than the dry process, where the crumb rubber is treated as a filler. Devulcanised rubber can be used in a similar manner, as for chip seals.

The modified binder can be mixed with the aggregate, normally in an open-graded or gap-graded design, to produce a rubberised asphalt mix similar to that of a PMB modified mix.

1.1.3 Other pavement layers

There are examples internationally where ELT rubber has been used in non-surfacing pavement layers and geotechnical applications such as embankments, usually in the form of larger rubber granules and/or chunks. In many instances, tyre waste can be incorporated into aggregates/fill used in geotechnical applications with no significant adverse effects. In some situations, it may even provide performance benefits, e.g. as a lightweight fill (Hylands and Shulman 2003, Reddy and Krishna 2017). However, there are very few case studies demonstrating the performance benefits of such approaches, and economics and potential environmental impacts (e.g. at the end of life) remain the key obstacles. In addition, the required particle/ fragment size and size distribution are likely to vary widely between applications, which complicates general adoption of such technologies. The general view is that crumb rubber for surfacing applications remains the key ELT application, with this use having the most potential and the highest value proposition from a roading perspective.

1.2 Tyre availability

It has been estimated that about 74,000 tonnes of ELTs (3R Group, June 2018) are generated annually in New Zealand, which is about 7.75 million passenger tyres equivalent. There are numerous ELT collectors across the country, with Waste Management New Zealand Limited (WMNZ) being the most publicised entity.

MfE recently funded WMNZ to construct and commission an ELT recycling facility. The facility in Wiri, Auckland will process ELTs into 'tyre-derived fuel' (TDF). TDF is composed of scrapped or misshaped tyres, which can be either shredded or chipped to between 2.5 to 10 cm. TDF can be mixed with coal and other fuels such as wood and chemical waste. These mixtures can then be burned in concrete kilns, paper mills or even power plants. WMNZ is already well-positioned in the supply chain, with an existing operation that can easily collect and store ELTs. Based on information provided by WMNZ, the Wiri recycling facility is capable of processing both truck and passenger car tyres, with a current processing capacity of about 14,000 tonnes of ELTs per annum. WMNZ is aiming to achieve its full capacity of 30,000 tonnes p.a. by 2020/2021.

The plan is to sell the TDF to Golden Bay Cement Ltd for their new cement kilns. The current projection is that once the Golden Bay TDF plant (also funded by the MfE) is fully operational, it will use 3.1 million shredded tyres per annum, which is approximately 30,000 tonnes of ELTs. In principle, there should still be at least 50% of the country's ELT waste stream remaining to be utilised. An accurate price of TDF per unit weight in New Zealand is difficult to obtain due to commercial sensitivity. However, based on international figures, TDFs are currently sold for between US$50 to US$150 per metric tonne. TDF is often used to replace coal, which has been between US$60 to US$70 per metric tonne over the past 6 months.

WMNZ currently has a supply agreement with Golden Bay Cement for the processed TDF, so there is no plan to extend its facility to produce crumb rubber. It is also understood from WMNZ that a plan is underway to build a similar ELT recycling facility in Christchurch with a capacity of roughly 30% of the Auckland facility (10,000 tonnes p.a.). Prior to commissioning of Golden Bay's TDF plant, it is understood that the manufactured TDF is currently exported out of NZ in container loads to overseas buyers. While TDF is a large volume application that can potentially solve some of the ELT disposal problem that New Zealand currently faces, the TDF market is highly dependent on pricing fluctuations within the global fuel market. Hence, from this perspective, it would be prudent for New Zealand to also consider alternative high volume applications for ELT use, including crumb rubber in roading.

1.3 Crumb rubber supply in New Zealand

There is currently very limited supply of crumb rubber in New Zealand due to the lack of demand and therefore lack of manufacturers. Sourcing crumb rubber from offshore suppliers is possible but costly, and it does not resolve the ELT disposal issues faced domestically in New Zealand.

The synthetic/natural rubber composition of car and truck tyres can differ significantly. Internationally in some jurisdictions, a minimum percentage natural rubber content is required for crumb rubber used in road surfacing applications (VicRoads 2019). In Australia, only truck tyres (with a higher natural rubber content) were used in the early years. The main limitation associated with using passenger tyres is the inferior compatibility of synthetic rubber with bitumen. Specialist equipment is needed to process these tyres with higher synthetic rubber content, and an end market would be needed for the waste nylon fibre generated during processing of passenger car tyres (VicRoads 2019). In Australia, there has been an increased focus on research and development efforts to find uses for large numbers of waste synthetic passenger tyres.

If we assume that only truck tyres were utilised to produce rubber crumb in New Zealand, there would be approximately 20% of the total ELT tonnage available to generate about 11,000 tonnes of crumb rubber (assuming 75% of a typical tyre is rubber) which is still a significant amount. To put this in perspective, in New Zealand at present, less than 5% of the, approximately, 200,000 tonnes of bitumen used annually is polymer modified. If similar levels of crumb rubber modified bitumen were to be used (at an 18% concentration) then only about 1,800 tonnes of rubber would be used per annum. If 25% of the total bitumen market in New Zealand was to be modified by crumb rubber, then 9,000 tonnes of rubber from ELT would be required. While there are more than enough ELTs as a feedstock to make into crumb rubber in New Zealand, the current issue with supply relates to limitations in processing capacity, specifically related to the manufacturing of rubber crumb that is of roading grade.

It was only in mid-2018 that a purpose-built tyre recycling facility was commissioned in New Zealand as the result of a targeted Waste Minimisation Funding round by the Ministry for the Environment (MfE). Prior to this, there were a handful of ELT collectors and fewer processors scattered around the country. Since 2018, there was just one supplier, Rubber Solutions in Upper Hutt, that was equipped to produce roading grade rubber crumb to the current Australian standard (AGPT/T190). The company had supplied crumb rubber products to Australia to meet their demand from time to time.

The picture has not changed significantly since then. Rubber Solutions is still the only known processor in New Zealand able to produce crumb rubber for roading applications (at approximately 6 tonnes per day over an approximately 250 day-per-year operation, i.e. 1,500 tonnes p.a.). However, it should be noted that Rubber Solutions' processing capability is also constrained by its feedstock requirement, which is the by-product from tyre retread operations. The by-product from retread is much smaller in size than whole ELT which requires specialist machinery to break down into smaller sizes. This means that Rubber Solutions cannot process whole ELT unless further capital investment is made.

Some in the roading industry view devulcanised rubber as the preferred material in road surfacing due to it being easier to work with compared to conventional crumb rubber. The odour and emission issues are lessened as well, due to lower operating temperatures. However, problems remain with supply, and manufacturing devulcanised rubber requires a further processing step in addition to the standard plant for making crumb rubber.

In terms of capacity to produce devulcanised rubber in New Zealand, there is currently only a research facility available at Scion, a Crown Research Institute in Rotorua. Scion has been developing a devulcanization process using a form of reactive extrusion. The feedstock Scion has been using is from Rubber Solutions and is free of metal and nylon. The prototype is not at a commercial scale yet, but Scion is confident that the process will be able to deal with feedstock that is less than 5 mm in size.

Based on commercial intelligence, producing crumb rubber from ELT requires specialised machinery with capital costs starting from NZ$5-10 million, depending on the nature of the output and plant capacity required. Significant additional costs would also be incurred in the development of specific crumb rubber products by contractors, as well as in training of the operators, development of quality control procedures, and other development and introduction variables. For the roading industry to justify the large investment required to produce rubber crumb in New

Zealand, there needs to be sufficient evidence that very few technological barriers exist (Chapter 2) and that sufficient performance benefits can be gained (Chapter 5) to ensure there will be competitive advantage in using crumb rubber over existing products.

In summary, from a resource point of view there is sufficient ELT for further processing into crumb rubber even after much of the waste stream has been utilised as TDF. To date, due to the lack of demand, there is minimal capacity for commercial scale crumb rubber production in New Zealand, and this only from tyre retread material (i.e. nothing from the ELT waste stream) to process into crumb rubber. There is currently only a research-scale capacity for supplying devulcanised rubber in New Zealand. The missing link at present, from a supply point of view, is the capacity to manufacture crumb rubber in New Zealand.

2 Technological Barriers

2.1 Use in asphalt mix

With respect to the use of crumb rubber in asphalt mix, the technology continues to advance and there are certainly no new technological barriers identified since the previous review (Wu et al. 2015). As the technology for this application is well established and commonly used internationally, it could be easily imported and implemented in New Zealand.

2.2 Use in chip seal surfacings

The use of crumb rubber in chip seals is a well proven technology in Australia (particularly in NSW and VIC) and South Africa. There are no technical barriers to using this technology in New Zealand, except for the lack of availability of specific blending and spraying plants. However, given the right financial incentives, contractors can obtain upgrades and capital equipment from Australia or other countries.

For chip sealing operations, the likely move by Waka Kotahi to the almost exclusive use of bitumen emulsions for this purpose poses an immediate problem.

Under the Health and Safety at Work Act (2015, 2016) Waka Kotahi has an obligation to reduce risks to those involved in the activities it undertakes. This includes the construction of chip seals. Under the Act, there is a requirement for "*a Person Conducting a Business or Undertaking (PCBU) so far as reasonably practicable to eliminate risk in the workplace*".

At the instigation of the contracting industry, Waka Kotahi has recently completed a review of the implications of replacing hot cut-back bitumen with safer bitumen emulsions for chip sealing operations (Mora et al. 2019). That review recommends a transition from the use of hot cut-back bitumen to emulsions wherever technically feasible. Waka Kotahi is currently considering the recommendation and is likely to favour its adoption (J. Donbavand, Waka Kotahi Lead Pavement Advisor, personal communication March 2020).

Bitumen emulsion consists of micron scale bitumen droplets suspended in water. Emulsions are used in chip sealing applications as an alternative to cut-back bitumen (bitumen with kerosene added). Emulsions are handled and applied by construction personnel at much lower temperatures (80-90 °C) than cut-backs (>160 °C), which reduces the severity of burns and any risks of explosion due to added kerosene.

Typical crumb rubber modified bitumen, as usually prepared, cannot be emulsified as the crumb rubber particles are generally too large, and so these bitumens must be sprayed at temperatures >180 °C. Processes do exist to treat crumb rubber modified bitumen to achieve a reduction of the crumb rubber particle size (to < 10 micron) or apparent solubilisation of the rubber, thus allowing emulsification (Wilkes 1986, Sylvester and Stevens 2006, Wu et al. 2015, Zhou et al. 2015). Although some of these technologies have been available for many years, their application internationally in commercial practice is limited. Use of this type of technology may involve some development costs, and may carry a greater risk and involve additional plant or processing costs for contractors wishing to make use of these methods – all considerable disincentives.

Considering the above, greater use of crumb rubber modified binders would likely result in increased spraying of hot binders and directly contradict Waka Kotahi's obligations under the Health and Safety Act. This is especially the case as the SBS and other polymer modified bitumen products currently in widespread use in New Zealand have very similar performance properties to crumb rubber modified binders. They can be emulsified using existing standard plants (and are almost exclusively used as emulsified products). In other words, there is a "reasonably practical" safer alternative to crumb rubber modified bitumen.

A case could be made that if Waka Kotahi has a legal duty or obligation to use waste tyre crumb rubber, then there is no "reasonably practical" alternative to sealing with hot bitumen. However, that is a legal argument beyond the scope of the current project.

2.2.1 ELTs as a substitute for sealing aggregate

A number of papers have recently been published that describe research into the use of ELT derived rubber "chunks", as partial substitutes for chip sealing aggregates (Gheni et al. 2017, Gheni et al. 2018a, Gheni et al. 2018b). This work has included laboratory studies and field trials in Missouri in the USA.

ELTs shredded or cut into pieces in the 4.75-9.5 mm size range were used for the investigations. Different proportions of tyre rubber pieces mixed with similar sized conventional aggregates were used to construct seals using standard plant and equipment. It was found that good retention of the rubber aggregates was obtained, and the resulting frictional characteristics of the seal textures were only slightly reduced compared to those for conventional aggregate at rubber loadings of up to 50%.

This approach has the advantages that minimal tyre processing is required (i.e. no crumbing is needed), no changes to existing or additional plants are needed, and much larger quantities of tyres can be utilised. The authors calculate that using crumb rubber in the standard way at 15% loading as an additive to the bitumen would use only 198 tyres per km compared to 1,250 per km when used at 50% loading as aggregate (Gheni et al. 2017).

Although this application is still in the developmental stages and would require investigation and trialling with local materials to understand its relevance and applicability to New Zealand conditions, the application could potentially avoid the problem of spraying hot crumb rubber modified bitumen and would also have much lower capital costs to establish compared with a crumb rubber manufacturing plant.

3 Specifications and Legislation

3.1 Existing NZTA specifications

As it currently stands, there are no Waka Kotahi material or construction specifications that expressly either prohibit or permit the use of crumb rubber. Some specifications (e.g. P11 for OGPA) may refer to "polymer modified" binders, by which is meant SBS modification, but would also technically allow crumb rubber modified materials. Some test methods however specified for design and quality control of asphalt mix may be inappropriate for crumb rubber mixes, for example, the determination of binder content by solvent extraction, and alternatives would need to be sought by investigation of the procedures used in the US and Australia for crumb rubber mixes.

The current asphalt binder specification (NZTA M1-A 2019) includes test methods which crumb rubber modified binders may pose issues with during testing. The specification is suitable for SBS polymer modified binders, but any rheometer based test results may be invalid for modified binders with undigested crumb rubber due to their two-phase nature. This issue has been highlighted by both Waka Kotahi as well as roading contractors and would need to be addressed to allow use of crumb rubber modified binders in asphalt production.

The M1 specification for chip seal binders currently assumes an unmodified bitumen and does not cover any type of polymer modified material. As a result, there is currently no NZTA specification covering the properties of polymer modified bitumen (crumb rubber or SBS) used in chip sealing. A revision of the M1 specification is underway, though that will result in the specification covering both materials.

The approach adopted in New Zealand is to have two performance-based specifications covering asphalt and chip seal binders separately (i.e. binders are specified in terms of the necessary properties and application, not their composition). In contrast, in Australia there are separate specifications for unmodified and polymer modified binders (including crumb rubber modified binders). The Polymer Modified Binders Framework AGPT/T190 specifies a range of polymer and crumb rubber modified binders for use in chip seals (known as sprayed seals in Australia) and asphalts. Unmodified binders are covered in AS2008. The Australian Asphalt Pavement Association (AAPA) has also published a draft specification for crumb rubber use in asphalt in both open-graded and gap-graded asphalt (OGA and GGA) mix designs (see 4.2.2).

3.2 Government legislation

Since 2015, there have been a number of Government funded reviews on gaps and barriers in the New Zealand legislation relevant to the use of ELTs. The current legislation doesn't pose any obstacles to crumb rubber technology in the roading industry, but it does have significant impacts on the supply chain for crumb rubber.

3.2.1 Storage of ELTs

The main risks associated with outdoor storage of ELTs are fire (causing toxic smoke and run-off), leachates into soil, and harbouring of pests. While not posing any direct obstacles for the uptake of crumb rubber in New Zealand, storage will, if not resolved, create problems for the supply chain.

In the original National Environmental Standard (NES) document proposed by the MfE, there were no national regulations that related specifically to the storage of tyres. The rules for storing tyres can be determined by regional and district councils under the Resource Management Act 1991 (RMA) and bylaw powers under the Local Government Act 2002. However, anecdotal evidence suggests that there has been limited use of these two Acts, and as a result regional and district plan rules that specifically address tyre storage almost certainly do not exist.

The proposed NES would provide a consistent regulatory approach for local authorities around how the outdoor storage of tyres should be managed, and MfE has recently sought feedback on the matter. The proposed standard builds on earlier consultation in 2017. The key change is that MfE is seeking to make the NES the responsibility of regional councils, with two options for volume thresholds for resource consent. The consultation closed on the 8th of April 2020, and the Government policy decisions and submissions are expected to be published by mid-2020 at the earliest.

3.2.2 Processing / manufacturing of tyre-derived products

It is recognised that there is a risk that if a new regulation (such as the proposed NES) is brought in without a concurrent product stewardship scheme for tyres, there may be unintended consequences such as illegal dumping or burying of tyres. A product stewardship scheme would make it easier for those storing tyres to reduce their stores, and would facilitate improved monitoring of tyre movements in the country.

With or without the proposed NES, New Zealand is already facing problems with unregulated dumping of ELTs, and this is not helped by the lack of end uses for these items. Product stewardship schemes are a common solution used internationally, and involve producers and industry across a supply chain taking responsibility for managing the environmental impacts of their products. The MfE is currently developing a Product Stewardship Scheme for a list of priority waste streams in New Zealand.

The New Zealand Government has recently consulted on the proposal to declare tyres a priority product under the Waste Minimisation Act 2008. If ELTs are declared a priority product, this will provide a strong framework for implementing an effective, comprehensive and nationwide product stewardship scheme that would support the objectives of the NES. It is understood that the Ministry is currently working on policies associated with such a scheme, with a formal announcement due later in 2020 or in 2021.

Currently, when a new tyre is purchased in New Zealand, the price typically includes a disposal fee through arrangement with the supplier. The fee is then used to pay for someone to collect the ELTs when they accumulate. However, there is no obligation for the tyre disposal to be environmentally sound. A product stewardship scheme with a disposal fee that is paid when the tyre goes to an environmentally sound end-use would encourage responsible operators, and could create an incentive for developing more uses for ELTs. This would help the owners of stockpiles to find legitimate destinations for excess tyres and to comply with the NES in terms of storage.

Implementation of these two initiatives would support and encourage the uptake of crumb rubber in the roading industry as they would remove several logistical barriers currently faced by ELTs collectors and processors.

In Australia, a national tyre product stewardship scheme administered by Tyre Stewardship Australia (TSA) was launched in 2014. This has improved awareness around options for, and impacts of, disposal and has resulted in a rise in research and development activities and trials in various jurisdictions across Australia. The efforts made by TSA are discussed in more detail in Chapter 5.

3.2.3 Environmental impacts of using crumb rubber in road surfacings

Concerns remain over the environmental impacts deriving from the use of crumb rubber and other tyre-derived products. In the roading industry, contractors are concerned over resource consent and odour complaints specific to modified binders and asphalt mixes produced by their plants in certain areas of the country. While these barriers will differ (or not exist) from location to location, it is certainly a significant issue for many of the plants near quarries or residential areas. The same issues may arise during the laying of asphalt mix or chip sealing in urban areas.

An air discharge consent sets the rules for a given site relating to management of dust, odour and specific compounds so as not to adversely impact neighbours or the environment. Once an air discharge consent is provided for a site, the site operator will follow an Environmental Management Plan (EMP) that ensures compliance with the rules detailed in the consent. The Resource Management Regulations 2004 includes a National Environmental Standards for Air Quality (NESAQ). Under Schedule 1, there is a list of ambient air quality standards for contaminants such as carbon monoxide, nitrogen dioxide, ozone, sulphur dioxide and PM_{10}.

In addition to NESAQ, the MfE also provides the Ambient Air Quality Guidelines to promote the sustainable management of the air resource in New Zealand. It is important to note that regional councils may have their own air quality guidelines arising from specific air quality issues in those regions. Therefore, it is entirely possible that some regional guidelines will be more stringent than the national guidelines when last updated in 2002.

Going forward, it is important for contractors to work with regional councils and the MfE to determine the following:

(i) Whether the introduction of crumb rubber use will change emission and odour levels and exceed the threshold concentrations set in the NES for Air Quality.

(ii) Whether the rules set out in consents need to be revised to allow for the use of crumb rubber without adverse impact on safety, health, and environment.

Findings from overseas studies on environmental impacts from crumb rubber use are discussed in more detail in Chapter 6.

4 Review of Australian Practice

4.1 Existing Specifications for the Use of Recycled Materials

As the previous review stated (Wu et al. 2015), chip sealing with crumb rubber modified bitumen has been practised in Australia, particularly in Victoria, New South Wales and Western Australia, since the 1970s.

Victoria has been a significant user of crumb rubber in road resurfacing using chip seals (better known as spray seals in Australia) since the 1970s. The recently revised Technical Note (VicRoads TN 107) by the Victorian State Roading Authority (VicRoads) summarises the key criteria for recycled materials: *Pavement materials, including those containing recycled material, must have properties that provide the required service life of the pavement.* Crumb rubber is no exception. Table 1 summarises the amount of crumb rubber permitted by VicRoads for various surfacing applications.

Table 1 Extracted summary from TN 107, VicRoads

Material Application	Permitted Recycled Material	VicRoads Document Reference
Chip Seal Surfacing	Crumb rubber content (by mass of binder) varies with sprayed seal type e.g. · Unmodified seals – up to 5% · High Stress Seal - 9% · Extreme Stress Seal - not less than 15%	VicRoads Standard Specification Section 408
Crumb Rubber Asphalt	Crumb Rubber - 2.5 to 3% (by mass of mix)	VicRoads Standard Specification Section 421

In VicRoads' Standard Specification Section 408: Sprayed Bituminous Surfacings, crumb rubber modified binders are classed as a type of polymer modified binder (PMB). Under the PMB classification, the document provides a guideline for the types of treatment where crumb rubber modified binders can be used. It also specifies the amount of crumb rubber required to meet the expected performance for the selected treatment.

At a national level, Austroads has published a Technical Specifications Framework AP-T41 and a guide to the use of PMBs: AP-T42, which included the use of crumb rubber modified binders in 2006. The use of these modified products is supported by the Austroads Specification Framework for Polymer Modified Binders (AGPT/T190-19), in which performance requirements for the modified binders are specified. Similarly, VicRoads' Standard Specification Section 421: Bitumen Crumb Rubber Asphalt and the AGPT/T190 both list the properties and performance requirements for crumb rubber modified binders for both dry and wet asphalt mix processes.

Due to increasing awareness and effort toward crumb rubber uptake in the roading industry, there are now also specifications in both Queensland and Western Australia, and a focus to harmonise the specifications across all jurisdictions in Australia.

4.2 Increasing crumb rubber use in Australia

It is important to note that there are a vast range of other PMB products in the market, which partly contributes to the limited use of crumb rubber in roading in certain parts of Australia, particularly in asphalt, due to the nature and cost of the product. Another contributing factor is the differing amounts of experience within each jurisdiction. In 2017, for instance, crumb rubber modified bitumen made up almost 75% of all modified bitumen market share in Victoria, whereas in Queensland the figure was less than 10%. Queensland has since ramped up its activities to familiarise industry within the state of the potential use of crumb rubber in asphalt. As a result, Queensland is expecting a significant increase in the uptake of crumb rubber modified bitumen over the next few years. Table 2 gives an overview of the market share in 2017 and the forecast for 2022.

Table 2 Total Modified Bitumen and Crumb Rubber Modified Bitumen Market Share in each Australian State (supplied by TSA)

	2017 (based on actual)		2022 (5-year projection)	
State	Total Modified Bitumen (tonnes)	Crumb Rubber Modified Bitumen share (%)	Total Modified Bitumen (tonnes)	Crumb Rubber Modified Bitumen share (%)
Victoria	47,000	74.4	63,193	78.9
NSW/ACT	52,000	48.1	65,533	58.7
Queensland	59,000	8.5	88,236	44.2
Western Australia	18,000	44.4	28,320	63.6
South Australia	8,000	37.5	10,532	61.7
Northern Territory	4,000	25	4,973	40.2
Tasmania	1,000	0	1,404	50.1

Opportunities to use more crumb rubber in conventional asphalt mixes are currently being investigated through projects funded by State Authorities, Austroads, and Tyre Stewardship Australia (TSA).

4.2.1 Product Stewardship Scheme

The launch of TSA and the national Tyre Product Stewardship Scheme in 2014 provided impetus to promote environmentally sustainable collection and recycling processes, as well as new uses for recycled ELTs in Australia.

According TSA's National Market Development Strategy for Used Tyres, a number of barriers which are not too dissimilar to the ones New Zealand faces, have persisted in Australia in recent years. These include:

- Lack of technical know-how for producing and applying crumb rubber modified seals and asphalt, given a historic usage of commercial, virgin polymer modified materials.
- In some jurisdictions, current specifications mainly allow for modifications using commercial polymer rather than other materials.
- Concerns about the impact of emissions, fumes, and odour on worker health and safety.
- Lack of awareness and incentives to drive the use of crumb rubber in asphalt and seals.
- Road construction companies' reluctance to invest in necessary equipment, methods and training in the absence of a mature market for roads containing ELT materials.

A 2015-2016 survey indicated there were then approximately 450,000 tonnes of ELTs in Australia. Only 14% of this was used productively at a local level, with a further 56% exported as TDF or tyre retread, and the rest (30%) disposed either to landfills or to unknown destinations. The Australian scheme consists of a levy of 25 cents per passenger tyre equivalent, paid voluntarily by the member tyre importers. Note that participation in the scheme itself is voluntary and free.

The markets which the Australian government and TSA have identified as key areas to support research and development and encourage greater use of ELTs include:

- Advanced manufacturing.
- Rail.
- Building construction.
- Civil infrastructure.
- Roads.

TSA follows the implementation pathway as summarised below, and has been working with the Australian road industry to target significant investments in different parts of the supply chain.

1. Use industry bodies and research organisations to create potential demand.
2. Use State Authorities and Local Government to demonstrate benefits.
3. Use Federal Government agencies to enable supply.

TSA has therefore been very active in funding projects to enable supply (see Figure 1).

Lead Organisations	Project Title	TSA Contribution	Potential Market Volumes (tonnes) p.a
Industry Partner	High Shear Crumb Rubber Mixer	**$175,000.00**	2,500
Industry Partner	Fume minimisation of crumb rubber asphalt investigation	**$90,000.00**	-
Industry Partner	Automated crumb rubber hopper system for asphalt production	**$90,000.00**	1,000
Industry Partner	Advanced crumb rubber bitumen plant	**$250,000.00**	1,500
Industry Partner	Crumb Rubber Capacity Expansion	**$300,000.00**	2,000
TOTAL		**$905,000.00**	7,000

Figure 1 Extracted from TSA AAPA Western Australia meeting PowerPoint Slideshow, 11th February 2020

The total bitumen market in Australia is in the order of 800,000 tonnes per annum, with almost 25% of this modified with commercial polymer or crumb rubber. It was estimated that in 2017, approximately 24,000 tonnes of rubber (plus 9,600 tonnes of steel) was recovered from ELT, and about half of the rubber was utilised in the road market. TSA estimates that 230,000 tonnes of collected passenger and truck tyres per annum (about half of the estimated total ELT volume in Australia per annum) is currently accessible for use, meaning there is plenty of potential for the road industry in Australia to utilise more crumb rubber. About 30% of total ELT volume ends up in landfill or is stockpiled. It is important to note that TSA's calculation assumes that each Equivalent Passenger Unit (EPU) processed at its end of life yields 6 kg of crumb rubber.

4.2.2 Product Trials

In addition to enabling supply, it was logical for Austroads to ensure that the national polymer modified binder specification is fit-for-purpose and supports the use of ELTs. The current national polymer modified binder specification is the AGPT/T190 Framework. This contains a specification for the properties of different crumb rubber binders for specific applications: plant-produced spray-sealing binder (S45R), field-produced spray-sealing binders (S15RF, S18RF), and field-produced 'dry mix' asphalt (A27RF).

Current Austroads-funded research, conducted by the Australian Road Research Board (ARRB), consists of a testing programme to determine the AGPT/T190 test properties of crumb rubber binders at a range of rubber contents. This builds from the base products above and provides a better understanding of the effect of crumb rubber levels on asphalt performance properties. Austroads also recognises that the binder specification needs to be robust to take into consideration possible changes in the crumb rubber supply stream and the tyre manufacturing industry. Crumb rubber composition has a significant effect on its behaviour with bitumen and its modified properties. Traditionally, due to their high natural latex rubber content, truck tyres have been favoured for crumb rubber modification of bituminous binders. There is a pressing need for the industry to explore the remaining ELT resource, i.e. passenger car tyres, which typically contain a higher percentage of synthetic rubber than truck tyres.

Since 2015, the Australia Asphalt Pavement Association (AAPA) has collaborated with Queensland Department of Transport and Main Roads (TMR) and Main Roads Western Australia (MRWA) to develop a set of specifications for crumb rubber modified asphalt mixes, namely for open graded asphalt (OGA) and gap-graded asphalt (GGA). The actual specifications can be found on https://www.aapa.asn.au/aapa-national-model-specifications/. MRWA are also conducting some trials in association with Fulton Hogan, using OGA and GGA and different proportions of crumb rubber. AAPA is monitoring this very closely and will be able to report the outcome in the near future.

There have been several demonstration projects led and funded by local councils and state governments in various jurisdictions. The outcome of one project in the City of Mitcham in South Australia has been positive, with beneficial properties confirmed in the lab and in the field. Such demonstrations have also served the purpose of generating interest from local governments and beyond. The majority of the funded projects are still in progress. For instance, ARRB reported in March 2020 that a road paving trial of crumb rubber modified asphalt mixes was carried out successfully in Melbourne. This work is funded by TSA and the Victorian Department of Transport. The purpose of the two-year project is to investigate the performance of four different crumb rubber asphalt mixes. Testing will be conducted regularly and a final report is due by mid-2022.

Finally, MRWA and ARRB under the Western Australia Road Research and Innovation Program (WARRIP) have investigated the recyclability of crumb rubber modified asphalt. This is an important step to address the questions surrounding the lifecycle of such modified material. This is discussed in more detail in Chapter 6.

4.2.3 Economic and Policy Considerations

To encourage greater use of recycled materials in general, production and transport costs must both compete with those for virgin materials. There are policy levers that impact on the cost of ELTs and crumb rubber: 1) waste export restrictions to minimise practices such as sending ELTs to China and other countries, and 2) waste levies.

Waste levies are designed to encourage waste avoidance and recycling by making landfilling as uneconomical as it is practical. It is worth noting that in New Zealand, waste levy is charged at NZ$10 per tonne. This needs to be examined further, as the equivalent levy is much higher in Australia and this could be one of the key barriers to crumb rubber use in New Zealand. The two main benefits associated with waste levies as shown in Australia are that firstly, there is increased landfill diversion and higher recovery rates for recycled materials. Secondly, the collected levies become a source of funding for investment in waste management and minimisation initiatives.

However, statistics from Australia do show a large variance in levies between states and within jurisdictions. For example, the waste levy for Queensland is AUD75 per tonne compared to AUD143.60 per tonne in metropolitan areas of New South Wales. In rural Victoria, it can be as low as AUD33.03 per tonne, and there is currently no levy in the Northern Territory. It has been noted that the uneven levies across Australia can have unintended outcomes, such as the unnecessary transporting of waste between jurisdictions and the profitability of recyclers.

5 Performance Benefits and Whole of Life Costs

5.1 Asphalt mix

5.1.1 Evidence for improved performance

An extensive review of the international literature in 2019 (Neaylon et al. 2019) concluded that there was evidence to support anecdotal observations that the use of elastomeric polymers, including crumb rubber, did increase the service life of asphalt surfacings in many situations.

In particular, a large US meta-study found that compared to an unmodified mix design life of 20 years, the estimated increase in life for polymer modified asphalt overlays ranged from 0-10 years depending on traffic levels, climate, and underlying pavement type and condition.

Appropriate use of crumb rubber modified bitumen in hot mix asphalt does provide improved fatigue and crack resistance, and thus provides the ability to construct thinner surfaces.

However, performance can be highly dependent on a range of site and construction factors that can override the effects of binder composition. For example, in road trials, Schuler et al. (2015) found that the cracking performance of mixes with crumb rubber (20%) modified bitumen was much worse than for unmodified control sections.

In Australia, as described earlier, there have been numerous field trials of crumb rubber modified asphalt in both open-graded and gap-graded designs. Early indications are encouraging, but most trials are still in their infancy and it is thus too soon to draw any conclusions on its comparative performance.

In New Zealand, the best data available is that for OGPA on the Auckland Motorway system. A change from unmodified bitumen to SBS polymer modified bitumen resulted in an average increase in life of about two years (Chappell 2017).

5.1.1.1 Material costs

Based on data from the US and Australia, where crumb rubber use has long been established, the unit cost of crumb rubber asphalt mixes (at 18-20%) was typically 1.5 to 2 times more expensive than unmodified asphalt. Nevertheless, the economics in Australia supports the use of crumb rubber in the modification of bitumen over the use of other polymers. In 2017, the indicative list price for bitumen in Victoria ranged between AUD835 and AUD1135 per tonne, while the price of crumb rubber ranged between AUD550 and AUD680 per tonne. Similar comparisons with synthetic polymers such as SBS (which is also commonly used in New Zealand) indicated a much broader fluctuation in pricing. More recently, an Australian manufacturer estimated that crumb rubber asphalt costs about AUD1,000 per tonne whereas PMB asphalt costs about AUD1,700 to AUD1,800 per tonne (TSA personal communication, April 2020).

In New Zealand, a cost estimate of about NZ$700-750 per tonne for crumb rubber was provided by a potential supplier in 2015, and this has not changed significantly (Steve Matthews, Rubber Solutions Ltd, personal communication April 2020). The cost was expected to reduce if large scale production was achieved (Wu et al. 2015), but to date production volumes have not changed significantly since 2015. For comparison, the price of bitumen fluctuates but is typically about NZ$800 per tonne (list price NZ$825/T + GST as at 1st of May 2020, data source Z Energy). Bitumen pricing fluctuates due to the crude oil price, exchange rate and supply/demand situation. Therefore, if the pricing of crumb rubber remains below the price of bitumen, then as a modifier of bitumen it provides a good economic outcome, particularly when used for various applications at high loading rates.

5.1.1.2 Whole of life costs

Wu et al. (2015) reviewed several US studies and found that crumb rubber modified asphalt mixes were significantly more cost effective than conventional mixes. This was due to the fact that despite costing more per unit volume, the crumb rubber modified mixes could be used as much thinner layers whilst still achieving the same performance levels. Similarly, a more recent study based on laboratory-measured and modelled fatigue cracking measurements also found that crumb rubber mixes are more cost effective than conventional mixes, all other factors being equal (Suliman et al. 2016).

Neaylon et al. (2019) carried out Net Present Value (NPV) calculations to estimate the additional life required to justify the use of 4% SBS modified binders in asphalt mixes. This analysis should also apply to crumb rubber mixes with equivalent performance properties if the mix material costs are approximately the same (as discussed above). The study found that the minimum additional life required to achieve an NPV equivalent, or better than that of a conventional binder mix over a 40-year period, was 8 years for a conventional asphalt life of 6 years, and 18 years for a conventional asphalt life of 12 years.

In summary, the conclusions drawn in the earlier review (Wu et al. 2015) still apply, and evidence to date indicates that crumb rubber mixes should have longer lives than unmodified mixes (all other factors being equal) and that crumb rubber mixes have a positive cost-benefit. Further investigation is needed to compare crumb rubber modified mixes against equivalent SBS modified mixes on whole-of-life costs.

5.2 Chip seals

5.2.1 Evidence for improved performance

The review by Neaylon et al. (2019) found that, internationally, only a few controlled studies comparing the benefits of crumb rubber and other polymers in chip seal surfacings had been reported, and these were inconclusive or showed only a relatively small benefit based on early life performance. For example, Lim and Lee (2009) in the US suggested, based on laboratory tests and extrapolation of visual assessments of field sites after two years, that polymer modified bitumen chip seal sites would have a two-year increase in life compared with unmodified bitumen chip seal control sites.

In Australia, particularly in Victoria and Western Australia, crumb rubber modified bitumen has been used in spray sealing (chip sealing) because of its ability to increase crack resistance, and to improve adhesion and thus achieve better chip retention. As for asphalt, the more crumb rubber used, the more viscous the modified binder becomes, meaning that there is increased ability to increase binder application rates and thus film thickness to improve durability of the chip seal.

In New Zealand, polymer modified bitumen chip seals tend to be used on sites with high traffic stresses based on the belief that these seals will give a longer life; however, the only controlled trial of polymer modified chip seals in New Zealand did not support this contention (Patrick 2000). The trial found that SBS modified seals performed no better than the control sites. More recently, an analysis of the RAMM database that compared polymer modified and conventional seals was inconclusive as there was a lack of data to allow for valid comparisons (Neaylon et al. 2019).

There have been no known trials of crumb rubber modified chip seals in New Zealand to date. It is understood that a New Zealand contractor was planning to undertake chip seal trials of a devulcanised crumb rubber product in 2019 as part of a Waste Minimisation Fund (from MfE) project, but that this has been cancelled due to resource consent problems.

5.2.2 Material costs

In New Zealand, a 4% SBS modified chip seal costs \$7.50 per m^2, about 1.4 times that of an equivalent conventional seal at \$5.50 per m^2 (Neaylon et al. 2019). If, as with asphalt mix, the approximation that about 18-20% crumb rubber is needed to achieve the same physical properties as a typical 4% SBS binder also holds true for chip seal, then the binder costs are likely to be roughly equivalent. In this case, the crumb rubber seal would be expected to be similar in cost to a typical SBS polymer modified seal.

In Australia, assuming SBS costs AUD4,000 per metric tonne and crumb rubber costs AUD680 per metric tonne, the crumb rubber modified binder is approximately 10% to 20% cheaper than a SBS-based PMB for a given seal application. The price variance is due to different dosage requirements per application type, e.g. standard high stress seals (HSS) versus stress alleviating membrane interlayer (SAMI). Once the application rate is taken into consideration, the cost saving gained from crumb rubber modified chip seals over SBS-PMB chip seals is between 2% and 12%, based on the 2017 estimates.

5.2.3 Whole of life costs

Apart from the minor saving arising from substitution of 18-20% of the bitumen in the binder, crumb rubber chip seals lack the opportunities for material cost savings compared to conventional binders, as is the case for asphalt mixes, i.e. there is no indication that bitumen application rates can be reduced when using crumb rubber or polymer modified bitumen compared to conventional binders. For this reason, crumb rubber chip seals need to have longer lives than conventional seals to be cost effective.

The lack of controlled trials for crumb rubber chip seals to date means that the actual increase in life achieved remains unclear, and so it is difficult to determine whole-of-life costs. Lim and Lee (2009) in the US calculated that a two-year increase in life would be needed for an SBS polymer modified binder seal to breakeven with a conventional seal that lasted 5 years. Similarly for a 40-year period, Neaylon et al. (2019) calculated that a 4% SBS polymer modified chip seal would require an increase of 6 years in life to be cost neutral, assuming a conventional seal life of 10 years. A lifespan increase of only 2.5 years would be needed for a conventional seal life of 5 years. These calculations are likely to apply to an equivalent crumb rubber modified bitumen at 18-20% concentration which would be essentially the same cost at the SBS binder.

6 Environmental Effects

The 2015 literature review highlighted three main environmental (and health and safety) impacts:

1. Emissions and worker exposure concerns.
2. Leaching by rainwater.
3. Recyclability of the material at the end of the surfacing life.

6.1 Emission and Worker Concerns

As the previous review (Wu et al. 2015) highlighted, the development of crumb rubber surfacings across the US raised concerns over fume emissions and other environmental and human health issues, along with costs to mitigate the concerns and other potential implications. The US Federal Government and each State Department of Transportation (DOT) funded extensive emissions testing programmes of asphalt and crumb rubber modified asphalt fumes to provide detailed information on health impacts 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 hot mix operations sometimes confounded the effect of crumb rubber on emission rates (Crockford et al. 1995). In many cases, increases in plant emissions were due to elevated operating temperatures rather than the presence of crumb rubber. Although no definitive results were obtained that indicated crumb rubber asphalt exposures are more hazardous than exposures from conventional asphalt production, the National Institute for Occupational Safety and Health (NIOSH) remains cautious and suggests that, based on the reports to date, crumb rubber emission exposures are potentially more hazardous than conventional asphalt without crumb rubber.

In a recent study (Nilsson et al. 2018), an investigation was carried out to assess the risk of asphalt workers developing adverse health effects due to their occupational exposure. The research compared bitumen and rubber modified bitumen in terms of the emission of, and workers' exposure to, particulates, polycyclic aromatic hydrocarbons (PAHs) and benzothiazole in the field at asphalt work sites. The exposure measurements on asphalt workers for respirable dust, total dust, particulate numbers and mass, and total PAH concentrations showed similar concentrations when both standard and rubber bitumen were used. As expected, due to proximity, asphalt-surfacing machine operators were the workers with the highest observed exposure, followed by screed operators and roller drivers.

Both laboratory and field measurements showed higher concentrations of benzothiazole when rubber bitumen was used – up to 7.5 times higher in the laboratory. The study referred to Swedish occupational exposure limits as well as health-based guideline values given by the World Health Organisation (WHO). The study concluded that air pollutants such as benzothiazole and PAHs are emitted into the air during asphalt work, but it was not evident whether exposure to rubber modified bitumen poses a higher health risk than exposure to standard bitumen in terms of asphalt worker exposure.

Also published in 2018, Xu et al. undertook a study in Sweden in which they investigated 267 asphalt paving workers (116 conventional asphalt exposed workers, 51 crumb rubber modified asphalt exposed workers, 100 non-exposed outdoor workers, 100% male). The study used personal exposure monitoring to test for dust, PAHs, benzothiazole and nitrosamines. Lung function was tested through spirometry and a self-reported questionnaire. An inflammatory response was investigated by measuring concentrations of interleukin-8 and C-reactive protein. Results from the study indicated that there were no significant differences in dust, PAH or nitrosamine levels between conventional and crumb rubber modified asphalt exposure. However, benzothiazole exposure was significantly higher in CRM asphalt workers (median 2.09 μg/m^3 [95% CL 1.01-3.69]) vs. conventional asphalt workers, (median 0.37 μg/m^3 [95% CL 0.17-2.63]). Benzothiazole is a common compound present in tyre rubber, and has sufficient volatility to be a source of inhalation and dermal irritant. However, there is a lack of toxicology data for its potential health risks. Based on work to date, it would be prudent to further investigate the health impacts of crumb rubber modified binder use in New Zealand to ensure the safety of workers, in particular with respect to benzothiazole levels.

There has been very little work done to date in New Zealand regarding assessment of the emission risks from rubber modified bitumen. Wu and van den Kerkhof (2018b) produced a laboratory test report as part of a Waste Minimisation Fund project for the Ministry for the Environment in 2018. The study compared a S45R, which is an Australian terminal blend crumb rubber modified binder, against a devulcanized crumb rubber modified binder and a standard unmodified binder. The volatile emissions from each of the binders when heated under simulated operating conditions were analysed. The analysis focused on PAHs, volatile organic compounds (VOCs), and benzothiazole. The lab result suggested the compounds would pose little or no risk to workers at the measured concentration levels. It was also encouraging to find the S45R control produced similar results as the devulcanized rubber binders. Additional chemical analysis did show the presence of zinc in the rubber modifier binder, which indicates the need for further assessment of the potential risks of heavy metal leaching.

Emissions and odours from crumb rubber bitumen use in Australia have apparently not been an issue, because crumb rubber chip seals are almost entirely used in regional or rural areas away from people, and these issues have not proven to be a major problem since 1970s. Many of the fixed asphalt and binder plants in Australia are almost entirely located in industrial areas away from residential neighbourhoods due to the hazardous nature of the activity, meaning that emissions have not been raised as a major issue. However, this may change due to the growing use of crumb rubber modified asphalt and chip seals in more urbanised area where emission risks are of concern to local authorities.

In 2019, a review was published by the Institute for Safety, Compensation and Recovery Research (ISCRR) – a joint venture between WorkSafe Victoria and Monash University to investigate the health effects associated with exposure to bitumen (Moo et al. 2019, Bywood and McMillan 2019). This project was initiated in response to a number of reports of acute incidents in response to fuming bitumen loads (bitumen fumes after heating to high temperatures 170-180 °C).

The project consisted of two components:

1. A systematic review of the scientific literature regarding adverse health effects and mitigation strategies for bitumen fumes; and,
2. An environmental scan – a worldwide search of publicly available documents surrounding health effects of high temperature bitumen fumes, and a series of key informant interviews of those in the asphalt industry in Victoria, Australia.

For the review and environmental scan, conditions included but were not limited to eye, nose, throat and skin irritation, headaches, nausea and respiratory discomfort. The focus of the review was on the entire industry and, thus, bitumen in general. There were many reports from asphalt workers of acute and chronic health effects regardless of the type of bitumen being used. An Australian Workers' Union (AWU) survey of asphalt workers found that more than 85% of those surveyed have had one or more conditions after exposure. It was reported that management staff at asphalt companies are often dismissive of the suggestion of negative health effects and suggest that incidents are 'occasional'. It is most likely, however, that such events are significantly under-reported (due to worker characteristics, desire to get the job finished, fear of reprisals, and perceived lack of response from management).

Asphalt companies have engaged with NATA-accredited laboratories to carry out independent testing such as job site monitoring and personal monitoring. To date, results show that all measures of exposure to bitumen fumes and the compounds they contain are within accepted limits.

The authors recommended that testing needs to be reviewed, and more investigations were needed to identify what is making workers unwell. As Safe Work Australia pointed out, exposure standards merely establish a statutory maximum upper limit and do not necessarily draw a dividing line between a healthy or unhealthy working environment due to individual susceptibilities. Overall, evidence of an association between exposure to bitumen contents/fumes and reported adverse health outcomes was mixed. Of the incidents reviewed in the ISCRR study, there were only two instances concerning the health effects of crumb rubber modified bitumen. It was highlighted that more studies need to be carried out and assessed to ascertain the health effects of crumb rubber use on workers.

The Australian National Asset Centre of Excellence (NACOE) carried out a study on emissions monitoring of crumb rubber modified binder and PMB in open graded asphalt. This was completed in 2017 for the Department of Transport and Main Roads in Queensland. The emissions from each asphalt were comparable, although there were elevated levels of benzene in the crumb rubber emissions compared with the PMB. It should be noted, however, that as for the previously discussed New Zealand study (Wu and van den Kerkhof 2018b), this study was also conducted in a laboratory emissions chamber and therefore cannot simply be directly be compared to the situation on a worksite.

The distinct harsh odour from heating crumb rubber binder at elevated temperatures is also often considered alongside measurements of emissions. While many of the various emission studies seem to indicate that the measured levels of specific emissions are within acceptable limits, the resultant odour, which is due to a complex mixture of different compounds, may still be an issue for the public and may result in breaches of resource consent conditions for asphalt plants.

Juntarachat et al. (2013) conducted a comprehensive investigation into the key compounds responsible for the acknowledged odour of natural rubber when heated. Some of the compounds are low-molecular-weight fatty acids like acetic and butyric acids, longer-chain acids like stearic acid, and aromatic compounds like p-xylene, phenol, benzaldehyde, benzoic acid and benzaldehyde. Trimethylamine, which has a strong fishy smell, was found in both rubbers used in this study and is believed to be another strong contributor to the overall odour of the rubber. A better understanding of the compounds involved is needed in order to devise appropriate odour treatment systems for rubber processing plants.

Commercially available odour management technologies currently exist – e.g. Ecosorb by OMI Industries, which works on a chemical absorption method for asphalt. This product has been used by contractors in Australia. However, it is worth noting that the roading industry in Australia addresses the odour issue partly by developing mobile plants to move the operation away from densely populated areas. There is also information on other odour control systems is available from the New Zealand Ministry for the Environment (Wu et al. 2015). The actual efficacy and additional costs associated with these potential solutions create uncertainty for contractors and would potentially place the continued operation of asphalt plants at risk.

Another viable solution for potentially reducing odour in asphalt applications is the use of warm mix asphalt (WMA). WMA technology was discussed in the 2015 review, and is readily available and used worldwide as well as in New Zealand. WMA allows for lower working temperatures, resulting in reduced emissions and odours (Yang et al. 2019).

6.2 Leaching Concerns

There is also concern around the potential for hazardous compounds from crumb rubber making their way into water sources by wear and leaching of crumb rubber modified 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 should also be noted that the tests were done on milled surfacings, which 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).

A recently published paper from the US (Gheni et al. 2018) highlighted interesting findings and reinforced findings previously reported. First of all, this research group from Missouri assessed the level of heavy metal leaching from two main types of crumb rubber, made under ambient and cryogenic conditions. It was found that the cryogenic crumb rubber had a different metal leaching behaviour compared with the ambient crumb rubber, depending on pH value. The metal leaching from all types of samples, including rubber, asphalt emulsion, and chip seal, decreased with increased pH value. The mechanically ground crumb rubber under ambient conditions produced significantly less heavy metal in the leachate. The reason for this result was not reported.

The study, using simulated acid rain as leaching solution, also found that using the crumb rubber as a mineral aggregate replacement in chip seal surfacing did not have a negative environmental impact in terms of heavy metal leaching. The toxic heavy metals leached from the recycled rubber or rubberised chip seal were below US EPA drinking water standards.

The main leached heavy metal from the recycled bare rubber particles was zinc, which is consistent with the known composition of the tyre component. However, zinc is not regulated in the primary US drinking water regulations. Under different pH conditions, a significant reduction in heavy metal leaching was recorded when rubber was used with emulsion in the form of chip seal pavement, because asphalt is hydrophobic and prohibits contact between tyre and solution. A reduction in zinc leaching of around 50% was recorded for chip seal specimens compared with leaching from bare crumb rubber.

In the New Zealand context, based on information gathered from the Ministry for the Environment website, the management of freshwater and marine water quality can be carried out with assistance from guidelines such as the Australian and New Zealand Guidelines for Fresh and Marine Water Quality, previously known as ANZECC (Australia and New Zealand Environment and Conservation Council). Although not mandatory in New Zealand, the guidelines provide a useful source to inform decision-making related to water management.

There is also an existing National Policy Statement for Freshwater Management (Freshwater NPS) to guide local governments around how to manage fresh water quality in New Zealand. The national guidance includes setting minimum acceptable standards called “national bottom lines”, which councils must meet, or work towards meeting, over time.

The Default Guideline Values (DGVs) within the guidelines indicate levels to trigger further analysis and monitoring to determine whether aquatic ecosystems are adequately protected against physical and chemical stressors and toxicants such as zinc, which can be directly toxic to aquatic species. The DGVs for specific compounds can be found at https://www.waterquality.gov.au/anz-guidelines/guideline-values/default. The DGVs are reported at different levels of species protection, namely 80, 90, 95 or 99% of species.

6.3 Recyclability

Reclaimed Asphalt Pavement (RAP) is a standard resource that the roading industry utilises for the construction of new asphalt pavements. It is an established practice around the world and is gaining popularity in New Zealand. As reported by Wu et al. (2015), crumb rubber modified asphalts have been successfully recycled in the US, although only a limited number of cases have been reported. Studies conducted by Caltrans (California Department of Transportation) indicate that full depth pavement reclamation has the highest feasibility, followed by hot plant recycling, cold in-place recycling and hot in-place recycling. Test results from a trial in the City of Los Angeles showed that the recycled asphalt rubber mix reclaimed met Caltrans specifications, passed all tests, and was recyclable using either microwave technology or conventional mixed design technology. Air quality testing found that employee exposure to air contaminants was well below OSHA-permissible exposure limits and, in most cases, also below the detection limit. Recommendations from the Caltrans study 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 severe of a problem than it was with conventional asphalt.

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 (>160 °C), it is possible to incorporate lower quantities of crumb rubber modified RAP (<30%) at temperatures similar to conventional hot mixes.

In Australia, the increased activity and promotion of the use of crumb rubber modified (CRM) asphalt presents a need to understand whether and how CRM asphalt can be recycled to produce CRM-RAP for use in road pavements. Both Main Roads Western Australia (MRWA) and the Australian Road Research Board (ARRB) are currently conducting a staged feasibility study (Rice 2019) as part of the Western Australian Road Research and Innovation Program (WARRIP). This study has been carried out with the support from Fulton Hogan (in Perth, Western Australia) and TSA.

There were no technical issues encountered during reclamation of CRM asphalt from the ground and during production of CRM-RAP when using conventional equipment used for standard RAP. It was noted that there was no noticeable odour during the works. The CRM-RAP was stockpiled and then successfully incorporated into a new asphalt mix at a dosage of 10% through a batch style asphalt plant, and the manufactured asphalt material was subsequently paved with no issues.

The overall outcome of the study was positive, with no barriers identified. The next phase is to trial a higher amount of CRM-RAP (>20%) in a drum style plant. This is planned for the next summer season in Australia to ensure that there are no implications on the use and processes associated with CRM-RAP material. Stage 2 will also comprise laboratory characterisation of the viscosity of extracted CRM-RAP binder for use in the viscosity blend design method, which has been developed for the design of new mixes containing more than 20% of RAP material.

The performance of CRM-RAP asphalt mix needs to be investigated and compared against standard RAP asphalt mix, and the environmental impacts, if any, noted. It would be valuable to test whether similar processes can be adopted in New Zealand, based on the type of asphalt plants and equipment set-ups currently in the country. As mentioned earlier, the use of warm mix technologies would be an effective solution to reduce mixing and compaction temperatures. There should be no further implications if the crumb rubber is devulcanised.

In summary, there are many encouraging international examples of technologies available to improve recycling of crumb rubber modified materials. The key to a 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.

7 Conclusions

The purpose of this project was to assess the current relevance of barriers to the use of crumb rubber in roads identified in 2015, to identify new ones that may have arisen since then, and to determine specific actions and recommendations that can be taken by Waka Kotahi to facilitate the sustainable use of crumb rubber modified materials by the New Zealand roading industry.

The key issues and corresponding opportunities are summarised below.

7.1 Economics and supply

The main barrier to producing crumb rubber and its use in road pavement and surfacing construction in New Zealand remains an economic one.

Economic disincentives include high capital costs for the plant needed to produce crumb rubber and then process and use crumb rubber in modified roading products. Significant additional costs would also be incurred in development of specific crumb rubber products by contractors, training, and development of quality control procedures, etc. High capital costs and continuing uncertain returns limit the supply of crumb rubber and the roll-out of new products.

The market view is that under current rules, regulations and economies of scale, crumb rubber technology cannot compete with existing SBS polymer options.

Initiatives that would remove the economic and supply barriers to crumb rubber are:

- An unequivocal commitment by Waka Kotahi, other road controlling authorities and the Government to use crumb rubber modified binders in place of or in addition to SBS polymer modified binders in road surfacings.

- Introduction of a mechanism by which funds are made available to invest in the use of crumb rubber modified binders, so that the cost is comparable or lower than that of SBS polymers or other alternatives. This may be through a user–pays levy on tyres via the proposed Product Stewardship Scheme (similar to the Australian “tyre stewardship” scheme) or by Waka Kotahi being prepared to pay a premium for crumb rubber modified binders.

- Demonstration of the performance benefits of crumb rubber modified binders in chip seal applications. The performance benefits of crumb rubber binders in asphalt mix are established, and these binders could readily be used as a substitute for SBS polymer modified binders. The volume of tyres that would be consumed in this way in New Zealand is, however, relatively small (assuming that asphalt takes 20-25% of the total bitumen market in New Zealand). Far greater volumes of ELTs would be consumed if crumb rubber binders were used in chip seal surfacings, but the performance benefits of crumb rubber modification in seals is unclear and evidence is needed to justify the additional cost. Use of larger volumes of crumb rubber would greatly improve the economics of investment in crumb rubber technology by the industry.

7.2 Implications of a move to emulsified binders

For health and safety reasons, Waka Kotahi is actively considering actions to encourage exclusive use of emulsified binders for chip sealing works. Technology for emulsification of crumb rubber modified binders exists but is not “mainstream” technology. It may currently be protected by patent and may require additional research and development for use in New Zealand. Given that SBS polymer emulsions are commonplace, then, as expressed in the Health and Safety at Work Act (2016), a safer “reasonably practicable” alternative to hot crumb rubber binders already exists. This would potentially expose Waka Kotahi and contractors to prosecution by WorkSafe for any accidents that may occur using hot crumb rubber binders. A move to the exclusive use of emulsified binders would therefore be a serious obstacle to crumb rubber binder use in chip seals.

7.3 Environmental considerations

Waterways contamination from crumb rubber modified road surfacing is unlikely, but the likelihood of air emissions during manufacture and application of road surfacings are higher and differ slightly in composition from those resulting from conventional bitumen processes. These emissions are usually found to be well within currently acceptable health and environmental limits internationally, but the sector remains cautious, and further investigation is required to assess the relevant New Zealand regulations and guidelines for air and water quality, and ensure that risks are mitigated and reduced to the minimum acceptable level.

The unpleasant acrid odour of emissions from hot crumb rubber modified binders is a more significant problem. Emissions odour may cause problems with breaches of consents for asphalt plants, but may be able to be resolved (at a cost) using odour suppression additives or other means such as warm mix additives or relocation or use of mobile plant and equipment. Odours generated during the laying of asphalt or seal construction will be short-lived, but may still generate complaints from the public in urban environments. This may place limits on areas where crumb rubber modified binders can be used.

Finally, international studies e.g. the WARRIP project in Western Australia, are currently underway to further assess the recyclability of crumb rubber modified binders, and these studies need to be followed closely. The ability to recycle crumb rubber modified materials ultimately means that these materials will have further use at the end of the surfacings life, improving sustainability and whole of life costs.

8 Recommendations

A number of key actions are believed necessary to facilitate the use of crumb rubber in road surfacing construction in New Zealand. These are set out below.

8.1 Economics and supply

Three initiatives that would largely remove economic and supply barriers are:

- An unequivocal commitment by Waka Kotahi to use crumb rubber modified binders in place of or in addition to SBS polymer modified binders, giving confidence to the market. This would include additions or modifications to the M1-A and draft M1-S binder specifications to include clauses explicitly allowing crumb rubber binders as an acceptable option. Promotion and education of the industry about the technology and investigation of a specific crumb rubber binder specification (based on the Australian AGPT/T190 specification), or at least a crumb rubber material specification, should also be undertaken.

- A mechanism by which funds are available to invest in the use of crumb rubber modified binders so that the product is competitive against SBS polymers or other alternatives. This may be through a user–pays levy on tyres via the proposed Product Stewardship Scheme (similar to the Australian "tyre stewardship" scheme) or by Waka Kotahi being prepared to pay a premium for crumb rubber modified binders.

- Demonstration of the performance benefits of crumb rubber (or SBS) modified binders in chip seal applications through controlled field trials or testing. The performance benefits of crumb rubber binders in asphalt mix are established, and these binders could readily be used as a substitute for SBS polymer modified binders. Greater volumes of ELTs would be consumed if crumb rubber binders were also used in chip seal surfacings, but the performance benefits of crumb rubber modification in seals is unclear and evidence is needed to justify the additional cost.

8.2 Implications of a move to emulsified binders

- A potential move by Waka Kotahi to emulsified binders for chip sealing would prevent use of crumb rubber binders in sealing using current mainstream technology. There is still merit in pursuing crumb rubber technology in asphalt applications, but the relative volumes utilised (consumption) would be much smaller than that of chip seals. However, in order to encourage crumb rubber use in chip seals, research is needed to determine whether practical technologies suitable for use in New Zealand are available for the emulsification of crumb rubber, or devulcanized crumb rubber.

8.3 Environmental considerations

- The relationship between levels of emissions expected from crumb rubber use in road surfacings and relevant New Zealand regulations and guidelines for air and water quality needs to be assessed.

- The potential effects of odour emissions from crumb rubber binders on existing resource consents for asphalt plants need to be assessed.

- Research into the effectiveness of odour suppressants and other technologies such as warm mix additives to reduce odour should be conducted to complement the regulatory work.

- The recyclability of crumb rubber modified road surfacing material needs to be evaluated further by following up international studies and conducting local trials.

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