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FINAL REPORT

Project Title: P31 and P32 Optimising the Use of Crumb Rubber Modified Bitumen in Seals and Asphalt (Year 1 – 2014/15)

ARRB Project No: 009176/009177

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Client: The Queensland Departments of Environment and Heritage Protection, and Transport and Main Roads

Date: June 2015

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SUMMARY

The aim of this report is to present the opportunities available to Queensland for using recycled tyres (crumb rubber) technologies for sprayed seal and asphalt applications. The benefits of crumb rubber are presented and possible barriers to increased use of it in seals and asphalt are identified.

Application of crumb rubber in seals and asphalt provides a high-value application of this recycled material. The available body of knowledge shows that the use of it in both asphalt and sprayed seals can provide improved field performance, specifically in terms of durability and cracking resistance. A growing number of road agencies are using crumb rubber technology to construct high performance sprayed seals and/or asphalt roads. Significant environmental benefits can also be achieved through this high value application of recycled waste tyres. It has been shown that crumb rubber can be applied to reduce road noise and CO_2 emissions, as well as the increase use of non-renewable road construction materials.

Currently, only a limited range of the crumb rubber technology available internationally is applied in Queensland. Estimates show that if it were more widely used in asphalt and sprayed seals in Queensland, a significant proportion of end-of-life tyres could be put to beneficial use.

The main barriers to wider application of crumb rubber in sprayed seals and asphalt are socio-economic factors, including environmental and occupational health and safety concerns and higher capital costs. Overseas experience indicates the potential for these concerns to be overcome by applying appropriate engineering measures. Overseas studies also indicate that from a whole-of-life cost perspective, crumb rubber modified (CRM) bitumen can provide a cost-effective alternative to ‘conventionally’ modified bitumen.

It is recommended that future research include working with industry to facilitate the transfer of a wider range of crumb rubber related seal and asphalt technologies to Queensland.

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1 INTRODUCTION

Millions of tyres reach their end-of-life every year in Australia. When expressed in equivalent passenger units (EPUs) to correct for the weight difference in tyres used by different vehicle types, 48 million (EPU) tyres reached their end-of-life in 2009-2010 (Brindley, Mountjoy & Mountjoy 2012). Eleven million EPUs were scrapped in Queensland alone, which equates to more than two EPUs per Queenslander per year. End-of-life tyres are a potentially valuable resource for recycling; however, at present, most tyres end up in a landfill or are exported overseas. To increase the beneficial use of these tyres, a national Tyre Product Stewardship Scheme was created by an industry-government working group.

Rubber and carbon black represent approximately 70% of the weight of a tyre. One high-value destination for these materials is as crumb rubber modifier (CRM) in bitumen (binder) used in road construction. To create CRM binder, suitable tyres are processed to crumbs and digested into bitumen at a high temperature. CRM binder has enhanced elastic properties, which results in more durable asphalt and sprayed seal surfacings. CRM binder has a long history of use in Australia, particularly in sprayed seal surfacing applications. There is, however, a need to investigate why this potentially valuable resource is not utilised on a larger scale. Especially with respect to the use of CRM binder for asphalt, there may be some barriers that have so far prevented wider adoption of the technology after the initial activity in the 1990s related to CRM binder in asphalt. For this reason, the Queensland Department of Environment and Heritage Protection (DEHP), together with the Queensland Department of Transport and Main Roads (TMR), initiated this project aimed at identifying options for maximising the use of recycled tyre rubber in asphalt and sprayed seals.

1.1 Objective

The aim of this report is to present the opportunities available in Queensland for using CRM binder technologies for sprayed seal and asphalt applications. The benefits of using CRM binders in seals and asphalt are presented, followed by the identification of possible barriers to the increased use of them in these applications.

Figure 1.1: Crumb rubber modified asphalt paving operation in California

1.2 Scope

This report focuses on the use of crumb rubber as a modifier for bitumen in two road applications: sprayed seals and hot mix asphalt. CRM binder has also been used extensively in Australia and around the world in rubberised crack sealant materials. End of use rubber tyres have also been shredded to sizes of approximately 50 mm to 300 mm and used as tyre derived aggregate in various geotechnical applications such as lightweight fill, drainage layers or insulation layers. Tyre derived aggregate has been used in the USA and various other countries. The use of rubber tyres in rubberised crack sealants and as tyre derived aggregate are beyond the scope of this project.

1.2.1 Sprayed Seal Surfacing Applications

Sprayed seals are a widely used surface treatment for roads where aggregate is applied directly to a bitumen layer sprayed onto a base or existing surfacing. Rolling of the stones (aggregate) into the bitumen layer and sweeping of the excess aggregate completes the operation. Seals can be applied in various different configurations, including as a single application or a double application. Approximately 75% of the Queensland state controlled road network has a sprayed seal surfacing.

Strain Alleviating Membranes (SAM) and Strain Alleviating Membrane Interlayers (SAMI) are two types of sprayed seals that incorporate a relatively large volume of crumb rubber or heavily polymer modified binder (PMB) (Austroads 2009). In rehabilitation projects, the products are applied to cracked/distressed pavements in order to alleviate the strains in the pavement and reduce the potential for reflective cracking in the surface. A SAM is trafficked by general traffic. A SAMI seal is placed as an interlayer between an asphalt layer and the layer below, with trafficking generally limited or temporary. (The asphalt is the final surfacing on which general traffic runs after construction is finished.)

1.2.2 Hot Mix Asphalt

Hot mix asphalt (HMA) is a mixture of aggregate and bitumen, which is sometimes modified. HMA is manufactured in a special plant. There are three general types of HMA, which are categorised by their aggregate gradations: open-graded, gap-graded and dense-graded mixes. CRM binder has been used with all three types of HMA although the greatest benefits have been with open-graded and gap-graded mixes. Limited performance improvements have been reported with dense-graded mixes due to the inadequate void space to accommodate sufficient CRM binder to improve performance (CalRecycle 2010).

1.3 Structure of the Report

A brief history of the development of CRM binder technology is provided in Section 2. Section 3 discusses the production of CRM binder and different processes for incorporating it into sprayed seals and asphalt. The environmental and performance benefits of the use of CRM binder in asphalt and sprayed seals are presented in Section 4. Sections 5 and 6 present an examination of Australian and selected international technical specifications for use of CRM binder in asphalt and seals. Section 7 explores the proportion of end-of-life tyres that could potentially be used in asphalt and seals. The perceived barriers to achieving wider use of CRM binder and how to overcome these barriers may be overcome are discussed in Sections 7 and 8 respectively. Section 9 outlines laboratory testing that demonstrates the effect of crumb rubber on the physical properties of the binder and the use of the dynamic shear rheometer (DSR) as a practical and cost-effective instrument in the characterisation of CRM binders. Air quality emission monitoring work conducted during a sprayed seal trial in the Darling Downs District is presented in Section 10. Conclusions and recommendations are presented in Section 11. Section 12 provides a discussion about future work to be undertaken.

2 HISTORY OF CRUMB RUBBER MODIFIER IN ROAD CONSTRUCTION

CRM binder has been successfully used in road construction since the 1960s. The first recorded use was by a materials engineer of the City of Phoenix, Arizona, who recognised the potential of dissolving crumb rubber in bitumen to provide a binder with increased elastic properties. This elastic binder would be ideally suited to bridge over cracks in asphalt roads. He developed pre-manufactured patches to be placed over cracks on asphalt roads. The patch, which he referred to as 'Band-Aids', a 0.6 m x 0.6 m pre-made chip seal with CRM bitumen on wax-coated paper. This technology was later extended to provide bitumen rubber modified slurry seals to cover larger cracked areas on asphalt roads (Way, Kaloush & Biligiri 2011). To this day, improved crack resistance is considered one of the main benefits of the use of CRM bitumen in asphalt mixes and sprayed surfacing seals. By 1975, the Arizona Department of Transport (ADOT) had successfully incorporated CRM binder in asphalt. Arizona remains one of the leaders in this area. Other jurisdictions in the USA that have been at the forefront of CRM binder technology include California, Florida and Texas. By 1990, 23 US states had placed test sections with CRM binder in asphalt (Roschen 2014). Most early forms of CRM binder technology were patented or proprietary, but the patents for the dominant forms of technology expired in the mid-1990s.

The introduction of CRM binder in Australia occurred in the mid-1970s. Since then, it has been predominantly applied in sprayed seals. Detailed local guidelines on its use in both asphalt and seals have been available at least since the 1990s (Gaughan 1995). At present, Victoria and New South Wales are the main users of CRM binder in sprayed seals (Austroads Pavements Research Group 1999, Widyatmoko & Elliott 2008). CRM binder seals are also used in Queensland, but not to the same extent. In contrast to the USA, where the use of CRM in asphalt has overtaken its use in seals, the use of CRM binder in asphalt is relatively uncommon in Australia. Various road agencies do have product specifications for asphalt with CRM binder in place, which have been applied sporadically in the past. From discussions with major Australian asphalt producers, it is understood that there are only two regions (one in Victoria and one in New South Wales) where asphalt with CRM binder is applied on a relatively regular basis. In both cases, it is applied in areas with very poor subgrade conditions because of the ability of asphalt with CRM binder to handle larger deflections without cracking.

Another early adopter of CRM binders is South Africa, where since the 1980s, it has been used extensively in seals and asphalt (Renshaw 1984, Lo Presti 2013). In Europe, CRM binders have been used in the production of asphalt in France, Austria, the Netherlands, Poland, Germany, Italy, Sweden, Greece and the UK (Lo Presti 2013), with a significant increase in the number of CRM binder projects in Spain and Portugal since 1999 (Widyatmoko & Elliott 2008). Recently, CRM binder technology has also been introduced in Brazil (Lo Presti, 2013) and China (Renshaw et al. 2007).

Although the principle of CRM binder technology has been around for decades, new applications and adaptations of the technology continue to be developed. Internationally, the technology is being adopted in more countries, as the recognition of the durability benefits offered by CRM binder technology continues to grow.

3 PRODUCTION OF CRUMB RUBBER MODIFIED BITUMEN

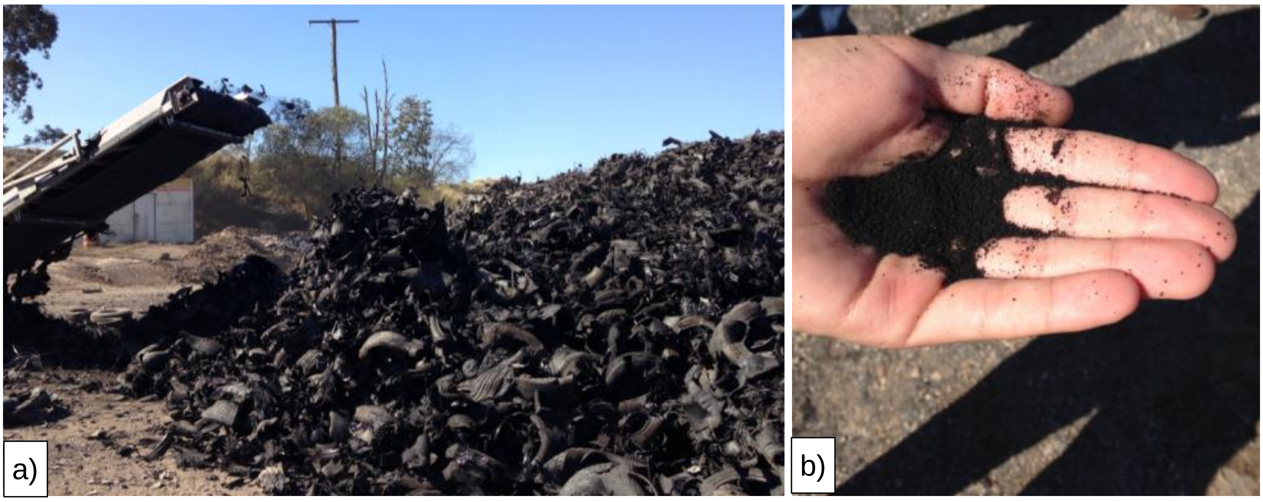
The production of CRM binder involves two distinct phases. In the first phase, end-of-life tyres are shredded, the steel and fibres are removed, and the rubber is ground into crumbs at a tyre recycling plant. These crumbs are added to bitumen at an oil refinery/bitumen terminal or field blending plant (wet process), or added dry and blended directly with mineral aggregate and binder at the hot mix asphalt plant (dry process).

3.1 From End-of-Life Tyre to Crumb Rubber

The composition of tyres differs across manufacturers, tyre sizes and intended use. A typical passenger car tyre contains about 27% synthetic rubber, 14% natural rubber, 28% carbon black, 15% steel and 16% fabric. Other constituents include fillers, accelerators, antiozonants, etc. (A more complete list of additives is provided in Section 8.3). As a general rule, tyres for higher demand situations (e.g. truck tyres) will contain a higher proportion of natural rubber. It is for this reason that some road agencies specify a certain minimum proportion of truck tyres in the crumb rubber blends.

There are various ways to produce crumb rubber from end-of-life tyres. The most common process is mechanical ambient grinding, where the scrap tyre rubber is ground by means of rotating blades at or above ambient room temperature to produce crumbs. After extraction of the fibres and metal, repeated grinding leads to rubber crumbs with a typical size range of 0.5 mm to 5 mm (Lo Presti 2013). Ambient grinding produces irregularly shaped, torn particles with relatively large surface areas. Figure 3.1 shows some of the steps in the ambient grinding process at a tyre recycling facility in Queensland.

Figure 3.1: a) Tyre chunks produced in the first stage of the tyre shredding process; b) crumb rubber



Cryogenic grinding involves the use of liquid nitrogen to freeze the rubber, after which the now brittle material is shattered in a hammer mill and produces smooth particles with a relatively small surface area. Cryogenic grinding can be used to reduce the size of tyre rubber particles prior to ambient grinding. Other less common processes include wet grinding and hydro jet size reduction (Lo Presti 2013). The type of processing can have an effect on the performance of the CRM binder and consequently on the paving mixture.

3.2 From Crumb Rubber to Modified Binder

Crumb rubber can be incorporated in asphalt mixes and sealing binder using a number of different approaches. The approaches are distinctly different for both the crumb rubber used and method of blending with the binder. These differences lead to different outcomes in terms of the finished product. Each approach should be viewed as a separate technology. Each technology also has distinct advantages and disadvantages, which has led to some jurisdictions favouring one over another. There are three dominant forms of production of CRM binder, i.e. the dry process, the high viscosity wet process, and the no agitation wet process.

3.2.1 Dry Process

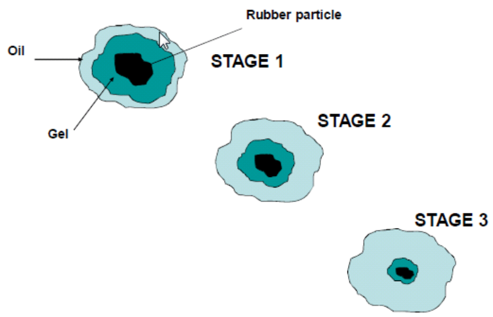
In Australia, the dry process has been the most widely applied approach in producing CRM binder asphalt. The rubber crumbs are mixed with the aggregate at the asphalt plant before bitumen is added. At the point of mixing, the rubber becomes part of the aggregate. When the bitumen is added, the rubber will partially dissolve and become part of the binder (Austroads Pavements Research Group 1999). The advantage of this process is that it provides an easy way for the manufacturer to produce CRM asphalt. A disadvantage is that properties of the binder blend are not well-controlled and with only partial blending of the crumb rubber into the binder, the full benefits of the CRM are not realised. The dry process has continued to be applied in Australia with success (Austroads Pavements Research Group 1999). However, in other parts of the world, as a standard practice it has been largely replaced by the wet process (Way, Kaloush & Biligiri 2011, Widyatmoko & Elliott 2008, California Department of Transportation 2003, South African Bitumen Association 2009, Hicks et al., 2013). The dry process is not used for sprayed seal applications.

3.2.2 High Viscosity Wet Process

In Australia, the high viscosity wet process is mainly used to produce CRM binders for sprayed sealing applications. However these binders can also be used to manufacture CRM binder asphalt. The process involves blending the crumb rubber with bitumen so that the rubber is partially digested. Blending can take place in a specialised unit at an asphalt plant or sealing site; this is known as field blending. Alternatively, the CRM binder can be produced at a refinery or bitumen terminal.

Digestion of the rubber crumbs in the bitumen occurs in different stages. When the crumb is added to the bitumen at high temperatures, the particles at first start to swell as some of the light phase of the bitumen is absorbed by the rubber; this process increases the resilience of the binder. With time, the rubber changes into a gel, which results in an increase in viscosity, and finally an oil, which leads to increased durability of the binder (Lo Presti 2013, South African Bitumen Association 2009). The phases of the process are shown schematically in Figure 3.2.

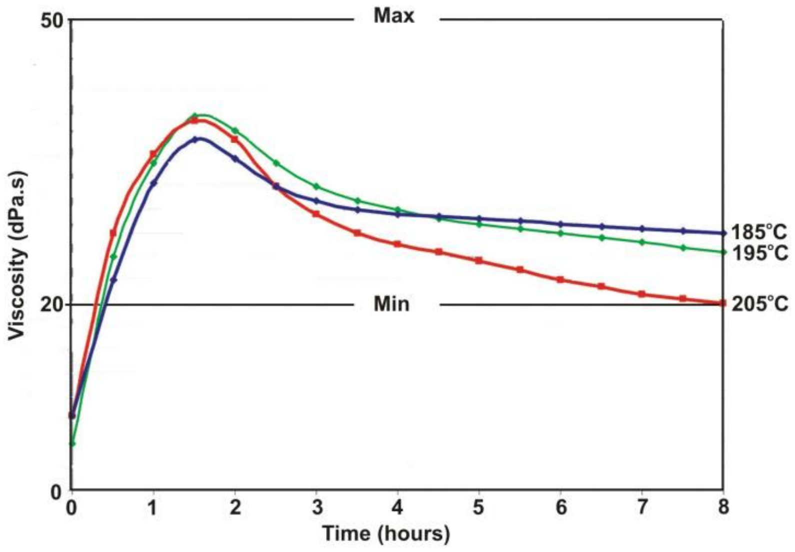
Figure 3.2: Digestion stages of crumb rubber in bitumen



Source: SABITA (South African Bitumen Association 2009).

Figure 3.3 shows the typical change of viscosity as a function of reaction time. The viscosity will initially increase steeply, then reach a maximum, after which it will start to decrease. The speed of digestion and steepness of the spike, and subsequent drop in viscosity, is dependent on time, temperature, and coarseness of the particles. Other factors include shear forces applied in blending, the grade of the base bitumen, use of extender oil, and the weight percentage of rubber added. The process implies that for high viscosity wet blends, the properties of the final product will depend on at what stage in the digestion process of the binder it is added to the asphalt, or sprayed as a seal. The partial digestion also means that, unless the binder is continuously agitated (stirred), phase separation may occur during transport or storage.

Figure 3.3: Typical change of viscosity as a function of reaction time at different temperatures



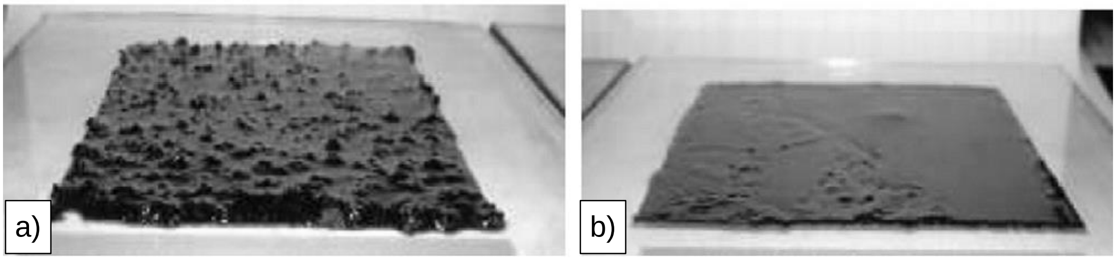
Source: SABITA (South African Bitumen Association 2009).

Outside of Australia, the high viscosity wet process is typically used in gap-graded or open-graded asphalt as well as chip seal applications (Hicks et al. 2013).

3.2.3 No Agitation Wet Process

The no agitation wet process takes its name from the fact that this is a storage-stable product that, in contrast to the high viscosity wet process, does not need to be agitated to keep the rubber particles dispersed. These products are often referred to as terminal blends as they are typically produced at a refinery or bitumen terminal. However, this term has become inaccurate as, internationally, these products are increasingly produced on site. Also, high viscosity blends are often produced at refineries or bitumen terminals, adding to confusion about the terminology. The no agitation wet process involves blending at high temperatures using high shear stresses and pressure. The crumb rubber is completely digested, resulting in a smooth and homogeneous final product. The contrasting appearance of high viscosity wet process binder and no agitation wet process binder are shown in Figure 3.4.

Figure 3.4: CRM binder produced using: a) high viscosity wet process; b) No agitation wet process



Source: Lo Presti (2013).

The performance of no agitation wet blended products is not as well-documented as for the wider applied high viscosity wet blends. The viscosity of the final CRM binder will be lower for the no agitation wet process than with the high viscosity wet process, which means that the optimum application rate in seals and asphalt will be reduced. Therefore, some of the performance benefits achieved with high viscosity wet blends will be reduced for the no agitation wet process. The no agitation wet process has a number of distinct benefits as well, including:

- No need for agitation during transport and construction.
- No need to either use or to reconstitute the product within a short time interval.
- Due to absence of rubber particles that expand and contract with temperature, it is more compatible with conventional dense-graded asphalt mix designs.
- Although the lower binder content leads to reduced durability compared to high viscosity products, lower binder content also leads to reduced initial costs.
- Reduces issues with fuming and odour at point-of-use.
- Asphalt mixing and seal spraying temperatures are reduced.

Outside of Australia, the no agitation wet process has been used in dense-graded, open-graded and gap-graded mixes, but is best for dense-graded mixes (Hicks et al. 2013).

4 BENEFITS OF CRUMB RUBBER MODIFICATION

Use of crumb rubber as a modifier and extender for bitumen is a high-value engineering utilisation of waste tyre rubber, which delivers environmental benefits. This was, however, not the driver for the development of CRM binder technology. The main driver was that digestion of crumb rubber in bitumen results in improved performance properties of the binder, such as an increase in viscosity (resistance to flow), elasticity and ductility. As such, CRM binder has performance characteristics that can compete with other forms of widely used and purposely manufactured polymer modifiers, such as styrene-butadiene-styrene (SBS).

4.1 Environmental Benefits

According to a recent Austroads (2014c) study, recycling and reuse of recycled aggregates have substantial environmental benefits. The magnitude of these gains is largely dependent on an efficient recycled aggregates collection and reuse supply chain. There are energy impacts at each life cycle stage of construction materials: from acquisition and manufacture through to disposal or recovery. Resource recovery in the form of recycling will usually require further resource use to recover and reprocess waste materials for reuse in some other (or the same) applications. Alternatively the recovered waste is disposed to a landfill.

Landfills impose a number of costs on the community, including:

- greenhouse gas (GHG) emissions arising from the burning and/or burial of waste, mainly carbon dioxide (CO_2) and methane (CH_4) gases, contributing to global warming and climate change
- air pollutants affecting health effects
- surface water and ground water impacts from leachate to soil and water and the discharge of waste
- site runoff to nearby receiving waters
- amenity effects of the disposal facility including visual, noise, odour and litter (Austroads 2014c).

Specific environmental benefits of incorporating crumb rubber into asphalt, in addition to the reduction of waste tyre stockpiles and landfill, are energy savings, reductions in CO_2 emissions, as well as road noise reduction.

Crumb rubber is subject to a range of health, safety and environmental requirements whereby the components being proposed should be fit-for-purpose, safe to use and appropriate to both the site and surrounding environment (Carswell 2004). These issues are considered further in the following section.

4.1.1 Rising Costs of Bitumen

Changes in oil supplies are likely to have significant consequences for the transportation industry, particularly road transport. Oil, like other fossil fuels, is a finite resource produced by natural processes. With a finite supply, there may come a time when production will peak in the face of continuing demand and rising supply costs. It is recognised that non-conventional fossil oil types are becoming more difficult to access and conventional oil reserves exist in remote locations, such as under deep oceans. As a result, there is a diminishing supply of low-cost oil at the global level (Austroads 2010a). This is directly connected to bitumen, whereby the annual usage of bitumen in Australia is approximately 800 000 metric tonnes (Asphalt Institute 2015).

The long term upward trend of oil prices has resulted in increases in the price of bitumen. This strongly suggests that the trend of increasing bitumen prices will continue into the future, at a rate primarily determined by the interplay of world oil prices and the value of the Australian dollar. Increased costs will require either increased maintenance funding, or cost-saving measures to maintain the same standard of road condition at current funding levels (Cosgrove et al. 2012).

If, as is expected, oil prices increase, and as oil becomes more limited, alternative materials to bitumen will in turn become more cost effective and necessary. Consequently, consideration of crumb rubber as a bitumen modifier or extender is an attractive option for government and industry because of the potential performance and sustainability benefits.

4.1.2 Energy Savings and Reduction of CO_2 Emissions

Studies by Sousa, Way and Carlson (2007 & 2009) found that the use of crumb rubber as a modifier for bitumen for road construction leads to significantly higher energy savings and reduction of CO_2 emissions, compared to alternative forms of tyre disposal. The study compared crumb rubber as a modifier for bitumen to shredding of tyres for use as tyre-derived fuel, and use of shredded tyres as alternate daily cover for landfills. It has also been postulated that compared to 'conventional' asphalt pavements, the use of CRM binder in asphalt can lead to significant reduction in CO_2 emissions and use of non-renewable resources due to a reduction in required layer thickness (White et al. 2010). It should be noted that such reductions are highly dependent on the pavement type, road agency specifications and design assumptions, and as such, may not be directly transferable from one jurisdiction to another.

4.1.3 Tyre Recycling

The Department of Environment (2014) notes that there is a large number of end-of-life tyres in Australia that are being disposed through landfill, stockpiles, exported as baled tyres or illegally dumped, and only a small proportion are being recycled. It is estimated that 48 million equivalent passenger unit (EPU) tyres reached their end-of-life in Australia in 2009 - 2010. Of these, approximately 66% were disposed either to landfill, stockpiled or illegally dumped or categorised as unknown, 16% were domestically recycled and 18% were exported.

As a result, there are costs to the community and governments through littering of landscapes and waterways, and using scarce landfill space. End-of-life tyres can be a source of health and environmental concerns; fires in stockpiles can release toxic gases; and tyre stockpiles provide breeding habitats for pests (Department of Environment 2014).

The growing number of tyre stockpiles is therefore a concern from an environmental perspective, and the utilisation of these stockpiles in CRM binders has advantages to alleviate this issue. Use of crumb rubber in CRM binders provides an attractive application for scrap tyres that may be otherwise placed in landfill.

In 2004, ARRB Group conducted a study for the Department of Environment and Heritage on the 'Economics of tyre recycling: final report' (Houghton et al. 2006). The purpose of the study was to investigate the economics of waste tyre recycling processes and their end uses and to provide advice on the financial viability of potential markets for waste tyres and the impact of a levy scheme on those markets.

4.1.4 Noise Reduction

Environmental benefits have been identified in the use of CRM binder for reducing noise emissions. It has been reported that when used in appropriate asphalt types, the use of this material improves night-time visibility and reduces traffic noise levels by upwards of 5 decibels (Carlson 2011).

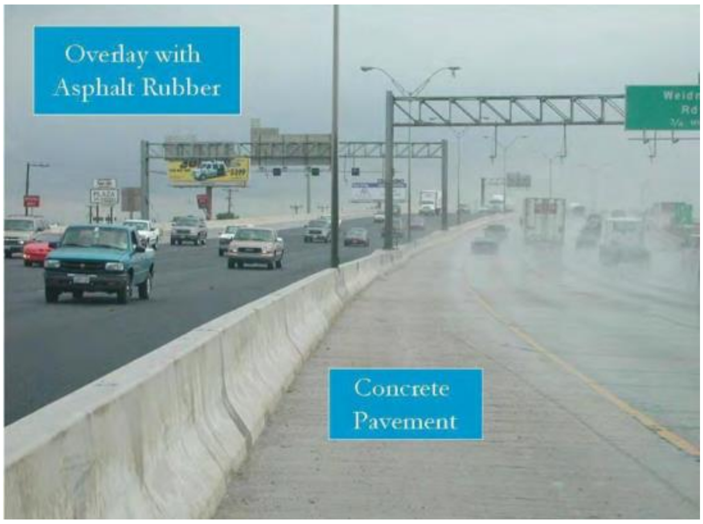
Notwithstanding these benefits, at the present time, the international scientific community is not unanimous in the positive effects of using CRM binder in asphalt in terms of road noise reduction.

According to Sandberg and Ejsmont (2002), there is no evidence that the insertion of small quantities of crumb rubber in binder within asphalt mixtures significantly reduces tyre and road noise.

CRM binder is widely applied in the manufacture of open-graded asphalt. Open-graded asphalt has well-documented safety and environmental advantages, including a reduction of splash and spray in wet weather conditions, and reduction of road noise. CRM binder's durability benefits in open-graded asphalt surfacing layers are explained in more detail in Section 4.3. CRM binder is widely used in thin porous friction courses (Way, Kaloush & Biligiri 2011) to improve the functional properties of concrete pavements. However, the use of open graded asphalt is typically limited to low shear applications (such as motorway/freeways) due to its poor resistance to traffic induced shear stresses.

Figure 4.1 shows the improvement in wet weather conditions on a concrete highway overlaid with a thin friction course. Studies in Arizona have shown a 5.7 decibel reduction in traffic noise after overlay of concrete roads with a layer of thin porous asphalt (Way, Kaloush & Biligiri 2011). Studies at the University of California have indicated that open-graded asphalt containing CRM binder outperforms open-graded mixes with 'conventional' binder, both in total noise reduction and longevity of the reduction (Jones 2014).

Figure 4.1: Thin porous asphalt used to reduce spray on a concrete freeway in Texas



Source: Rubber Pavements Association (Way, Kaloush & Biligiri 2011).

A recent project, developed by the University of Pisa in collaboration with the Environmental Protection Agency of Tuscany region, explores these issues further and evaluates the advantages, in terms of pavement sustainability, of using CRM binder in the construction of specifically designed low-noise gap-graded asphalt mixtures by using wet and dry processes. In order to assess their potential use as a viable solution to enhance environmental, social and economic sustainability of asphalt pavements, the study compares the mechanical and functional performances of the resulting mixes as evaluated by laboratory and in situ tests carried out in field trials (Losa, Leandri & Cerchiai 2012).

The results highlight the benefits in terms of tyre and road noise reduction, which can be obtained by using CRM binder in the production of low noise gap graded asphalt surfaces. It was found that there were reductions of about 5 dB (A) which could be obtained with CRM binder low noise porous asphalt surfaces when compared to 'conventional' dense graded asphalt (Losa, Leandri & Cerchiai 2012).

4.2 Performance Benefits of CRM binder in Sprayed Seals

In sealing, CRM binder can be applied at a higher spray rate than bitumen and polymer modified bitumen, without flushing (fattening-up of the road surface under traffic) occurring. The higher spray rate, in combination with the improved elastic, viscous and ductile properties of the binder, leads to benefits of CRM binder seals compared to seals with ‘conventional’ binder. These benefits include:

- Service life is significantly increased The higher spray rate and increased binder film thickness lead to later onset of oxidation cracking and stone loss. The carbon black component of the tyres working as an antioxidant is also believed to contribute to the superior longevity of CRM binder seals (Hoffmann & Potgieter 2007).
- Durability of skid resistance is improved. The higher viscosity of the CRM binder leads to reduced stone embedment, and as a result, the seal maintains its texture depth (Hoffmann & Potgieter 2007).
- There is superior resistance against reflective cracking (California Department of Transportation, 2003). CRM binder use originated from a desire to create a durable seal over cracks in asphalt roads. Its ability to arrest cracking is still one of the main reasons why CRM binder technology is used in sprayed seals. CRM binder seals are used as a maintenance action over cracked road surfaces. They are also used in specialised applications to insulate new pavement layers placed over existing pavements from cracks reflecting up from underlying layers. This application is known as a strain alleviating membrane interlayer (SAMI) (Austroads 2013).
- Improvement in waterproofing of the road surface (Hoffmann & Potgieter 2007). One of the main functions of a sprayed seal is to keep water out of the pavement. The high spray rate of a CRM binder seal leads to a durable waterproof surface, which protects the underlying material.

Similar benefits can also be achieved by modifying bitumen with other polymers (such styrene-butadiene-styrene (SBS) and polybutadiene (PBD)).

4.3 Performance Benefits of CRM binder in Asphalt

In asphalt, the use of CRM binder allows higher binder application rates in certain asphalt types without excessive drain down or bleeding due to the high viscosity of the binder (Lo Presti, 2013). The higher binder film thickness comes with considerable durability benefits (AGPT Part 4B). High binder film thicknesses retard oxidative aging, which is especially important in open grade (porous) asphalt mixes. In these mixes oxidation eventually leads to ravelling of the material, which is the main mode of failure for such asphalt.

The high binder film thickness, in combination with the improved elastic properties of CRM binder, results in much improved resistance to reflective and fatigue cracking (California Department of Transportation 2003). This was also verified in laboratory tests on Australian mixes (Austroads Pavements Research Group 1999). Accelerated pavement testing conducted by the University of California has shown that CRM binder asphalt placed at half the thickness of conventional asphalt outperforms the conventional asphalt in terms of resistance to reflective cracking (Jones, Harvey & Monismith 2007). This has led the California Department of Transportation to implement the rule that for overlays, conventional dense-graded asphalt may be substituted with CRM binder gap graded asphalt at one-half the intended dense-graded mix thickness (California Department of Transportation 2003). Note that this half- thickness rule is relevant to resistance to crack reflection only, it does not pertain to the asphalt design thickness required to protect underlying layers.

Long-term pavement performance monitoring in Arizona has shown that CRM binder asphalt outperformed conventional asphalt in terms of cracking, maintenance costs, ride quality, skid resistance and rutting (Way, Kaloush & Biligiri 2011). Other studies have found CRM binder asphalt to have rut resistance similar to conventional asphalt, although there are indications that CRM binder gap-graded asphalt may be more susceptible to rutting than conventional asphalt (Jones, Harvey & Monismith 2007).

In Australia, the reported benefits of using CRM binder in asphalt mixes are (Roads and Traffic Authority 1995):

- cost-effectiveness due to increased pavement life,
- increased shear resistance including resistance to permanent deformation (rutting and shoving)
- increased resistance to fatigue and reflective cracking
- the use of an otherwise waste material.

5 AUSTRALIAN TECHNICAL SPECIFICATIONS

This section provides an overview of the technical specifications for use of CRM binder in asphalt and seals published by various road jurisdictions in Australia. The current Queensland Department of Transport and Main Roads (TMR) specifications are presented first and these are then compared with the requirements in other Australian road jurisdictions.

5.1 Queensland Transport and Main Roads

TMR provides requirements on polymer modified binder properties including CRM binder in their technical specification MRTS18 *Polymer modified binder* (Transport and Main Roads 2011). The document includes three CRM binder classes for sprayed sealing applications (S1.8R, S15RF and S18RF). The specification provides requirements for the crumb rubber material and individual binder requirements for the three binder classes for seals, including minimum rubber contents. TMR does not currently have a CRM binder specification for asphalt. The crumb rubber requirements are shown in Table 5.1 and the requirements for the CRM binder for seals are shown in Table 5.2.

5.2 Crumb Rubber Requirements

This section compares the requirements for the crumb rubber material used in CRM binder for seals or asphalt.

A review of Australian state road jurisdiction specifications identified specifications for crumb rubber material that are currently in use (refer Table 5.1). The Northern Territory (Department of Infrastructure) does not specify requirements for the crumb rubber, but they have a specification for CRM binder (Department of Infrastructure 2014).

Table 5.1: Australian crumb rubber properties

Property	TMR (for sealing)	Austroads Size 16 (for sealing)	Austroads Size 30 (for sealing or asphalt)	RMS Size 16 (for sealing)	RMS Size 30 (for asphalt)	DPTI (for sealing)	VicRoads (for asphalt)	MRWA (for sealing)
Grading (%)								
passing 2.36 mm		100		100				
passing 1.18 mm	100	80-100	100	80-100	100	100	100	100
passing 600 µm	70-100	0-10	60-100	0-10	60-100	70-100	80-100	60-100
passing 300 µm	-	-	0-20	-	0-20	-	-	0-20
passing 150 µm	0-5	-	-	-	-	0-5	0-20	-
passing 75 µm	-	-	-	-	-	-	-	0.2
Particle length (mm) max.	3	3	3	7.5(1)	-	3	3	3
Bulk density (kg/m^3)	350 max	Report	Report	Report	Report	350 max	350 max	350 max
Water content (%) max.	1	1	1	1	1	1		1
Foreign materials – other than iron/steel (%) max.	0	0.1	0.1	-	-	0	-	0
Foreign materials – metallic iron/steel (%) max.	0.1	0.1	0.1	0	-	0	-	0.1

Property	TMR (for sealing)	Austroads Size 16 (for sealing)	Austroads Size 30 (for sealing or asphalt)	RMS Size 16 (for sealing)	RMS Size 30 (for asphalt)	DPTI (for sealing)	VicRoads (for asphalt)	MRWA (for sealing)
Elongated particles (%) max.	-	-	-	-	-	-	-	20

1 10th percentile of length of particles retained on 0.6 mm.
2 Source: Transport and Main Roads (2011), Austroads (2014b), Roads and Maritime Services (2011), Department of Planning, Transport and Infrastructure (2011), VicRoads (2005), Main Roads Western Australia (2014).

5.3 CRM Binder Requirements for Seals

This section compares the CRM binder requirements for seals. CRM binder requirements are typically included in the PMB specifications of state road agencies in Australia.

A review of the CRM binder requirements in Australian state road jurisdictions specifications indicated they are the same or similar to the Austroads specification. All agencies had similar requirements for the S45R terminal (no agitation wet process) CRM binder. TMR, RMS, DPTI and VicRoads were the only agencies specifically referencing field blended (high viscosity wet process) CRM binders, with these binders being based on the Austroads S15RF and S18RF requirements. MRWA specifies the S45R requirements for their terminal blend requirements although contractors have the option of field blending the binder. A summary of CRM binder requirements nominated in Australian state road jurisdiction specifications is provided in Table 5.2 and indicates essentially similar requirements are specified by each road jurisdiction, with TMR specifying several additional tests for field-produced CRM binders when compared to the other road agencies.

Table 5.2: Australian CRM binder properties for seal applications

Property	TMR			Austroads, RMS, DPTI & MRWA				DI	
	Terminal	Field produced		Terminal	Field produced			Terminal	
	S1.8R	S15RF	S18RF	S45R (Austroads, RMS, DIER, DPTI, MRWA, & VicRoads)	S15RF (Austroads, RMS, DPTI & VicRoads)	S18RF (Austroads, DPTI & VicRoads)	S20RF (RMS)	S45R	S55R
Consistency at 60°C (Pa.s) min.	1000	1000	4000	1000	Report	Report	Report	1800	4000
Underlying viscosity at 60 °C	Report	Report	Report	–	–	–	–	–	–
Elastic Modulus at 60°C	Report	Report	Report	–	–	–	–	–	–
Consistency 6% at 60 °C	–	–	–	Report	–	–	–	–	–
Stiffness at 15°C (kPa) max.	180	180	140	180	–	–	–	180	140
Nominal rubber Content (%)	–	–	–	–	15	18	20	-	-
Rubber content (%) min.	10	13	16	10	13	16	16	Report	Report
Compression limit at 70 °C, 2 kg (mm) min.	0.2	0.2	0.2	0.2	–	–	–	0.2	0.2

Property	TMR			Austroads, RMS, DPTI & MRWA				DI	
	Terminal	Field produced		Terminal	Field produced			Terminal	
	S1.8R	S15RF	S18RF	S45R (Austroads, RMS, DIER, DPTI, MRWA, & VicRoads)	S15RF (Austroads, RMS, DPTI & VicRoads)	S18RF (Austroads, DPTI & VicRoads)	S20RF (RMS)	S45R	S55R
Elastic recovery at 60 °C and 100 s (%) min.	25	25	35	25	–	–	–	25	35
Viscosity at 165 °C (Pa.s) max.	4.5	4.5	4.5	4.5	–	–	–	4.5	4.5
Flash Point (°C) min.	250	250	250	250	–	–	–	250	250
Loss on heating (%) max.	0.6	0.6	0.6	0.6	–	–	–	0.6	0.6
Torsional recovery at 25 °C and 30 s (%) min–max.	25-55	25-55	30-60	25-55	25 min.	30 min.	30 min,	25 min.	30 min.
Softening point (°C) min–max.	55-65	55-65	62-80	55-65	55 min.	62 min,	62 min,	55 min.	62 min.
Segregation (%) max.	8	8	8	8	–	–	–	–	–
Ease of remixing (%)	2[1]	2[1]	2[1]	–	–	–	–	–	–
Elastic recovery at 60 °C and 100 s (%) min.	–	–	–	–	–	–	–	30	50
Toughness at 4 °C, 100 mm (Nm) min.	–	–	–	–	–	–	–	Report	Report
Nearest Austroads equivalent class	S45R	S15RF	S18RF	–	–	–	–		

Source: Transport and Main Roads (2011a), Austroads (2014b), Roads and Maritime Services (2011), Department of Planning, Transport and Infrastructure (2011), VicRoads (2013a), Main Roads Western Australia (2014), Department of Infrastructure (2014).

[1] Ease of remixing limit applies when the segregation limit is exceeded.

VicRoads and DPTI are probably the two jurisdictions in Australia where CRM binders are more commonly used for sprayed sealing applications.

VicRoads standards document '*Section 408 – Sprayed bituminous surfacings'* (VicRoads 2013a) is performance based which requires certain performance properties (e.g. surface texture depth) to be complied with during the defect liability period. It provides guidelines to select binders that provide equivalent performance. The document is similar to the Austroads guide to the selection and use of PMBs and multigrade bitumens (Austroads 2013) with some deviations. The VicRoads document provides a list of the binder types that are acceptable for the agency-specified treatment. The contractor is typically allowed the flexibility to select a field produced CRM binder, a terminal CRM binder or non-CRM PMB. In addition, all seal treatments are typically designed by the Contractor on VicRoads projects. This differs from TMR practice where the Principal (i.e. TMR) often designs the seal treatment. VicRoads also tends to have longer defect liability periods so that the Contractor accepts more responsibility for the seal.

The choice of binders listed in the VicRoads standards document (VicRoads 2013a) is slightly different than the Austroads guide (Austroads 2013) where the binders are suggested according to the service conditions (e.g. site severity and traffic loading). A comparison of the suggested binder type applications as suggested by the Austroads guide and VicRoads standards documents is summarised in Table 5.3. The comparison indicates that the VicRoads selection criteria are more stringent than Austroads.

Table 5.3: Comparison between Austroads Guide (Austroads 2013) and VicRoads (2013a) standard documents to the selection of binders for sprayed sealing applications

Application	Jurisdiction	Binder class								
		M500/ 170	S10E	S15E	S20E	S25E	S35E	S45R/ S15RF	S18RF	Other
HSS	Austroads	✓	✓	✓	✓		✓	✓		-
	VicRoads		✓				✓			5 parts crumb rubber/alternative as approved by the superintendent
XSS	Austroads			✓	✓			✓		-
	VicRoads				✓			✓		-
SAM	Austroads		✓	✓	✓		✓	✓	✓	-
	VicRoads				✓			✓		-
SAMI	Austroads					✓			✓	-
	VicRoads					✓			✓	-

Source: Austroads (2013), VicRoads (2013a).

There are no specific guidelines in the DPTI documents on the selection of type of binders and treatment. DPTI specifies the binder type in their contracts. DPTI stated the following typical uses for rubber tyre based on a discussion (personal communication with Mark Moreland, DPTI, 18 February 2015):

- DPTI S15RF has higher tendency to be used in reducing stripping and flushing. Two of the three key contractors are geared to manufacture field produced S15RF. There is limited response from industry in South Australia to make plant produced S45R and, as a result, DPTI has limited experience on the use and performance of S45R.
- DPTI also stated that the S15E binder may not be providing equivalent performance to the S15RF and S45R binders.

5.4 CRM Binder Requirements for Asphalt

This section compares the CRM binder requirements for asphalt, based on wet (Section 5.4.1) and dry (Section 5.4.2) processes.

5.4.1 Wet Processes

Crumb rubber can be incorporated into asphalt through direct modification of the binder using either the high viscosity wet process or no agitation wet process. A review of Australian specifications found no specifications for CRM binder for asphalt using the wet process. Where the use of CRM binder is allowed in asphalt in Australian road jurisdictions, the dry process is specified.

5.4.2 Dry Process

Crumb rubber can be incorporated into asphalt through the dry process, where crumb rubber is added to the aggregate. In the dry process, the crumb rubber partially modifies the binder and the partially modified binder properties cannot be easily measured. As a result, there are requirements for incorporating the crumb rubber into the asphalt although the partially modified binder properties are not evaluated. Austroads (2014b) provides a binder class known as A27RF for addition of crumb rubber for asphalt mix using the dry process. The specification requires a nominal rubber concentration of between 25-30% and notes that ‘dry mix’ asphalt is normally based on an asphalt mix design with, typically, 25% crumb rubber in the total binder. The finer grade rubber (i.e. size 30) is normally used for the ‘dry mix’ asphalt system (Austroads 2014a).

RMS provides requirements for their dry-processed asphalt mix properties in the QA specification R118 (Roads and Maritime Services 2013). The class of binder used in the work must be as specified in Annexure A of R118 (Roads and Maritime Services 2013), and unless otherwise specified, the binder must be Class 450 (AS 2008:2013). An exception being that, an alternative class of binder may be proposed, subject to the approval of the Principal, for asphalt containing warm mix asphalt (WMA) additive. The minimum crumb rubber content is 2.0% by mass of the total mix, which based on a required binder content of 7.3-8.3% by mass of the total mix, equates to 24-27% crumb rubber in the total binder. Either a 14 mm or 10 mm mix size can be used.

VicRoads provides requirements on their dry-processed crumb rubber asphalt mix properties (including component material properties) in Section 421 (VicRoads 2005). The minimum crumb rubber content is 2.5-3.0% by mass of the total mix, which based on a required binder content of 7.5-9.0% by mass of the total mix, equates to 28-40% crumb rubber in the total binder. A size 14 and size 10 mix size can be used.

6 SELECTED INTERNATIONAL SPECIFICATIONS

Internationally, the use of CRM binder in road construction is growing. This section describes CRM binder related specifications in selected international road/transport jurisdictions with a long track record of CRM binder use.

6.1 United States of America

Specifications from several lead road jurisdictions in the United States of America were reviewed, including the American Society for Testing and Materials (ASTM) and the Departments of Transport in Arizona, California and Texas.

6.1.1 American Society for Testing and Materials

ASTM D6114 specifies properties for crumb rubber and CRM binder (ASTM D6114/D6114M-09: 2009). ASTM requirements differ from those of other agencies in that it does not specify gradation requirements other than recommending that no crumb rubber particles should be retained on the 2.36 mm (#8) sieve. ASTM states that the crumb rubber gradation should be agreed upon between purchasers and CRM binder suppliers for the specific mix applications. ASTM crumb rubber requirements are similar for seal and asphalt applications, with the only difference being a maximum fibre content of 0.1% for sprayed seal and 0.5% for hot mix asphalt applications. ASTM requirements are provided in Table 6.3 for seals and Table 6.4 for asphalt. The CRM binder requirements are provided in Table 6.6.

The CRM binder needs to be an interacted blend of paving grade bituminous binder and crumb rubber (manufactured using the wet process). Other additives and other types of crumb rubbers not cited in ASTM D6114 are permitted. It is noted in ASTM D6114 that at least 15% rubber by weight of the total binder blend is usually necessary to provide acceptable properties of CRM binder.

6.1.2 Arizona Department of Transportation

The Arizona Department of Transportation (ADOT) Section 1009 provides requirements for crumb rubber and CRM binder properties (ADOT 2008). ADOT specifies a Type A gradation for chip seal applications (i.e. stress-absorbing membrane) and a Type B gradation for asphalt. ADOT requires the CRM binder to contain a minimum of 20% rubber by the weight of bituminous binder. CRM binder properties and handling/temperature requirements are also specified. The ADOT crumb rubber requirements are provided in Table 6.3 for seals and Table 6.4 for asphalt. The CRM binder requirements are provided in Table 6.6.

Arizona uses two CRM binder asphalt mixes, i.e. a gap-graded mix (Arizona Department of Transportation n.d.) and an open-graded friction course (Arizona Department of Transportation 2005).

6.1.3 California Department of Transportation

The California Department of Transportation (Caltrans) has CRM binder specifications for sprayed seals, gap-graded asphalt and open-graded asphalt (California Department of Transportation 2010). The use of high viscosity (field blend) CRM binder is not recommended in dense-graded mixtures because there is insufficient void space to accommodate enough of the high viscosity rubber modified binder to significantly improve performance of the resulting pavement (California Department of Transportation 2006). Caltrans has two crumb rubber gradations, one for scrap tyre crumb rubber and one for high natural crumb binder. Caltrans is the only agency to specify high natural crumb rubber, which they define as a scrap rubber product that includes 40-48% high natural rubber. Sources of high natural rubber include tyre rubber from some types of heavy truck tyres as well as tennis balls and mat rubber (Hicks et al. 2013). A blend of the two crumb rubber materials (75% scrap tyre crumb rubber and 25% high natural crumb rubber) are used with sprayed seal, gap-graded and open-graded applications. In addition to the typical crumb rubber properties provided in Table 6.3 for seals and Table 6.4 for asphalt, Caltrans also provides crumb rubber component requirements, the addition of an asphalt modifier of between 2-6% and requirements for the asphalt modifier. These additional requirements are provided in Table 6.1 and Table 6.2 below.

Table 6.1: Caltrans component requirements on crumb rubber

Test parameter	Scrap tyre CRM		High natural CRM	
	Min.	Max.	Min.	Max.
Acetone extract (%)	6.0	16.0	4.0	16.0
Rubber hydrocarbon (%)	42.0	65.0	50	-
Natural rubber content (%)	22.0	39.0	40.0	48.0
Carbon black content (%)	28.0	38.0	-	-
Ash content (%)	-	8.0	-	-

Source: California Department of Transportation 2010.

Table 6.2: Caltrans asphalt modifier requirements

Test parameter	ASTM designation	Requirement
Viscosity, m^2/s (10-6) at 100 °C	D 445	X ± 3 *
Flash Point, °C	D 92	207 min.
Molecular analysis		
Asphaltenes, percent by mass	D 2007	0.1 max.
Aromatics, percent by mass	D 2007	55 min.

* The symbol "X" is the viscosity of the asphalt modifier the contractor proposes to provide. The value "X" which the contractor proposes shall be between the limits 19 and 36 and shall be submitted in writing to the engineer. Any proposed change, requested by the contractor, in the value "X" shall require a new asphalt-rubber binder design.

Source: California Department of Transportation (2010).

6.1.4 Texas Department of Transportation

The Texas Department of Transportation (Texas DOT) uses CRM binder in sprayed seals, stone mastic asphalt, open graded asphalt (porous) and thin bonded friction courses (Texas Department of Transportation 2014). Texas DOT has some crumb rubber requirements including referencing ASTM D6114, three crumb rubber grades (gradations) and requiring a minimum of 15% crumb rubber by weight. ASTM Type I and II CRM binder containing crumb rubber of Grade C are used in asphalt. ASTM Type II and III containing crumb rubber of Grade B are used in sprayed seals. Grade A and B crumb rubber are used for crack sealant material. Suppliers can request approval for alternative crumb rubber gradations.

These Texas DOT requirements are identical to those of ASTM D6114 except that the tests are mostly conducted according to Texas DOT methods. For use in asphalt mix applications, Type I or II binders containing crumb rubber Grade C are to be used. Type II or III binders containing crumb rubber Grade B are to be used for surface treatment (also known as sprayed seal) applications. Grades A and B crumb rubber are used for crack sealant material. Suppliers can request approval for alternative crumb rubber gradations.

6.2 South Africa

The Asphalt Academy in South Africa published a technical guide in 2007 which provides comprehensive information on the use of crumb rubber binders for road construction (Asphalt

Academy 2007). Further information on the design of asphalt mixes including CRM binder is contained in SABITA Manual 19 (South African Bitumen Association 2009). Specifications for the crumb rubber and CRM binder are provided in TG1 (South African Bitumen Association 2007). The high viscosity wet process is used to manufacture CRM binders for sprayed seals. Both the wet and dry processes can be used for hot mix asphalt production with CRM binder but the wet process is a more common method. The crumb rubber used in South Africa contains a minimum of 30% carbon black, which has been shown to add reinforcing properties and antioxidants to bitumen to increase the durability of the CRM binder seals.

The Asphalt Academy technical guide (2007) advises that crumb rubber should be added to asphalt binder that contains a quantity of heavy extender oil. Following the addition of the crumb rubber, a digestion period is required for the crumb rubber to swell and partially dissolve in the bitumen/extender oil blend. The guide also advises that CRM binders degrade rapidly at application temperatures which are in excess of 200°C. Therefore the blending of crumb rubber and bitumen generally takes place in close proximity to the spray site or asphalt mixing plant. On completion of the digestion period, the product generally has a further useable life at the application temperature of approximately four hours. Typical maximum temperature and time limits for short- term handling, storage and asphalt mixing/application are also provided in the guide. The requirements for crumb rubber are provided in Table 6.3 for seals and Table 6.4 for asphalt. The CRM binder requirements are provided in Table 6.6.

6.3 Summary of Crumb Rubber Specifications

A comparison of the selected international road/transport jurisdictions is provided in Table 6.3 for sprayed seal applications and Table 6.4 for asphalt applications.

TMR does not currently have crumb rubber or CRM binder requirements for asphalt. The main differences in properties are the crumb rubber gradations. TMR's crumb rubber gradation for sprayed seals is the finest gradation of all the agencies (not considering ASTM, which does not have a gradation). Some agencies do not specify actual water content or foreign material maximum but have clauses relating to the crumb rubber being non-foaming when added to hot binder, free flowing and free of contaminants. ADOT and Texas TDOT both provide finer gradations for crumb rubber used in CRM binder asphalt applications. RMS also has a finer gradation for crumb rubber used in CRM binder asphalt applications. It should also be noted that ADOT and ASTM require the crumb rubber used for seal applications to have a lower fabric content than for asphalt applications. TMR and several other Australian agencies specify a crumb rubber density in terms of bulk density rather than specifying maximum density (or specific gravity) as other jurisdictions do.

Table 6.3: International crumb rubber properties for seals

Property	TMR (1)	South Africa	ASTM D6114	ADOT	CalTrans		Texas DOT
				Type A	Scrap tyre crumb rubber	High natural crumb rubber	Grade B
Grading (%)							
passing 2.36 mm		100	100	100	100		
passing 2.00 mm		-	-	95-100	98-100	100	100
passing 1.18 mm	100	-	-	0-10	45-75	95-100	70-100
passing 600 µm	70-100	40-70	-	-	2-20	35-85	25-60
passing 300 µm	-	-	-	-	0-6	10-30	-
passing 150 µm	0-5	-	-	-	0-2	0-4	-
passing 75 µm	-	0-5	-	-	0	0-1	0-5

Property	TMR [(1)]	South Africa	ASTM D6114	ADOT	CalTrans		Texas DOT
				Type A	Scrap tyre crumb rubber	High natural crumb rubber	Grade B
Particle length (mm) max.	3	6	-	-	4.75	4.75	-
Bulk density (kg/m^3)	350 max						
Maximum density (kg/m^3)		1100-1250	1100-1200	1100-1200	1100-1200	1100-1200	ASTM
Water content (%) max.	1	-	0.75	-	-	-	ASTM
Foreign materials – other than iron/steel (%) max.	0	-	0.25 [(2)] 0.1 (fibres)	0.1	0.05	0.05	0
Foreign materials – metallic iron/steel (%) max.	0.1	-	0.01	0	0.01	0.01	0
Mineral Powder (%) max.	-	-	4	4	3	3	ASTM
Polyisoprene content (total hydrocarbon) (%) min.	-	25	-	-	-	-	-

1 TMR crumb rubber requirements are for sealing applications and provided as comparison only.
2 ASTM requirement is 0.25 % foreign materials (e.g. glass/sand) and 0.1% fibres for seals (0.5% fibres for asphalt).

Source: Arizona Department of Transportation (2008), Asphalt Academy (2007), ASTM D6114/D6114M-09: 2009, California Department of Transportation (2010), Texas Department of Transportation (2014), Transport and Main Roads (2011).

Table 6.4: International crumb rubber properties for asphalt

Property	South Africa	ASTM D6114	ADOT	CalTrans		Texas DOT
			Type B	Scrap tyre crumb rubber	High natural crumb rubber	Grade C
Grading (%)						
passing 2.36 mm	100	100		100		
passing 2.00 mm	-	-	100	98-100	100	
passing 1.18 mm	-	-	65-100	45-75	95-100	100
passing 600 µm	40-70	-	20-100	2-20	35-85	90-100
passing 420 µm	-	-	-	-	-	45-100
passing 300 µm	-	-	0-45	0-6	10-30	-
passing 150 µm	-	-	-	0-2	0-4	-
passing 75 µm	0-5	-	0-5	0	0-1	-
Particle length (mm) max.	6	-	-	4.75	4.75	-
Bulk density (kg/m^3)	1100-1250	1100-1200	1100-1200	1100-1200	1100-1200	1100-1200
Water content (%) max.	-	0.75	-	-	-	0.75
Foreign materials – other than iron/steel (%) max.	-	0.25[2] 0.5 (fibres)	0.5	0.05	0.05	0
Foreign materials – metallic iron/steel (%) max.	-	0.01	0	0.01	0.01	0
Mineral powder (%) max	-	4	4	3	3	4
Polyisoprene content (total hydrocarbon) (%) min.	25	-	-	-	-	-

1 ASTM requirement is 0.25 % foreign materials (e.g. glass/sand) and 0.5% fibres for asphalt (0.1% fibres for seals).

Source: Arizona Department of Transportation (2008), Asphalt Academy (2007), ASTM D6114/D6114M-09: 2009, California Department of Transportation (2010), Texas Department of Transportation (2014).

6.4 Comparison of CRM Binder Specifications

Typical crumb rubber contents for the CRM binder blends used in sprayed sealing are summarised in Table 6.5, along with cutter oil requirements. The comparison shows that similar crumb rubber contents and cutter oil portions are used by the various road jurisdictions.

Table 6.5: Rubber content of CRM binders used in sprayed sealing applications

Jurisdiction	Grade	Nominal rubber content (% w/w)	Additional component	Note	Reference
Austroads	S15RF	15	Not stated	-	AGPT/T190 (Austroads 2014b)
	S18RF	18			
TMR	S15RF	15	Varies depending on pavement temperature	-	TMR MRTS11 (Transport and Main Roads 2010)
	S18RF	18			
VicRoads	S15RF	15 min.	Extender oil (4 parts max. by volume)	Can be used for Extreme Stress Seal (XSS) or Strain Alleviating Membrane (SAM) treatments	VicRoads Section 408 (VicRoads 2013a)
	S18RF	18 min.	Extender oil (4 parts max. by volume)	Can be used for Strain Alleviating Membrane Interlayer (SAMI) treatments	
South Africa	S-R1	18-24% (1)	Extender oil (0-4%)	-	Asphalt Academy (2007)
California	-	$20 \pm 2\%$	Extender oil (2.5-6.0%)	Used for asphalt-rubber (2) seal coats.	Caltrans 5B specification (California Department of Transportation 2010)
Arizona	-	$20 \pm 3\%$	Not stated	Used for asphalt-rubber(2) surface treatments	ADOT Section 418 (Arizona Department of Transportation 2008)

Notes:
1 Asphalt Academy (2007) states a typical range of rubber contents in Table 2 of the document. It is however understood that this range includes asphalt mix applications.
2 Asphalt means bituminous binder in USA.

A comparison of selected international CRM binder properties is provided in Table 6.6 for sprayed seal and asphalt applications. It is difficult to compare TMR CRM binder requirements for seals to the other CRM binder requirements from international jurisdictions as most of the TMR requirements differ from the other jurisdictions and some agency requirements are only for asphalt purposes. The three common properties were viscosity at high temperature (although the temperatures vary from 165°C – 190°C), softening point and flash point. It is worth noting that TMR specifies elastic recovery, which is similar to resilience. CalRecycle reports that resilience is a more reliable measure of elasticity making it as one of the most important specification properties (CalRecycle 2010). The comparison of road jurisdiction specifications also indicates that international jurisdictions and other Australian road jurisdictions have fewer test requirements than TMR.

Table 6.6: International CRM binder properties

Test Method	South Africa		ASTM and Texas DOT			ADOT			CalTrans
	A-R1 (asphalt)	S-R1 (seal)	Type I	Type II	Type III	Type I	Type II	Type III	
Base asphalt grade	–	–	–	–	–	PG 64-16	PG 58-22	PG 52-28	–
Viscosity at 175 °C (Pa.s)	–	–	1.5–5.0	1.5–5.0	1.5–5.0	1.5-4.0	1.5-4.0	1.5-4.0	–
Viscosity at 190 °C (Pa.s)	2.0 – 5.0	2.0 - 5.0	–	–	–	–	–	–	1.5-3.0 (seal) 1.5-4.0 (asphalt)
Penetration at 25°C (dmm)	–	–	25–75	25–75	50–100	–	–	–	–
Penetration at 4 °C (dmm) min.	–	–	10	15	25	10	15	25	–
Softening point (°C)	55-65	55-62	57 min.	54 min.	52 min.	57 min.	54 min.	52 min.	52-74
Resilience at 25 °C (%) min.	13-40	13-35	25.	20	10	30	25	15	18
Flashpoint (°C) min	–	–	232	232	232	–	–	–	–
Thin-film oven residue Penetration retention at 4 °C (%) min.	–	–	75	75	75	–	–	–	–
Flow (mm)	10-50	15-70	–	–	–	–	–	–	–
Compression recovery - 5 minutes (%) min.	80	70	–	–	–	–	–	–	–
Compression recovery – 1 hour (%) min.	70	70	–	–	–	–	–	–	–
Cone penetration at 25 °C (mm)	–	–	–	–	–	–	–	–	2.5-7.0

Source: Arizona Department of Transportation (2008), Asphalt Academy (2007), ASTM D6114/D6114M-09:2009, California Department of Transportation (2010), Texas Department of Transportation (2014).

For high viscosity wet process CRM binders, blending time is a major factor affecting the CRM binder properties (as reported in Section 3.2.2). The field blend viscosity, normally measured by a Haake viscometer, increases at the beginning of the blending process, reaches a peak value, and then starts to drop or remain constant with longer blending times. This trend, however, was not observed during the preliminary experiment reported in Section 9.4. The CRM binders with varying blending time (up to 4 hours) did not show marked changes in their rheological properties, and this appeared to support the statement in Section 3.2.2 that property changes during the blending process could be affected by many factors (e.g. properties may not noticeably change under certain conditions). Established industry best practice is to develop a profile of the bitumen-rubber interaction over a period of 24 hours by measuring the physical properties of the CRM binder sampled at specific time intervals. This procedure is called CRM binder design profile and is required by CalTrans and Texas DOT. This profile indicates the compatibility of the components and the quality and stability of the resulting CRM binder properties over time.

7 POTENTIAL FOR INCREASED USE OF RECYCLED TYRE RUBBER

Polymer modification of bitumen for use in sprayed seals and asphalt offers the potential for high-value application of recycled tyre rubber. In 2009 it was reported that only 2% of all PMB used for sprayed seals in Queensland contained CRM binder (SAMI Bitumen Technologies 2009), and as far as could be ascertained, no CRM binder was used for asphalt in the state.

It is worth investigating how much of the available recycled tyre rubber could potentially be put to beneficial use as CRM binder in sprayed seals and asphalt in Queensland and across Australia. To this end, as part of this study, the hypothetical potential use of CRM binder in asphalt and seals on the TMR road network was estimated based on recent information. Table 7.1 shows the annual improvements in lane kilometres to the TMR road network from 2004/2005 to 2011/2012. Eighty seven percent of the sealed TMR road network consists of sprayed seal roads and 10.5% of it consists of pavements with asphalt.

The figures for potential use are indicative only and based on limited information. They are also based on a number of assumptions which should be noted.

Table 7.1: TMR annual road system improvements expressed in lane kilometres (2004/2005 to 2011/2012)

Road System Improvements	2004 - 2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	Average
New Routes/ deviations (lane km)	60	24	48	107	192	60	57	119	83
Upgraded to bitumen seal (lane km)	167	202	213	211	294	74	169	128	182
Roads widened /realigned (lane km)	718	761	803	1077	677	909	859	389	774
Roads rehabilitated (lane km)	439	209	300	561	386	385	101	846	403
Roads resealed (lane km)	4033	3788	2970	2981	2790	4426	4370	3326	3586
Total									5029

Source: Transport and Main Roads (2013).

7.1 Potential use of Crumb Rubber Modified Binder in Sprayed Seals on the TMR Network

To estimate the potential use of CRM binder in sprayed seals, it was assumed that all of the average annual sprayed sealing work would be performed with CRM binder. Based on the proportion of the road network that has sprayed seals and the figures for the average annual work from Table 7.1, it was estimated that 3,770 lane kilometres of sprayed seals (75% of the total lane kilometres of annual road improvements) were placed over the 2004/2005 to 2011/2012 period.

To calculate the number of tyres (expressed in EPUs) that would be used per kilometre of sprayed seal, the following assumptions were made:

- EPUs consist of 70% rubber, which amounts to 5.6 kg of crumb rubber per EPU.
- Two-thirds of the road network carries less than 500 vehicles per day, while the rest carries more. Binder application rates were adjusted accordingly.

- The binder complies with the criteria for S15RF (CRM) binder, in accordance with the current TMR specification (MRTS18) for sprayed bituminous surfacing, and contains 15% crumb rubber by mass.

Based on these assumptions, it was estimated that the maximum potential for annual use of crumb rubber in sprayed seals on the TMR network could amount to approximately 550,000 EPUs, or 3,100 tonnes of crumb rubber per year, with an average of 146 EPUs used per lane kilometre. This scenario implies that 7% of all end-of life EPUs in Queensland could be recycled into sprayed seals each year.

7.2 Potential Use of Crumb Rubber Modified Binder in Asphalt on the TMR Network

CRM binder asphalt is most often applied in surfacing layers, typically in an open-graded or gap-graded mix. To estimate the potential use of CRM binder asphalt on the TMR network, it was therefore assumed that CRM binder asphalt could be used as a 40 mm wearing course only. Based on the information in Table 7.1 and the composition of the TMR road network, it was estimated that 455 lane kilometres of asphalt surfacing are paved annually. It was further assumed that 80% of the surfacing would be constructed using a CRM binder asphalt mix produced using the dry process, with 2.5% rubber by mass of total mix. Finally, it was assumed that the remaining 20% of the asphalt surfacing would consist of CRM binder open graded asphalt with 1.3% rubber by mass of total mix. This would require 3,300 tonnes of crumb rubber annually, which equates to 588,000 EPUs, or 1300 EPUs per lane kilometre. This again represents about 7% of the annual end of life EPUs in Queensland.

7.3 Estimate of Total Potential Use of Crumb Rubber Modified Binder on All Queensland Roads

According to the rough estimates in the previous sections, the potential for the use of crumb rubber from end-of-life tyres on the TMR road network could annually amount to 1.1 million EPUs. This is 14% of the total number of end-of-life EPUs produced by Queensland every year. It needs to be noted, however, that at this stage, there is only a single tyre recycling plant in Queensland and the total tonnage of crumb rubber used in this example would account for approximately 75% of the production of that facility.

TMR is not the only road jurisdiction in Queensland. The majority of the roads in Queensland are managed by local governments. According to statistics from the Bureau of Resources and Energy Economics (Bureau of Energy Resources and Energy Economics 2014), approximately 300,000 tonnes of bitumen is sold in Queensland annually and roughly half this bitumen is used in sprayed sealing (with the other half used in asphalt). If all local governments choose to use CRM binder, it would theoretically be possible to increase the use of CRM considerably. Adding 15% crumb rubber to all bitumen used for sprayed sealing would amount to approximately 20,000 tonnes of crumb rubber, equating to 3.6 million EPUs.

7.4 Probable Impact of Use of Crumb Rubber Modified Binder on the Tyre Stockpile

From the discussion in the sections above it is clear that increasing the use of CRM binder in sprayed seals and asphalt in Queensland will not by itself resolve the issue of the end-of-life tyre stockpiles in Queensland. Even in very optimistic scenarios, only a modest percentage of tyres will be beneficially recycled into road surfacings. Promotion of the wider use of CRM binder should therefore be seen as part of a larger strategy to recycle tyres in various applications.

8 OVERCOMING (PERCEIVED) BARRIERS TO WIDER USE

CRM binder technology was introduced to Australia decades ago. From a technical perspective, the performance benefits of this binder over conventional binders were discussed in previous sections. Therefore, the question can be asked why CRM binder is not used on a larger scale in sprayed seals and asphalt. It appears that the main barriers to increased use of CRM binder are related to socio-economic rather than technological factors. Technical specifications for the use of CRM binder in asphalt and sprayed seals are already available, but could be updated based on the current international practice. Key issues that need to be overcome include concerns regarding environmental impact, occupational health and safety, and costs.

8.1 Costs

There are costs involved with processing end-of-life tyres into graded crumb rubber suitable for the production of CRM binder. The impact of this varies depending on whether CRM binder is being considered as an alternative to (unmodified) bitumen or (non-CRM) PMB.

8.1.1 CRM binders in lieu of bitumen

Generally, the binder application rate for CRM binder in asphalt and sprayed seals is higher than for bitumen, which results in increased capital costs. Accordingly, the initial cost of asphalt and sprayed seals that contain CRM binder will be higher than if bitumen is used. For this reason, the use of CRM binder only becomes economically viable as an alternative to bitumen if the performance benefits and life-cycle costs are taken into account. However, this is also true for other types of polymer modifier products widely used in bitumen.

8.1.2 CRM binders in lieu of other PMBs

In many instances in Queensland, PMB is used in both asphalt and sprayed seals. The polymers are imported, and can be more expensive than the equivalent CRM binder.

8.1.3 Life cycle cost analyses

The outcome of life-cycle cost analysis (LCCA) is highly dependent on the assumptions with regard to the relative life of CRM binders, compared to bitumen, or other PMBs. Therefore, meaningful LCCA is only possible if reliable performance data are available for different products. There are examples of LCCA analysis for CRM binders in the literature. Perhaps the most extensive comparative LCCA study was performed by researchers at the University of Nevada in Reno (Hicks & Epps 2000). LCCA was performed for different scenarios in Arizona and California, based on data from the departments of transportation in the respective states. The study found that CRM binder was cost-effective in most scenarios, both for use in asphalt and in sprayed seals. CRM binder was most cost-effective when reflective cracking was expected. Use of CRM binder in asphalt was not cost-effective in all cases, and it was recommended that a LCCA be performed on each project when deciding whether to use a CRM binder.

Another Arizona study considering both road owner and road user costs also concluded that CRM binder asphalt has the lowest life cycle cost for the roads included in the investigation (Jung, Kaloush & Way 2002). Yet another study from South Africa indicated that sprayed seals containing CRM binder are approximately 10% more expensive to construct, but deliver a 50% increase in service life (Hoffmann & Potgieter 2007).

In California there is an initiative under which local governments can apply for grants from CalRecycle for the first use of CRM binder in projects within its jurisdiction (Roschen 2014). The initiative is aimed at encouraging the use of CRM binder by reducing the barrier posed by the higher initial costs of CRM binder and demonstrating the improved performance benefits of CRM binder products.

8.2 Occupational Health and Safety

Potential health concerns related to the emissions from CRM binder applications have been the subject of several studies. A large study by the US National Institute for Occupational Safety and Health (NIOSH) found that exposure to emissions from CRM binder in asphalt is potentially more hazardous to workers than exposure to emissions from asphalt paving operations where conventional binder is used (Burr et al. 2001). The exposure to total particulate, benzene soluble particulate, polycyclic aromatic hydrocarbons, organic sulphur containing compounds, and benzothiazole, was higher during paving operations where a CRM binder was used.

In contrast, a study in California found no indications that emission exposure for CRM binder operations differed from those using conventional bitumen (California Department of Transportation 2003). Also, a study in Michigan comparing harmful emissions from different asphalt types, including reclaimed asphalt, found no evidence to suggest that the use of CRM binder increased worker exposure to hazardous compounds. This study concluded that, in all cases, the exposures were significantly lower than the mandated limits (Gunkel 1994).

It is important to note that the NIOSH report did not recommend any additional preventative measures over what is recommended for when paving asphalt with a conventional binder. However, the NIOSH recommendations for preventative measures to be used in asphalt paving do, in some instances, go beyond what is currently applied in many jurisdictions. NIOSH recommended keeping application temperatures as low as possible to minimise emissions. This could be achieved by using warm mix additives discussed in Section 8.3.1 of this report. NIOSH further recommended using engineering controls to minimise worker exposure to fumes. The extraction system on the sprayed sealing truck in Figure 8.2 is an example of such an engineering control. However, there are few, if any, sprayers in Australia currently fitted with this type of equipment.

General guidelines on the handling of CRM binders are provided in AAPA's 'Guide to the manufacture, storage and handling of polymer modified binders' (AAPA 2013a) and 'Guide to the heating and storage of binders for sprayed sealing and asphalt' (AAPA 2013b). Further information is also available in Section 2 of the Austroads 'Guide to the selection and use of polymer modified binders and multigrade bitumens' (Austroads 2013) and the Austroads 'Bituminous materials safety guide' (Austroads 2015). Further health and safety information is also provided by suppliers of equipment and products.

8.3 Environmental Considerations

The use of CRM binder in asphalt and sprayed sealing has significant environmental benefits, including reducing the volume of waste tyres in to landfill, road noise reduction, and the sustainability benefits stemming from increased durability of roads and therefore reduced use of non-renewable resources. However, besides natural rubber, synthetic rubber, steel and fibres, tyres will contain a mixture of other components, and some of these may have detrimental effects if released into the environment. The composition of tyres and the proportion of different compounds used in the tyres will differ between manufacturers and tyre types. It is therefore impossible to provide a definitive statement on which compounds may be expected to be present in the manufacture of CRM binder. The US Environmental Protection Agency (EPA) provided an incomplete list of known compounds that may be present in tyres (Environmental Protection Agency 2009), which are acetone, aniline, benzene, benzothiazole, chloromethane, halogenated flame retardants, isoprene, methyl ethyl ketone, methyl isobutyl ketone, naphthalene, phenol, polycyclic aromatic hydrocarbons (PAH), styrene-butadiene, toluene, trichloroethylene, arsenic, barium, cadmium, chromium, cobalt, copper, lead, manganese, mercury, nickel, sulphur, zinc, pigments, nylon, polyester, rayon and latex.

Internationally, there have been various studies performed into emissions caused by production and processing of CRM binder at high temperatures and into the potential of leaching of harmful substances from CRM binders in service. It is important that the effect of these chemicals on people and the environment is understood in order to inform any decision on more widespread use of CRM binder.

8.3.1 Emissions and Air Quality

International studies of emissions due to crumb rubber modification of bitumen have mainly focused on the use of CRM binder in asphalt. There is, however, no reason to assume that the findings would not be applicable to its use in sprayed seals.

Research results regarding environmental and health issues associated with the application of CRM binder are inconclusive. In a FHWA/EPA study (FHWA1993) on the use of recycled paving materials, it was noted that information available at the time showed no compelling evidence that the use of asphalt with a CRM binder substantially increased the threat to human health or the environment, as compared to threats associated with asphalt with conventional binders. Additionally, in a study conducted in 1989 to evaluate the effectiveness of CRM binders in asphalt, the emission data indicated that use of CRM binder does not appear to pose a threat to the health of the workers or the environment (Bischoff & Toepelb 2004). However, between 1994 and 1997, the National Institute for Occupational Safety and Health (NIOSH), and the Federal Highway Administration, studied asphalt paving workers at seven road paving sites in the USA. In 2002, NIOSH, working on behalf of FHWA, released a health hazard evaluation report on the use of CRM binders in asphalt in which they compared worker exposures to asphalt with CRM binder and asphalt with conventional binder, and evaluated acute health effects and occupational exposures in road paving operations. Tests were conducted for total particulate (TP), benzene soluble particulate (BSP), polycyclic aromatic compounds (PACs), organic sulphur-containing compounds (OSCs), and benzothiazole. Only TP and BSP have occupational exposure limits. It was highlighted that, compared with asphalt with conventional binder, asphalt with CRM binder resulted in higher worker exposures to various particulates. In both cases workers experienced acute respiratory symptoms (eye, nose and throat irritation), and the occurrence rate was higher among the workers involved with the asphalt with CRM binder (Carswell 2004). It is noted that although an exposure–response relationship has not been established in this study, the identification of health effects related to personal exposure to contaminants (measured as TP and BSP) in both scenarios indicates that such a relationship may exist (Burr et at. 2001).

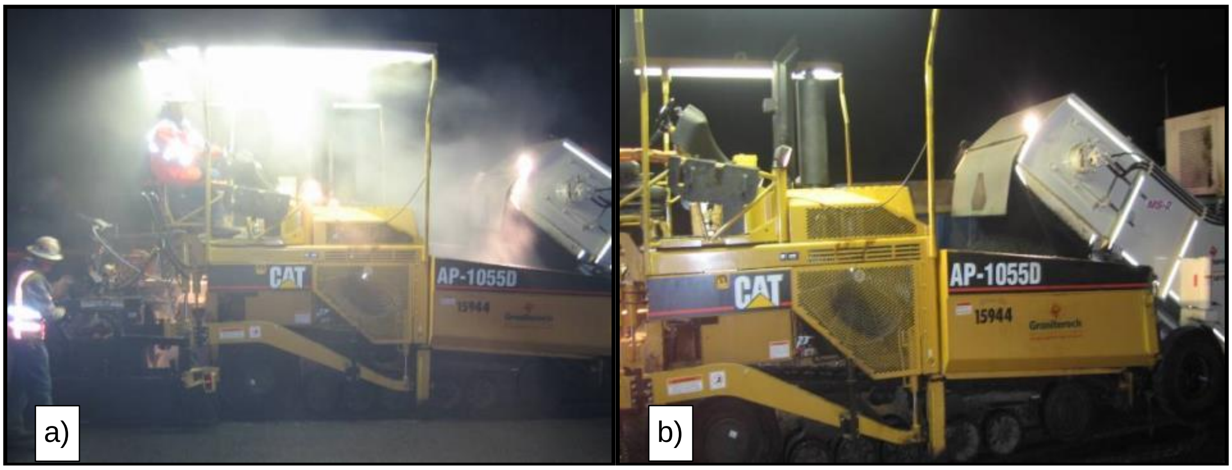
Studies in New Jersey, Michigan, Texas and California have shown that emissions at asphalt plants for mixes containing CRM binder are similar to mixes containing conventional binder and below the limits set by the EPA (California Department of Transportation 2003). It was found that the use of softer bitumen and extender oil may increase emissions. Overall, it was found that emissions from asphalt are more dependent on the production temperature than whether or not it contains CRM binder. A broad literature study by a different author found that the body of available work suggests that the use of CRM binder does not result in additional emissions compared to asphalt that contains conventional binder (Widyatmoko & Elliott 2008).

Both the production and paving of asphalt with CRM binder, and placement of CRM binder seals do increase the potential for more smoke and odour. CRM binders, when heated, typically smells like burned tyres. Recently, the production of asphalt with CRM binder at a plant in New South Wales was discontinued after the local community complained about the odour. Similar situations have occurred elsewhere - in Colorado Springs (USA) it was reported that asphalt producers initially did not want to participate in CRM binder trials for fear of odour and smoke-related complaints (Lo Presti 2013).

The past decade has seen the rapid development of warm mix asphalt (WMA) technology, which is aimed at producing and placing asphalt at lower temperatures. This technology can also be applied to asphalt with a CRM binder. It has been shown that emissions from such asphalt can be reduced by using WMA technology (Jones, Farshidi & Harvey 2013). WMA for CRM binders can be produced by the addition of chemicals to the binder used in the asphalt mix. Figure 8.1 provides a visual comparison of the smoke produced during placement of asphalt with a CRM binder at conventional (high) paving temperatures versus paving at a lower temperature using WMA technology. Importantly, the emission of polycyclic aromatic hydrocarbons reduces with a reduction in temperature.

Issues with smoke and odour can also be significantly reduced through the use of WMA technology (Jones, Farshidi & Harvey 2013).

Figure 8.1: a) hot mixed CRM binder asphalt, b) warm mixed CRM binder asphalt



Source: Jones (2014).

In Los Angeles it has been demonstrated that, for sprayed seal applications in urban areas, the nuisance caused by odour and smoke can be significantly reduced by adding warm mix additives to the CRM binder and applying it at reduced temperatures (Dragos et al. 2010).

Other engineering controls to reduce odour and smoke include addition of commercial deodorants, and lowering the rate of production at the asphalt plant (Hicks 2002). Some jurisdictions also require fume exhaust ventilation and capture devices on paving equipment. Figure 8.2 shows a sealing truck with an extraction device over the spray bar. Asphalt pavers with integrated extraction systems are also available. However, there are few, if any, asphalt pavers in Australia currently fitted with this type of equipment.

Figure 8.2: Sealing truck with extraction device at spray bar

Source: Roschen (2014).

8.3.2 Leaching and Water Quality

The EPA identified a lack of easily accessible information on the water quality and environmental toxicity effects of tyre-derived aggregate and asphalt with CRM binder as a barrier to increased use of these technologies. It therefore contracted the University of Maine to perform an extensive literature review on the topic. The review found that the available body of work evaluating the leaching potential and water quality effects of asphalt with CRM binder was limited to three studies. The conclusion of the review was that the limited available data suggested that the use of asphalt with CRM binder would have negligible off-site effects on water quality and toxicity (Humphrey & Swett 2006).

8.4 Supply Chain Challenges

At present, there is limited capacity in industry to manufacture suitable crumbed rubber, process it into CRM binder, and to place CRM binder sprayed seals and asphalt. However, this is quite likely a function of the limited demand for CRM binders asphalt and sprayed seals in Queensland. Based on the available information and discussion with industry stakeholders it appears that the use of CRM binder can be significantly increased without encountering serious supply chain issues. However, it is noted that some specialised applications, especially in the field of asphalt technology and the supply of CRM binder for seals in remote areas of Queensland, would require significant investments by industry. Possible challenges in parts of the supply chain are discussed below.

8.4.1 Availability of Crumb Rubber

As highlighted in Section 7, in Queensland only a small portion of end-of-life tyres could be used on TMR roads as CRM binder. However, at present there is only one tyre recycling facility in Queensland that can produce crumb rubber from end-of-life tyres. This facility produces approximately 8600 tonne of rubber crumbs annually and at the moment only a very small fraction of this is used for the production of CRM binder. Based on this, it is unlikely that the supply of crumb rubber will be a constraint to the wider use of CRM for roads. However, if the cost of tyre recycling in Australia proves to be too expensive, crumb rubber for use in CRM binder may be imported from overseas rather than from existing tyre stockpiles in Australia.

8.4.2 Production of CRM Binder

There is currently capacity to produce CRM binder in Queensland. One of the largest producers of CRM binder indicated that they currently supply about 1500 tonnes of refinery produced CRM binder for sealing applications to Queensland annually (compared to 6000 tonne to NSW and 5000 tonne to Victoria). This supplier also indicated that there is significant redundant capacity that could be used to increase the supply in Queensland if the demand existed. A limitation of these refinery produced products is that the production facilities for CRM binder are located in South-East Queensland, which limits the availability of the product in the north and west of the state.

Field blending plants used to produce CRM binder locally is available, although limited. One of the main sealing and asphalt contractors commenced commissioning a new field blending unit in 2012. However, due to a safety incident, the field blending unit has yet to be used on any TMR projects. .

8.4.3 Specialised Sealing Equipment

To prevent segregation of CRM binder during transport, tankers should ideally be equipped with agitation devices to keep the crumb rubber in suspension. Such tankers are currently not readily available in Queensland. Also, to spray CRM binder effectively without a need to cut it back, sealing trucks should be equipped with larger spray nozzles than those typically used to spray bitumen and polymer modified binders (other than CRM binder).

8.4.4 CRM Asphalt Production

The production of asphalt with CRM binder using the dry process can be done by simply adding the dry blend of crumb rubber to the pugmill or a drum of an asphalt plant. No alterations to the plant are required, which explains to an extent the preference for the dry process in Australia to date.

The production of asphalt with CRM binder using the wet process requires a number of alterations to the typical asphalt plant in Queensland. First of all, unless WMA additives are used, the CRM binder has to be heated to about 190°C. Not all plants are capable of achieving this temperature. Then, the pumps at the plant need to have sufficient power to pump the more viscous CRM binder. Lastly, the typical asphalt plant in Queensland has a limited number of tanks for storage of bitumen, which are used for the types of bitumen typically used in the local area. Adding CRM binder would often necessitate an additional tank, which should also be equipped with an agitator for the CRM binder. Alternatively, a field blending system that includes an agitator tank could be used to supply an asphalt plant with CRM binder.

Notwithstanding these challenges, at least one asphalt supplier in Queensland is currently commissioning an installation that will allow the production of CRM asphalt using the wet process.

8.4.5 Discussion on Supply Chain Challenges

Currently there is sufficient installed capacity of CRM binder -related equipment in Queensland that would allow an increase in use of CRM binder in both asphalt and sprayed seals. Further increasing the availability of the specialised plant used throughout the CRM binder supply chain would require significant capital investment by industry. Such investment can be encouraged by providing industry with reasonable certainty that demand for CRM binder products will exist in the future. The policy in place in California, requiring 35% of asphalt placed by CalTrans to contain rubber, is an example of a measure that provides industry with such certainty. Policy measures and incentive schemes could provide an effective way of ensuring wider use of CRM binder in Queensland. However, as was the case in California, research would first be needed. In addition an appropriate implementation strategy (which would include the construction of a number of demonstration projects) would need to be employed to ensure acceptable performance is achieved prior to full implementation. In addition, there may also be commercial implications for existing suppliers who have invested in the manufacture of other PMB technologies (such as SBS and PBD modifiers).

9 LABORATORY EXPERIMENTS

An exploratory laboratory test program of limited scope was included as a task in the first year of the study. The aim was to demonstrate the effect of crumb rubber on the physical properties of the binder. A further aim was to demonstrate the use of the dynamic shear rheometer (DSR) as a practical and cost-effective instrument in the characterisation of CRM binders. Different standard sizes of rubber crumb were sampled from a crumb rubber manufacturer in Queensland.

This work provides an indication of the effects for one bitumen/crumb rubber blend/source. It may not be typical of various CRM binders. For example, bitumen from another source combined with crumb rubber from a different source may have different properties.

9.1 Laboratory Work Plan

This laboratory study on CRM binder included the following tasks:

1. Testing of component materials
   — The component materials used to manufacture CRM binders (i.e. crumb rubbers and C170 bitumen) were assessed for their conformance to pertinent specifications (e.g. AS 2008, AGPT/T190).
2. Rubber content investigation
   — A series of CRM binders with varying rubber content (i.e. 5, 15, 20 and 25%) were produced in the laboratory and tested using a DSR device.
3. Blending time investigation
   — A CRM binder with a 20% rubber content was produced and blended for up to 4 hours. During blending, samples were collected at hourly intervals and tested using a DSR device.
4. Comparison to other binders
   — A 6% SBS PMB was manufactured using the same C170 bitumen and DSR testing was conducted on the binder. The base C170 was also tested using the DSR device for comparison purposes.

9.2 Testing of Component Materials

9.2.1 C170 Bitumen

C170 bitumen was used as a base bitumen for the modified binders. The bitumen was tested for its conformance to some requirements of the Australian specification (AS 2008). The results are presented in Table 9.1 and show that the bitumen conformed to these criteria.

Table 9.1: C170 bitumen test results

Property	Test method	Unit	Value	Conformance
Capillary viscosity at 60 °C	AS 2341.2	Pa.s	176.3	Conforming
% change (after RTFO treatment)	AS 2341.2 AS 2341.10	%	150	Conforming
Penetration at 25 °C	AS 2341.12	pu	69	Conforming
Viscosity at 135 °C	AGPT-T111	Pa.s	0.328	Conforming

9.2.2 Crumb Rubbers

Two crumb rubber products were used as a modifier for the CRM binders. The properties of these rubbers are compared with the requirements of the Size 16 and Size 30 rubbers as specified in the Australian PMB specification (AGPT-T190-14) in Table 9.2. It is noted that the specified rubber properties are intended for use in sprayed sealing grade CRM binders. The CRM binders investigated in this study are intended for asphalt mix applications and thus the specification is presented here only for reference purposes since the criteria for the use of CRM binders in asphalt mix applications does not exist in Australia.

Table 9.2: Crumb rubber test results

Material	Property		Test method	Unit	Value	Conformance
Rubber A (comparable to Size 30)	Bulk density		AGPT/T144	kg/m^3	365.9	-
	Steel content		AGPT/T143	%	0.02	Conforming
	Moisture content		AGPT/T143	%	0.80	Conforming
	Grading	Sieve size (mm)	AS 1141.11.1	% passing		
		1.18			99.9	Non-conforming
		0.6			95.0	Non-conforming
		0.3			27.0	Non-conforming
		0.15			6.5	-
		0.075			0.9	-
Rubber B (comparable to Size 16)	Grading	Sieve size (mm)	AS 1141.11.1	% passing		
		1.18			95.3	Conforming
		0.6			18.5	Non-conforming
		0.3			0.6	-
		0.15			0.3	-
		0.075			0.1	-

Table 9.2 shows that Rubber A conforms to these criteria except for grading. Rubber B was only tested for gradation to ensure that this rubber has a larger size than Rubber A.

9.3 Rubber Content Investigation

9.3.1 Manufacturing of CRM Binders

CRM binders were manufactured with rubber contents of 5%, 15%, 20% and 25% (by weight of bitumen), respectively. The fine grade rubber (i.e. Rubber A in Table 9.2) and the C170 bitumen were blended at an elevated temperature of 190 °C for 1 hour. The procedure is briefly described as follows:

1. A defined amount of C170 bitumen is placed in a 5 L tin (about 3 L was used so that the binder does not overflow the tin after adding the required volume of crumb rubber).
2. The tin is placed on a heating block to heat up the binder to the target temperature (190 °C ± 10 °C). A low shear mixer is used to stir the binder during heating. The atmosphere inside the heating block is saturated with carbon dioxide (fed at a constant rate from a pressurised gas container) to minimise oxidation of the binder during the heating and blending process.
3. Once the binder has reached the target temperature, a defined amount of crumb rubber is added to the binder.
4. The stirring of the binder blend is maintained for 1 hour at the target temperature.

5. Once the blending process is completed, the tin is removed from the heating block and small amounts of samples are taken from the tin for subsequent DSR testing. The remaining CRM binder is stored in the tin for future use.

9.3.2 DSR Testing of CRM Binders

The manufactured CRM binders with different rubber contents were tested using a DSR device. The sample preparation method largely followed that of ASTM D7175. The test was conducted in a strain controlled oscillation mode, as follows:

- Specimen diameter (spindle diameter) = 25 mm
- Specimen film thickness (parallel plate gap) = 2 mm
- Test temperature = from 60 °C to 20 °C (at 10 °C intervals)
- Oscillation frequency = 0.1 to 10 rad/s
- Target shear strain = 0.05 strain.

The temperature and frequency ranges/intervals were selected to produce a large amount of test data sufficient to construct a typical master curve. Presenting DSR oscillation test results in the form of a master curve is a common practice, particularly when general rheological property trends are the main observation of the experiment as for this study. Master curves of complex modulus (G*) and phase angle (δ) were constructed to a reference temperature of 40°C (i.e. the middle point of the temperature sweep range) and used for data analysis throughout this report.

DSR tests were conducted up to duplicate as shown in Table 9.3.

Table 9.3: Number of DSR tests conducted per binder

Binder	DSR plate gap (mm)	Blending time (hour)	Number of tests	Related section
C170 bitumen	1	-	2	Section 9.3.3 Section 9.5.2
	2	-	2	
5% CRM binder	1	1	1	Section 9.3.3 Section 9.3.4
	2	1	1	
15% CRM binder	2	1	2	Section 9.3.4
20% CRM binder	2	1	1	Section 9.3.4 Section 9.4
	2	2	1	
	2	3	1	
	2	4	1	
25% CRM binder	2	1	2	Section 9.3.4 Section 9.3.5
SBS 6% PMB	2	1	2	Section 9.5.1

9.3.3 Selection of DSR Test Plate Gap

For DSR testing of bituminous binders, it is normal to use a 1 mm gap when the 25 mm spindle is used. However for the testing of CRM binders, using a larger gap is a common practice since rubber particles may interfere with the plates if the gap is too small compared to the rubber size. The maximum size of Rubber A is about 1 mm (refer to Table 9.2) and thus using a 2 mm gap was considered appropriate as was the case for Mturi et al. (2014) who investigated the effect of using different gap sizes for testing CRM binders. They found that using a 2 mm gap was appropriate for testing CRM binders, manufactured using locally sourced rubbers that had similar sizes (about 1 mm) to the rubbers used in this study.

The complex modulus and phase angle master curves of the unmodified C170 bitumen (refer to Section 9.2.1) and the 5% CRM binder that were tested using the two different gaps (1 mm and 2 mm) are presented from Figure 9.1 to Figure 9.4 respectively. The figures show that for the unmodified bitumen and the 5% CRM binder that used the fine grade rubber (particle size less than 1 mm), the different gap spacing provided similar results.

Figure 9.1: Complex modulus master curves of the C170 bitumen tested with 1 mm and 2 mm gaps respectively

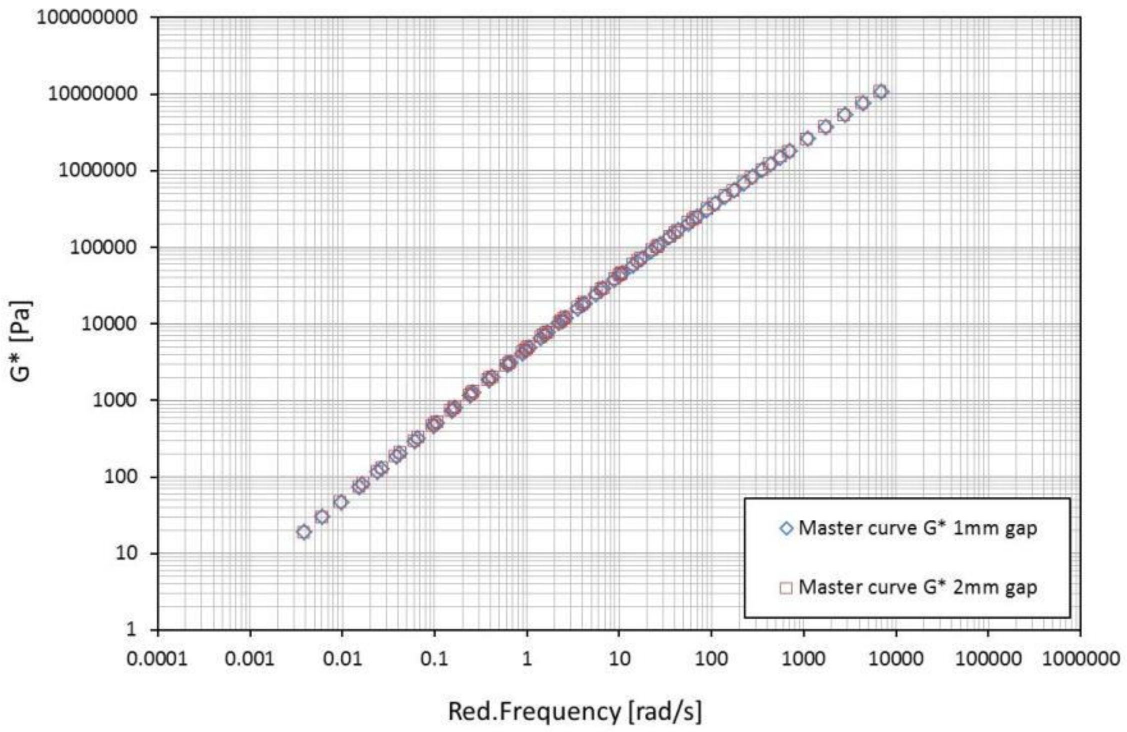


Figure 9.2: Phase angle master curves of the C170 bitumen tested with 1 mm and 2 mm gaps respectively

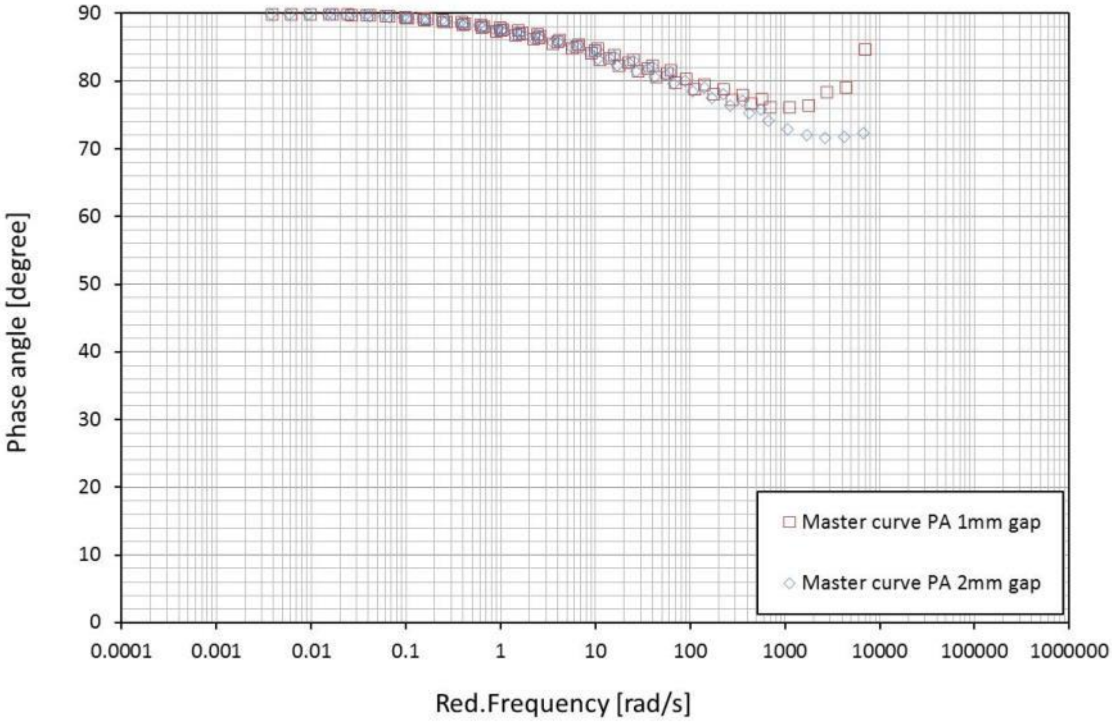


Figure 9.3: Complex modulus master curves of 5% CRM binder tested with 1 mm and 2 mm gaps respectively

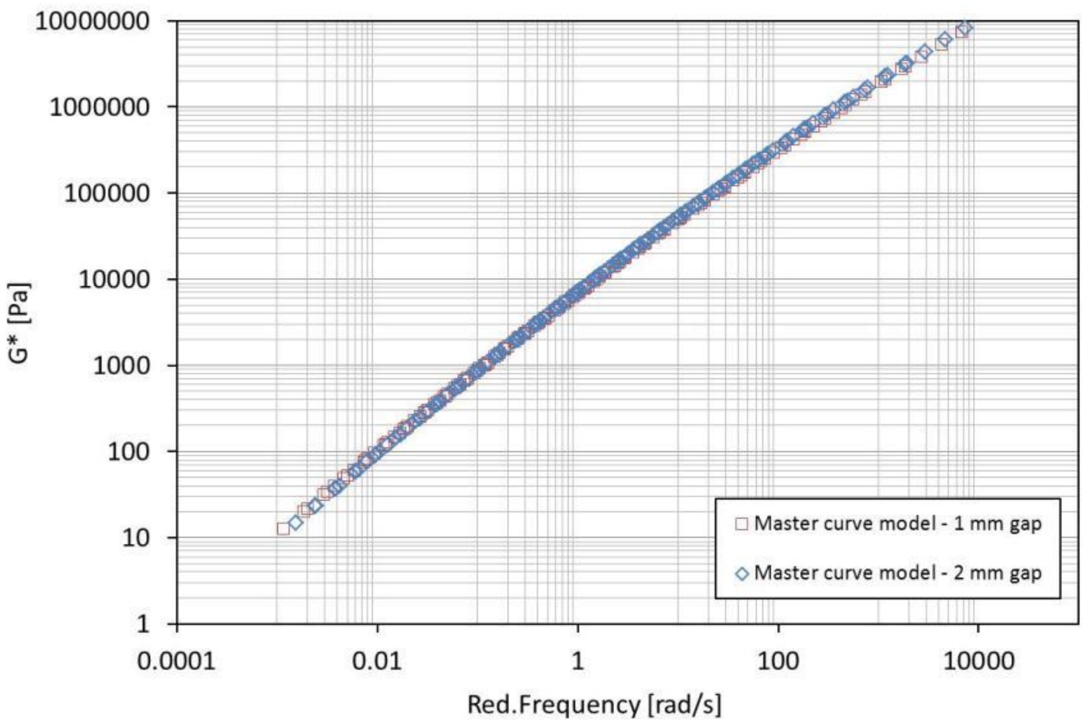
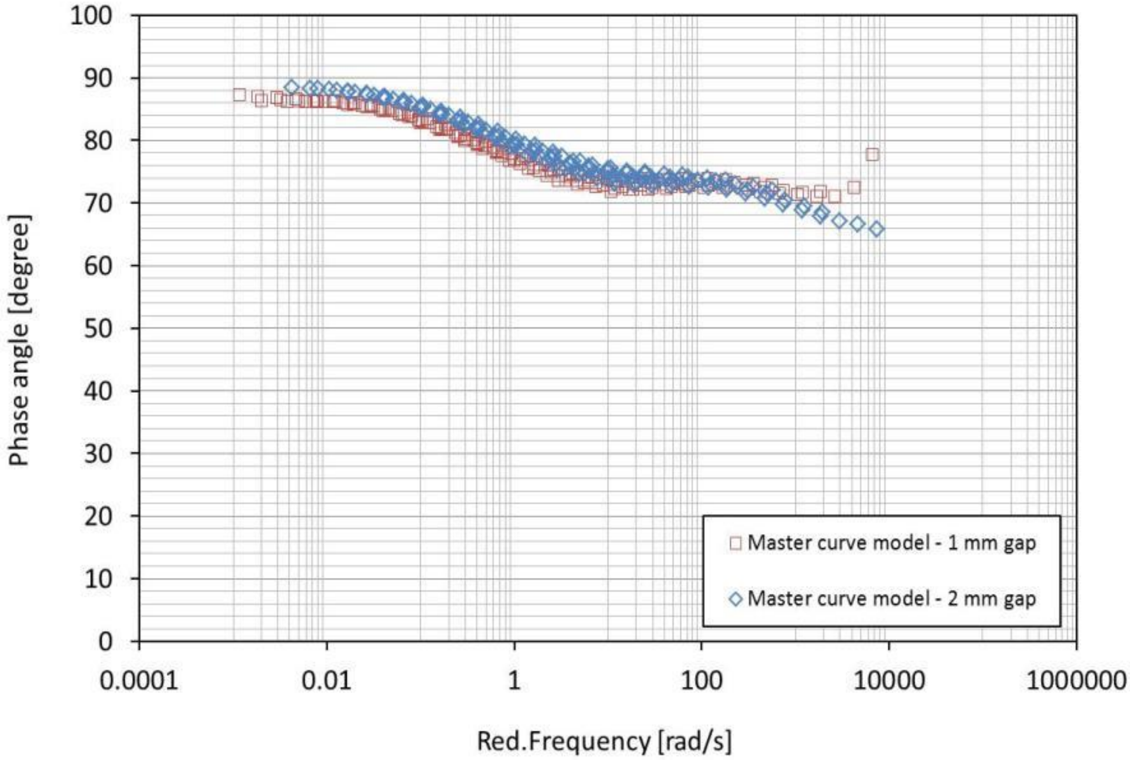


Figure 9.4: Phase angle master curves of 5% CRM binder tested with 1 mm and 2 mm gaps respectively



9.3.4 CRM Binders with Varying Rubber Content

The complex modulus and phase angle of the manufactured CRM binders with varying rubber content are presented in Figure 9.5 and Figure 9.6 in the form a master curve, respectively. It can be seen in Figure 9.5 and Figure 9.6 that varying rubber content had a significant effect on the rheological properties of CRM binders. Noteworthy observations on the rheological properties are:

- From Figure 9.5, as rubber content increases, complex modulus of CRM binder increases (indicating that the binder becomes stiffer). This trend is more apparent at low oscillation frequencies (analogous with slow traffic speeds).
- From Figure 9.6, as rubber content increases, phase angle of CRM binder decreases (indicating that the binder becomes more elastic than viscous). This trend is more apparent at low oscillation frequencies (analogous with slow traffic speeds).

Figure 9.5: Complex modulus of CRM binders with varying crumb rubber content

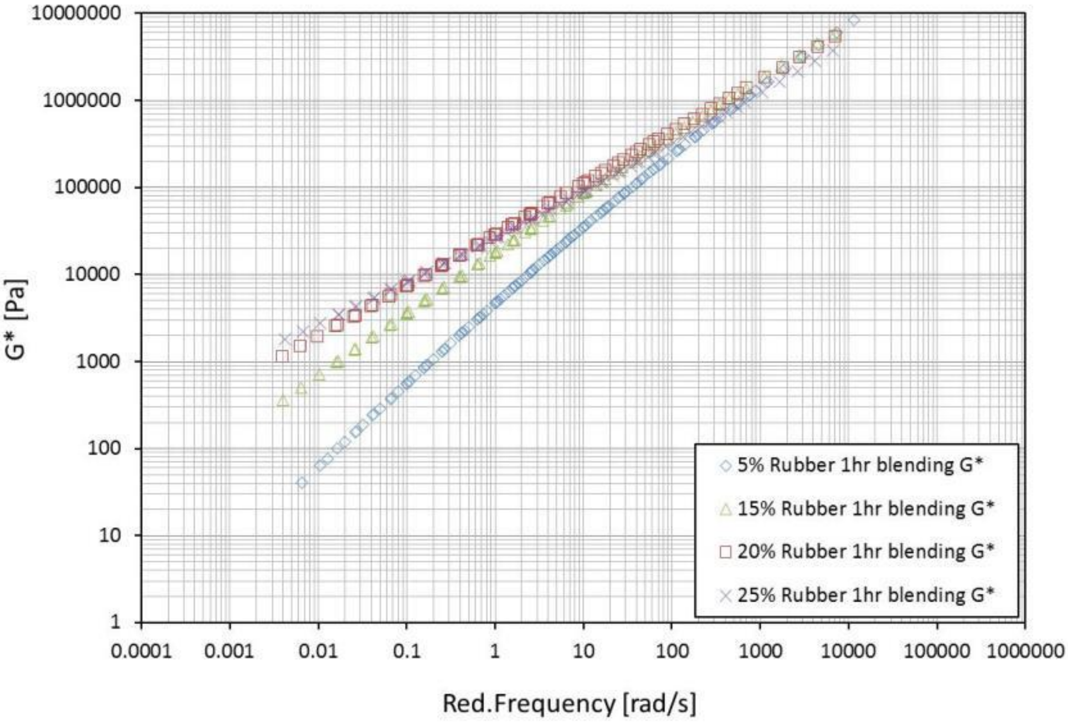
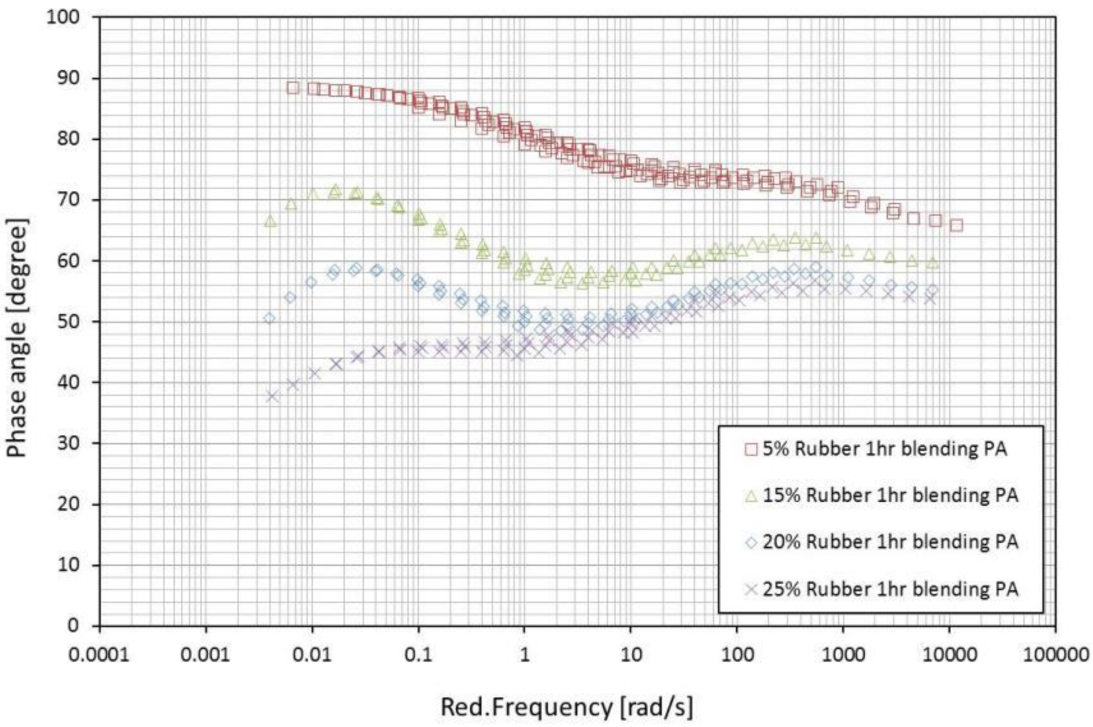


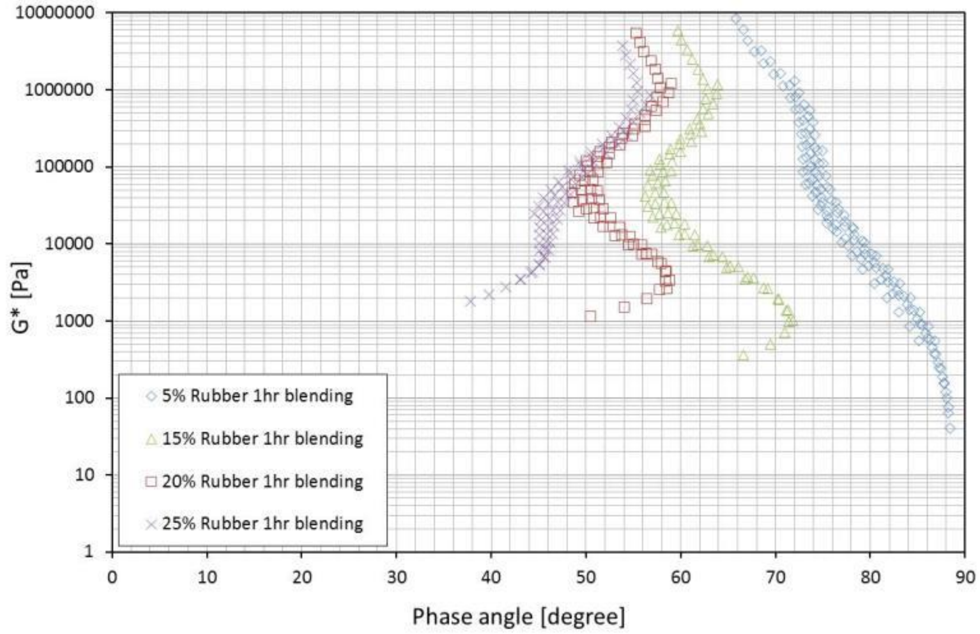
Figure 9.6: Phase angle of CRM binders with varying crumb rubber content



The two sets of master curves above were combined to construct a series of 'black diagrams' in Figure 9.7. The black diagram is provided here as supplementary information to the master curves since it describes the direct relationship between the two basic DSR parameters. For example, it can be seen how visco-elastic properties of a binder change when the binder becomes softer (e.g.

the binder being heated up, decreasing complex modulus). Some binders (e.g. 5% rubber binder) can gradually change into a liquid-like status (i.e. phase angle approaching 90 degrees as G* decreases) as they are heated up but other binders (e.g. 20% rubber CRM binder) can maintain their solid-like status at elevated temperatures (i.e. phase angle does not increase even if G* decreases).

Figure 9.7: Black diagrams of CRM binders with varying crumb rubber content



9.3.5 Maximum Rubber Content

The initial aim was to manufacture a CRM binder with a rubber content as high as 30%. However, during the production of CRM binder with 25% crumb rubber, it was noted that the rubber content was too high and the CRM binder was considered too thick/viscous to use in practice (Figure 9.8). The proposed testing of CRM binder with 30% crumb rubber was therefore omitted from the test program. While the CRM binder with 25% crumb rubber was not considered usable in practice (as it would not have been able to flow through sprayer nozzles), DSR testing was still conducted (Figure 9.9).

Figure 9.8: CRM binder with 25% crumb rubber during blending

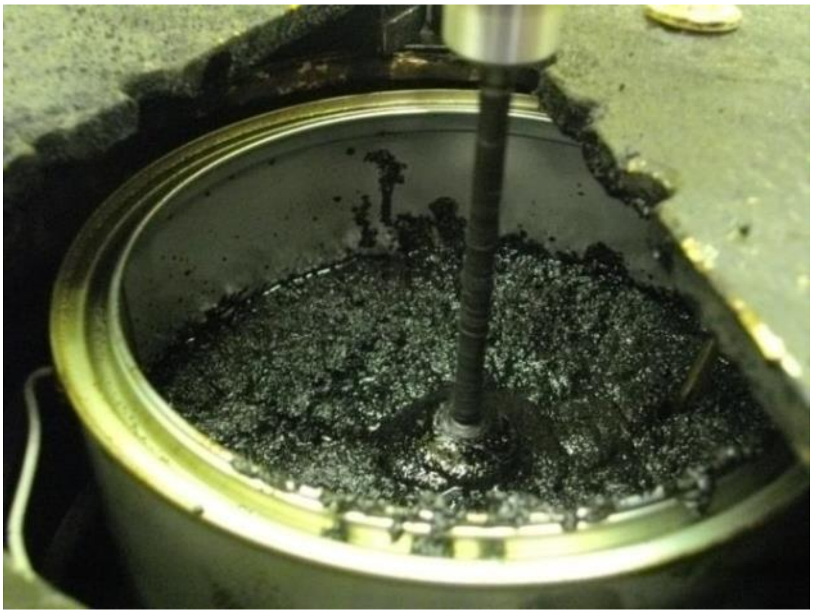


Figure 9.9: CRM binder with 25% crumb rubber prepared on silicone rubber mould for DSR testing

The complex modulus and phase angle data of the CRM binder with 25% crumb rubber is included in Figure 9.5, Figure 9.6 and Figure 9.7 to compare with the binders with lower crumb rubber contents.

This experiment suggested that a crumb rubber content of about 20% (without the use of extender oil) may be the practical upper limit for CRM binders. This corresponds with the crumb rubber content limits specified in some CRM binder specifications. A review of jurisdictional specifications regarding rubber content was presented in Section 5.2 and Section 6.3.

9.4 Extended Blending Time Investigation

A CRM binder with 20% crumb rubber was manufactured using the same procedure as described in Section 9.3.1, except that a longer blending time of 4 hours was used. During blending, a small volume of sample was taken at 1hourly intervals. These samples were tested using the DSR as described in Section 9.3.2. Test results are presented in Figure 9.10, Figure 9.11 and Figure 9.12.

Figure 9.10: Complex modulus of CRM binder with 20% crumb rubber over extended blending time

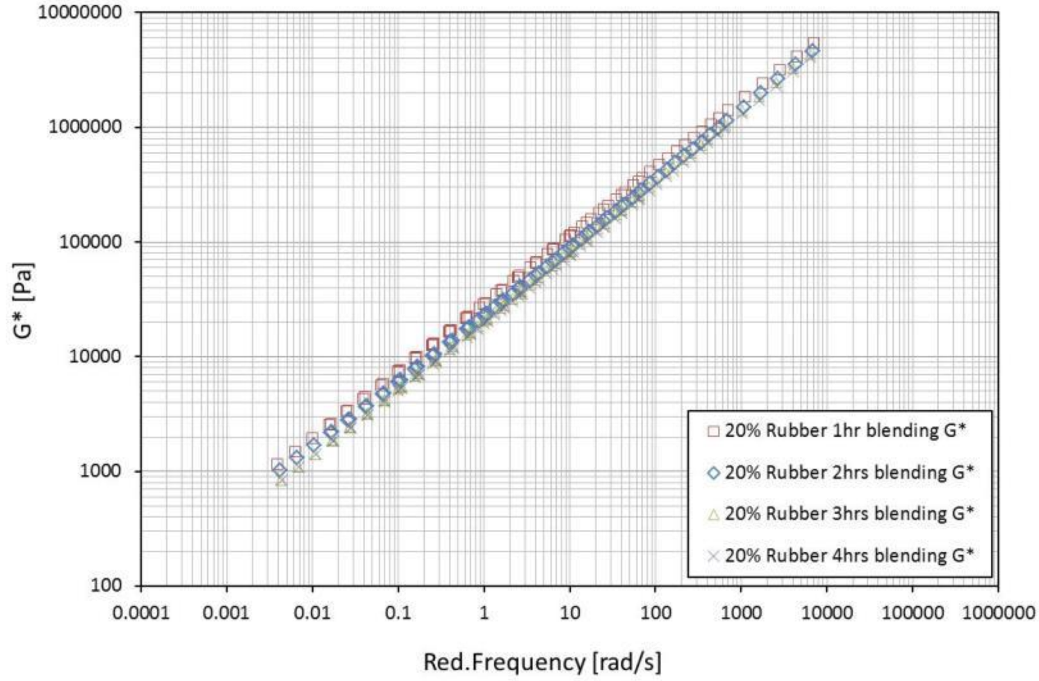


Figure 9.11: Phase angle of CRM binder with 20% crumb rubber over extended blending time

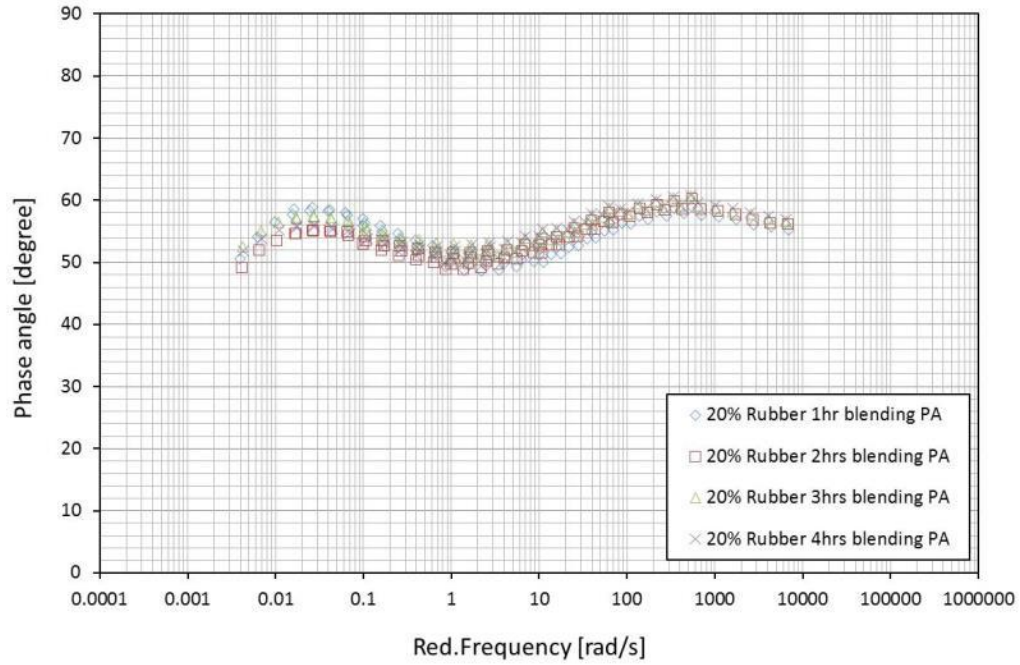
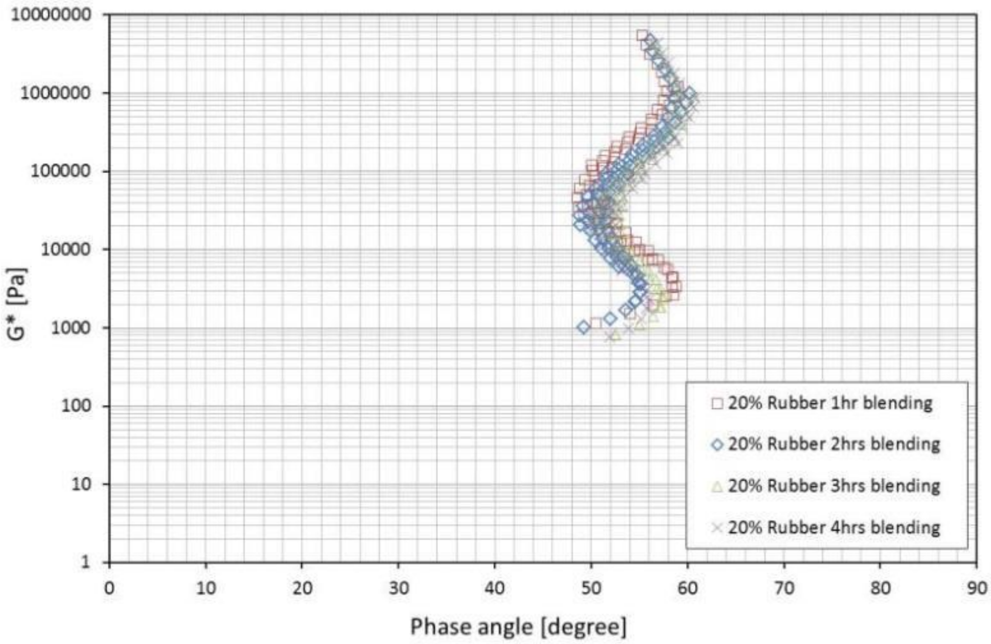


Figure 9.12: Black diagram of CRM binder 20% crumb rubber over extended blending time



It can be seen that longer blending time did not have a significant effect on the rheological properties of the CRM binder with 20% crumb rubber. This outcome was not expected, as a peak in viscosity is typically reported in this type of work. It appears, however, that the viscosity of this particular bitumen/crumb rubber blend was relatively stable over the investigated time frame.

9.5 Comparison with Other Binders

9.5.1 SBS Polymer Modified Binder

An elastomeric (SBS) PMB (i.e. non-CRM binder) was manufactured using the same C170 bitumen that was used for the manufactured CRM binders. The 6% SBS PMB was manufactured at the laboratory by blending a mixture containing 85% w/w C170 bitumen, 6% w/w SBS polymer and 9% w/w of a commercial polymer-combining oil at 190 ± 10 °C for one hour using the same heating block (Section 9.3.1). The purpose of this experiment was to compare the CRM binder properties with those of the SBS PMB so that the changes in rheological properties made by adding a crumb rubber or an elastomeric polymer modifier could be compared. It is noted that the manufacturing method of PMB was not identical to that of the CRM binders. The SBS PMB used a commercial polymer-combining oil while the CRM binders did not use any extender oil. A Silverson high shear laboratory mixer was used for the SBS PMB blending, while a low shear mixer was used for the CRM binders. These different conditions were chosen to match the typical commercial manufacturing process of each type of binder.

The SBS PMB binder was tested using the DSR in the same manner as used for the CRM binders (Section 9.3.2). The master curve and black diagram results are presented in Figure 9.13, Figure 9.14 and Figure 9.15, together with the results of other binders.

9.5.2 C170 Bitumen

The Class 170 (C170, unmodified) bitumen (Section 9.2.1) used as the base binder of the CRM binders and the SBS PMB were tested using the DSR in the same manner as used for the CRM binders (Section 9.3.2). The results are presented in Figure 9.13, Figure 9.14 and Figure 9.15, together with the results of the modified binders.

Figure 9.13: Complex modulus of CRM binders, SBS PMB and C170 bitumen

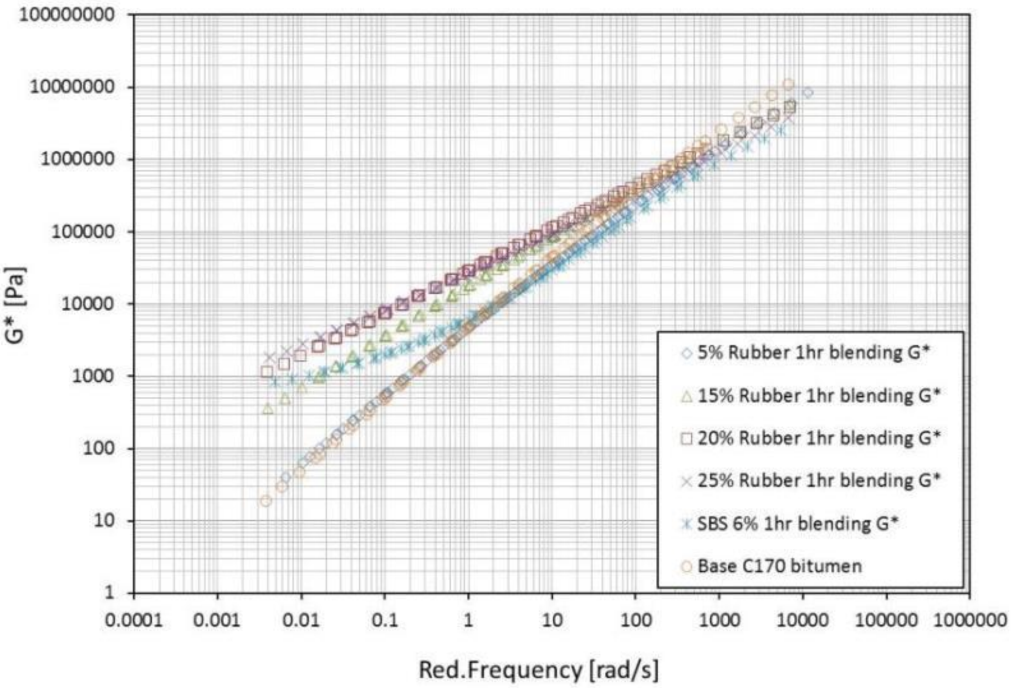


Figure 9.14: Phase angle of CRM binders, SBS PMB and C170 bitumen

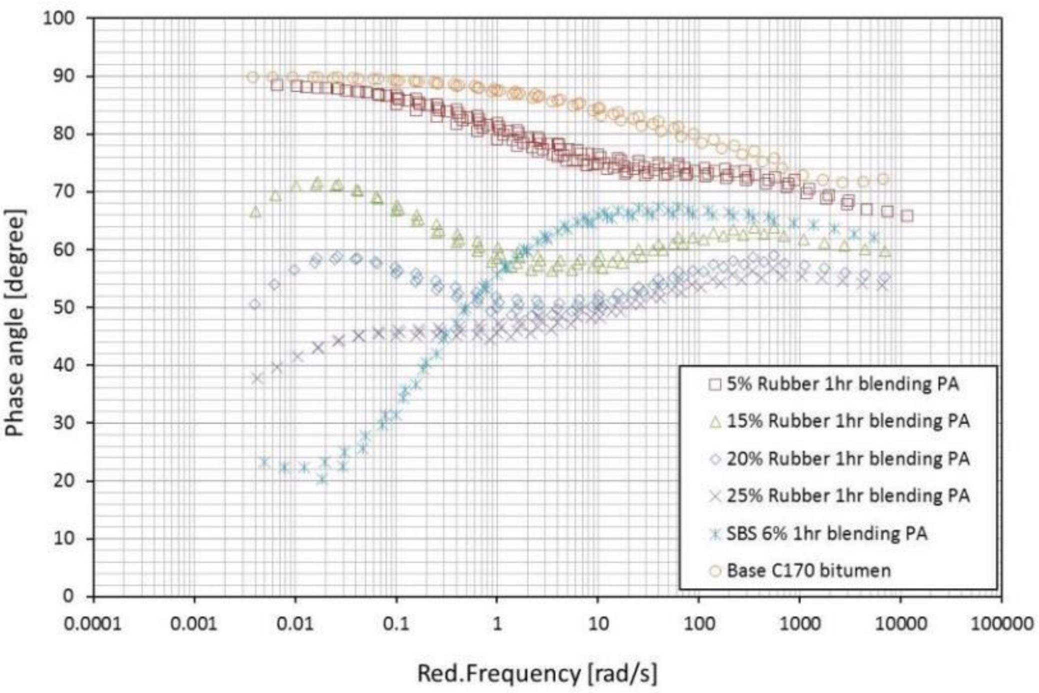
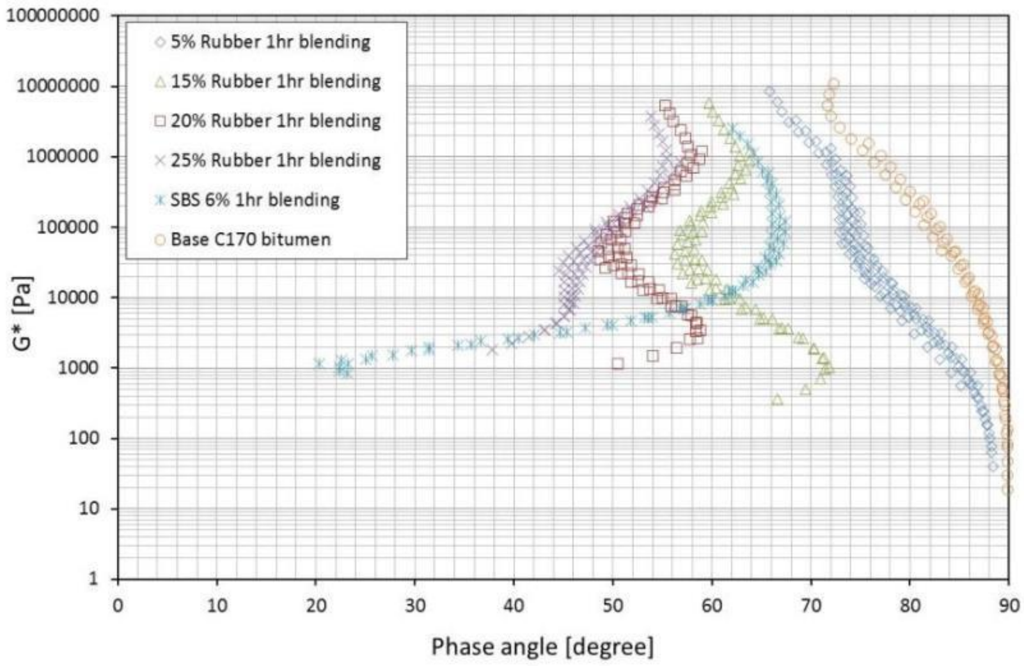


Figure 9.15: Black diagrams for CRM binders, SBS PMB and C170 bitumen



It can be seen from Figure 9.13 to Figure 9.15 that adding a SBS polymer to bitumen had a significant effect on the rheological properties of the binder as in the case of CRM binders. Noteworthy observations on the rheological properties are:

- From Figure 9.13, the SBS PMB has relatively lower complex modulus values particularly towards high oscillation frequencies (analogous with high traffic speeds). This is possibly because the SBS PMB contained polymer-combining oil. The SBS PMB however maintained its stiffness towards low oscillation frequencies better than the C170 bitumen and the CRM binder with 5% crumb rubber, which became softer rapidly (i.e. complex modulus decreased). Low oscillation frequencies generally represent low traffic speeds and/or high temperatures, which are the conditions that 'rutting performance' of binders, are closely related with. This suggests that the modified binders (either with crumb rubber or SBS polymer) would perform better at high temperatures than the C170 bitumen would.
- From Figure 9.14, the SBS PMB has phase angle values similar to the CRM binder with 15% crumb rubber (about 60°) at high oscillation frequencies. The SBS PMB, however, displayed very low phase angle values (as low as 20°, indicating the binder is predominantly elastic) as the oscillation frequency decreased. At the low oscillation frequencies, the C170 bitumen was fully viscous (i.e. phase angle close to 90°). Adding crumb rubber or SBS polymer then improved the elasticity of binders. Increasing rubber content (up to 25%) increased the elasticity gradually (with the phase angle as low as 40°) as expected, but the CRM binders were still less elastic than the SBS PMB at the lower oscillation frequencies. Studies have suggested that having high elasticity would be beneficial for both high temperature performance (e.g. rutting) and low temperature performance (e.g. cracking) of binders.
- From Figure 9.15, the C170 bitumen becomes more viscous (i.e. phase angle increased) as the binder becomes softer (i.e. towards low complex moduli). The CRM binders, on the other hand, maintained their elasticity well, particularly with high crumb rubber contents. The SBS PMB became more elastic (i.e. phase angle decreased) as the binder became softer (towards low complex moduli).

10 AIR QUALITY EMISSION MONITORING DURING CRUMB RUBBER SPRAYED SEAL TRIAL

On 2 March 2015, TMR and ARRB attended a CRM binder sprayed seal trial along Laidley – Plainlands Road in the Lockyer Valley. Two types of binder were used during the trial, a conventional PMB (TMR Class S0.7S) and a CRM binder (TMR Class S1.8R).

As part of the sprayed seal trial, ARRB engaged Entox (National Research Centre for Environmental Toxicology) of the University of Queensland to monitor the air quality emissions at two monitoring sites, one for the S1.8R binder, and the other one for the S0.7S binder. The aim of the field emission monitoring work was to measure and compare the following list of chemical groups at both monitoring sites:

- Total Suspended Particles (TSP),
- Volatile Organic Compounds (VOCs),
- Polycyclic Aromatic Hydrocarbons (PAHs) and Benzo(a) pyrene (BaP).

Measurements of the above chemical groups were taken to establish the background levels before construction. Further measurements were taken during construction of the S1.8R and S0.7S sections at various time intervals during (0-3 hours), and after (3-6 hours and 6-9 hours intervals) the trial.

An Entox report describing the experimental set-up and air quality emission findings is included in Appendix A of this report.

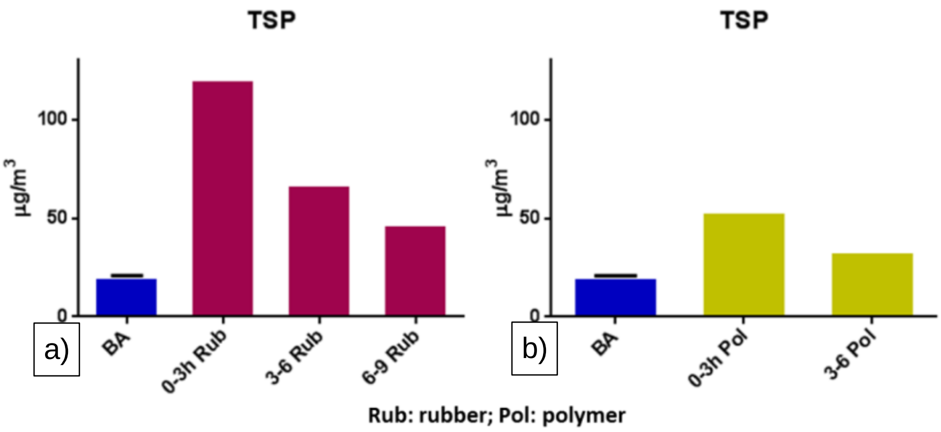
The monitoring was done for one sprayed seal project. Further monitoring research is needed, for asphalt and may also be needed for other aspects.

10.1 Summary of Findings during the Air Quality Emission Monitoring

10.1.1 Total Suspended Particles (TSP)

The analysis shows greater levels of TSP (dust) for the CRM binder sprayed seal site when compared with the conventional PMB spray seal, as shown in Figure 10.1. The TSP levels were found to be 2.5 times higher for the CRM binder sprayed seal operation than the conventional PMB, and the average concentration was higher than the Queensland air quality goal of 90 µg/m^3 (average exposure over the period of a year) in the first 3 hours after spraying the binder. However, the report acknowledged that the average annual concentration will be lower than the concentration measured during the first three hours after sealing and that the risk to the public (i.e. non-occupational population) is therefore reduced. The report also suggested that further studies would be required to determine the occupational risk for construction workers as a result of CRM binders in sprayed seals.

Figure 10.1: Results for total suspended particles (TSP): a) S1.8R, b) S0.7S



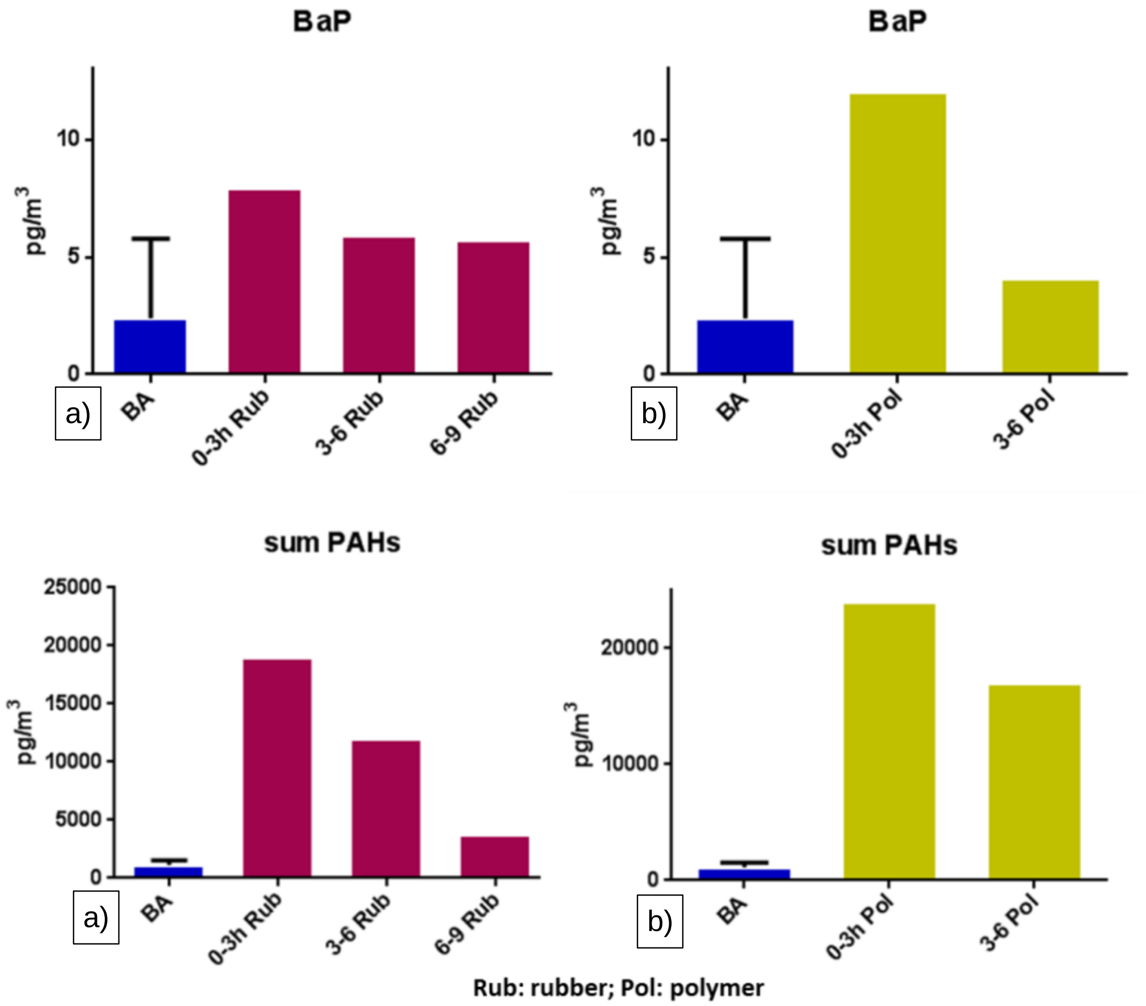
10.1.2 Volatile Organic Compounds (VOC)

Apart from the appearance of some alkanes and naphthalene during the construction work, the levels of other VOCs are low (i.e. mostly below limit of report (LOR)). It is noted that some heavy alkanes were detected during the spraying of the CRM binder while only trace levels of undecane were detected in the fume of the conventional PMB sprayed seal section. The report pointed out that this may be caused by the larger amount of cutter oil added to the CRM binder.

10.1.3 Polycyclic Aromatic Hydrocarbons (PAH) and Benzo(a)pyrene (BaP)

The BaP and total PAH levels are reported in Figure 10.2. Although there was an increase in the level of BaP and PAHs in the ambient air during and shortly after the construction, the highest concentrations measured (0 – 3 hrs after spray) in both treatments were much lower than the air quality objective of 300 pg BaP/m^3 set by the State of Queensland.

Figure 10.2: Concentration of BaP and total PAHs before and after sprayed sealing trial: a) S1.8R, b) S0.7S



11 CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to describe the potential for wider use of CRM binder in asphalt and sprayed seals, and investigate the benefits of doing so. The study further sought to identify any barriers to the increased use of CRM binder in Queensland.

Use of crumb rubber in the binder used for asphalt and sprayed seals provides a high-value application of this recycled material. The available body of knowledge shows that the use of CRM binders these applications can lead to much-improved field performance (e.g. improved durability and/or cracking resistance). Significant environmental benefits may also be achieved in the form of road noise reduction when compared to conventional bitumen, reduction of CO_2 emissions and reduction in the use of non-renewable road construction materials on a whole-of-life basis.

Currently, only a limited range of the CRM technologies available internationally are applied in Queensland. Estimates show that if CRM binder was used widely in asphalt and sprayed seals in Queensland, on both the state-controlled network and the local government network, a significant proportion of end-of-life tyres could be put to beneficial use.

The main barriers to wider application of CRM binders are socio-economic factors including cost, environmental and occupational health and safety concerns. Overseas experience indicates that these concerns may be mitigated by applying appropriate engineering measures. The supply of CRM binder to TMR projects will also require industry to invest in additional infrastructure/equipment. This is more likely to occur when industry is confident of the future usage of CRM binders.

Overseas studies also indicate that CRM binders can provide a cost-effective alternative to conventional binders on a whole-of-life basis. However, these studies have also included that the initial construction costs are likely to increase when CRM binders are used in some cases (e.g. if used in place of unmodified bitumen in a sprayed seal or in asphalt). In other cases their initial cost may be cost competitive when compared to the equivalent (non-CRM) PMB alternative (e.g. when used on a like for like basis for a PMB sprayed seal).

It is recommended that, going forward, this project focus on working with industry to facilitate the transfer of CRM binder technologies for use in sprayed seals and asphalt to Queensland and/or increased use of CRM binders. This would involve the construction of carefully controlled demonstration trial sections combined with appropriate laboratory experiments. The field and laboratory experimental matrix should be designed in such a way that meaningful conclusions can be drawn with respect to the performance of CRM binder technology compared to conventional alternatives. The development of performance-based specifications for both asphalt and seals will allow for a wide range of innovative technologies to be included. TMR has recently completed a demonstration CRM binder sprayed seal project in its Darling Downs Distirct which should be monitored to confirm the long term performance of CRM binders.

It is also recommended that comparative emission studies be performed locally to pre-empt and alleviate any future concerns regarding occupational health and safety and environmental impact. Trials should include the use of warm mix technologies for asphalt, and possibly for sprayed seals, to assess possible reductions in emissions, including odour, fumes and smoke.

11.1 Queensland Specifications for Sprayed Seals

Specifications for the use of CRM binders in sprayed seals in Queensland already exist. The specifications (like most current asphalt and sealing specifications) were, however, written to suit a certain range of products. The current sealing specifications are for high viscosity wet process

CRM binders with a minimum crumb rubber content of approximately 15%. It is worthwhile investigating whether it is possible to widen the specifications to allow:

- the use of no-agitation wet process CRM binder, which can be hauled for longer distances and used in remote areas without segregation of the binder. CRM binder sprayed seals have been used on selected contracts in Western Queensland although some problems with segregation of the rubber have limited increased use.
- the use of combinations of crumb rubber and other polymers such as SBS, which may lead to superior binders
- the use of combinations of CRM binders and warm mix technologies
- the use of different percentages of crumb rubber
- the use of alternative crumb rubber gradations that may be more cost effective to produce.

11.2 Queensland Specifications for Asphalt

There are currently no specifications for the use of CRM binders in asphalt in Queensland. It would however be possible to adapt the specifications used in Victoria or New South Wales. However, these only cover a very specific type of CRM binder technology and will not maximise the opportunities available for using CRM binders, as these specifications use older technology.

More advanced technology (such as the wet – agitation or wet – no agitation processes) already exists, as it is used in various forms around the world. Research is needed to facilitate the transfer of this technology to Queensland. This could be achieved in much the same way as high modulus asphalt technology (EME2), which was recently introduced in Australia in cooperation between road jurisdictions, industry and ARRB.

12 RECOMMENDATIONS AND FUTURE WORK

This report documents that the use of CRM binder in both asphalt and sprayed seals can lead to improved field performance. The main barriers to wider application of CRM binder are socio-economic factors including environmental and occupational health and safety concerns, the potential for higher capital costs, availability of equipment and expertise locally. Overseas experience indicates that environmental and health and safety issues may be mitigated by applying appropriate engineering measures. Overseas studies also indicate that CRM binders can provide a cost-effective alternative to conventional binders when considered from a whole-of-life cost perspective.

Methods have been identified to capture emissions from field trials. Explorative laboratory testing was conducted to demonstrate how crumb rubber affects the performance properties of bitumen at different crumb rubber contents, rubber grading and digestion times.

The report presents the benefits of wider use of CRM binder technology and strategies to overcome barriers to further implementation. It is proposed that going forward, future work focusses on working with industry to facilitate the use of CRM binders in sprayed seals and asphalt in Queensland. Two options are identified to achieve increased use of CRM binders in Queensland:

1. Enable contractors to choose between CRM binder and conventional PMB for any sprayed seal project where conventional PMB would normally be specified. This option involves consultation with industry to update the TMR specifications to facilitate increased use of CRM binders in sprayed seals while addressing supply/binder stability concerns with existing CRM binder grades.
2. Conduct trials of CRM open-graded asphalt (OGA) surfacings. It is proposed that the TMR OGA specification be used to develop a specification for demonstration trials with OGA containing CRM binder. The construction of carefully selected and controlled demonstration trial sections combined with appropriate laboratory experiments will facilitate meaningful conclusions on the performance of CRM binder technology compared to conventional alternatives.

Future work proposed for Year 2 of the project includes:

- Working with industry to develop a set of specifications for asphalt and sprayed seals to be considered for inclusion in demonstration trial(s).
- Working with industry and TMR to organise the construction of carefully selected and controlled demonstration trial sections combined with appropriate laboratory experiments. The process followed for the EME2 technology transfer project will be used as a model. The short-term focus will be on organising a demonstration trial with OGA containing CRM binder, although trials of other technologies will also be considered. Completing this component of the project is contingent on a suitable site being identified and the construction trials being funded by the Queensland Transport and Roads Investment Program (QTRIP).
- Comparative emission studies will be conducted locally to pre-empt and alleviate any future concerns regarding occupational health and safety and environmental impact. The aim is to include trials of warm mix technologies for asphalt to assess possible reductions in emissions including odour, fumes and smoke. Completing this component of the project is contingent on a suitable site being identified and construction of pavements being funded by QTRIP.
- Comparing of the performance properties of CRM binders produced in accordance with various available international specifications. This will benchmark the performance of local CRM binders against current international practices. Sealing binders from South Africa and California, and asphalt binders from the US and Europe, are of particular interest.

- Based on findings of trials and laboratory testing, revising CRM asphalt and CRM seal specifications for further trials/use on TMR projects.

In addition, it is recommended that future years include the development of training material and provision of technical workshops to disseminate the research findings to stakeholders. Information and training packages for the Queensland Department of Environment and Heritage Protection can also be developed, as required if included in the scope of the project.

The methodologies for Year 3 and 4 will be revisited based on the findings of previous years.

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APPENDIX A ENTOX REPORT ON MONITORING OF EMISSION AT A CRUMB RUBBER SPRAYED SEAL TRIAL

national research centre for environmental toxicology

Monitoring of emission from bitumen and crumb rubber mixed bitumen

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April 2015

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Abbreviations

BaP	Benzo(a)pyrene
CRM	Crumb rubber modified
PAHs	Polycyclic aromatic hydrocarbons
TMR	Transport and Main Roads, Queensland
TSP	Total suspended particles
VOCs	Volatile organic compounds
LOR	Limit of Report

Introduction

Introduction of crumb rubber in bitumen used in road construction can be a potentially valuable way to recycle the vast amount of used tyres in Australia. However, there are concerns about the environmental and occupational health and safety regarding the use of crumb rubber modified (CRM) binder/asphalt, especially about the emission of harmful organic chemicals during road construction (i.e. high temperature condition).

In this study we monitored the level of chemicals, namely Volatile organic compounds (VOCs) and Polycyclic aromatic hydrocarbons (PAHs), as well as the Total Suspended Particles (TSP) emitted from mixes containing CRM binder and conventional Polymer Modified Binder (PMB) during pavement sprayed seal trial held in South East Queensland.

VOCs are defined here as organic compounds having a vapour pressure greater than 10 Torr at 25°C and 760 mm Hg and the VOCs measured in this study are among the 189 hazardous air pollutants (HAPs) listed in the US Clean Air Act (1990). Some of them are routinely monitored in the atmosphere due to their toxicity, e.g. the BTEX (Benzene, Toluene, Ethylbenzene and Xylenes) group and some chloroalkanes. Both groups are included in the Air Policy Act of Queensland (2008).

PAHs are a complex class of organic compounds containing two or more fused aromatic rings, and containing only carbon and hydrogen atoms. The smallest member of the PAH family is naphthalene and the most extensively studied PAH compound is benzo(a)pyrene or BaP, due to its carcinogenic property. The State of Queensland also includes the maximum level of BaP in the Air Policy Act (2008). In this study, we measure 13 PAHs that are in the priority list of the USEPA including BaP.

Total suspended particles (TSP) is an measure of the mass concentration of particulate matter (PM) suspended in the air. They are tiny airborne particles or aerosols that are less than 100 micrometers. Particulate matter is composed of both coarse and fine particles with fine particles having more impact on human health than the coarse ones.

The objectives of the project were to:

a) Measure the levels of TSPs, VOCs and PAHs on site during asphalt work.
b) Find out if there is any difference in pollutant emission between CRM and conventional spray sealing operations.

Methodology

Monitoring Sites

There were two monitoring sites, one for CRM sprayed seal section (TMR Class S1.8R) and other for conventional PMB sprayed seal section (TMR Class S0.7S). The sites were located on the same side of the road (6.5 m from the edge of the lane line) downward of the wind direction to maximise the chance of catching the emission plume.

Methods of Air sampling

a) Sampling for VOCs using vacuum canister.

For VOCs analysis, air samples were collected using a special vacuum canister which consisted of a pre-evacuated canister with a vacuum gauge and a critical orifice controller. The sampling flow rate was preadjusted to fill the 6-L canister in 3 hours and was calibrated against an Air Flow Calibrator. Sampling canisters were cleaned by repeated evacuating and filling of clean air for 4–5 circles. All the samples were collected in the field from a height of 1.0 m.

Two background samples were collected in two consecutive days before the construction work at one of the monitoring site (346 Laidley Plainland Rd).
During construction, samples were collected every 3-h after bitumen spray. Due to time constraint, only 2 samples were collected for the conventional spray while 3 samples were collected for the CRM spray.

b) Sampling for TSP and PAHs using active air sampler.

Samples were collected onthe roadside,downwind from the application stripes. Two air samplers, including one high volume sampler (HVS) and one low volume sampler (LVS) operated at flow rates of ~4 and ~60 m^3/hour respectively. As shown in Figure 1, air was drawn through a glass fibre filter (GFF) to collect suspended particles and thus particle-associated chemicals and then through a polyurethane foam (PUF) plug to collect compounds in the vapour phase. After sampling, GFF and PUF samples were stored at -20 ℃ until analysis.

Background sample (24-hour) was collected at site 1 before the application. 3-hour event samples were collected at both site 1 and site 2 (where polymer-based bitumen applied), namely 0~3 hour (3 hours from the start of the application), 3~6 hour and 6~9 hour.

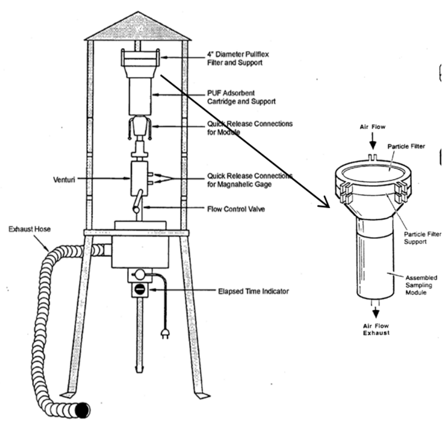

Figure 1. Schematic graph of air samplers

Details for the samples collection are shown in Table 1.

Table 1. Sample collection information

	VOCs			PAHs		
Site #	**Date Deployed**	**Purpose**	**Time sampled (h)**	**Date Deployed**	**Purpose**	**Time sampled (h)**
Site 1	27/2/2015	Background	24	27/2/2015 (HVS)	Background	24
CRM section	28/2/2015	Background	24	27/2/2015 (LVS)	Background	24
	2/3/2015	During construction	3	2/3/2015 (HVS)	During construction	3
	2/3/2015	3h after	3	2/3/2015 (HVS)	3h after	3
	2/3/2015	6h after	3	2/3/2015 (HVS)	6h after	3
				2/3/2015 (LVS)	During & after	6

Site 2	2/3/2015	During construction	3	2/3/2015 (HVS)	During construction	3
Conventional section	2/3/2015	3h after	3	2/3/2015 (HVS)	3h after	3
				2/3/2015 (LVS)	During & after	6

Chemical Analysis

a) VOCs analysis

Analysis of VOCs was performed by Qld Health Forensic Scientific Services using established protocol (USEPA Method TO-15). Air samples from the canisters were analysed using gas chromatography-mass spectrometry (GC-MS). The detailed list of compounds can be seen in Table 2.

Table 2. Main groups of VOC chemicals analysed

Group	No. of substances analysed	LOR (ppb)
Alkanes	9	0.5
BTEX & related compounds	11	0.5
Alcohols & ketones	13	0.5
Halogen alkanes	21	0.5
Chloro-benzenes	6	0.5

b) PAHs analysis

Analysis of PAHs was performed by Entox. PAHs in particulate phase (GFF samples) and from gas phase (PUF samples) were extracted separately using an Accelerated Solvent Extractor after being spiked with a solution containing 8 deuterated PAHs at different levels as the internal standards. Extracts were concentrated to 1 mL in hexane before being cleaned up by neutral alumina and silica. After clean-up, the samples were carefully blown down to 25 µL and a recovery standard was added before instrument analysis.

Samples were analysed using a Thermo DFS high resolution mass spectrometer (HRMS) coupled to a Thermo TRACE 1310 gas chromatograph (GC). 1.6 µL of each sample was injected in splitless mode and a DB-5MS column (J&W Scientific) was used to separate the compounds. The HRMS was operated in electron impact (EI) mode applying an electron energy of 70eV. Resolution was set to ≥10,000 (10% valley). The instrument was operated in multiple ion detection (MID) mode and a total of 13 PAHs were screened and quantified: phenanthrene (Phe), anthracene (Ant), fluoranthene (Flu), pyrene (Pyr), benzo[a]anthrancene (BaA), chrysene (Chr), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[e]pyrene (BeP), benzo[a]pyrene (BaP), indeno[1,2,3-c,d]pyrene (IcdP), dibenzo[a,h]anthracene (DahA) and benzo[g,h,i]perylene (BghiP).

Results and Discussion

VOCs

Background:
The levels of all VOCs were <LOR in background samples except 4 compounds (hexane, ethanol, acetone, methylene chloride). However, their levels were low and in the range previously reported for ambient air.

During and after construction:
Apart from the appearance of some alkanes and napthalene during the construction work, the levels of other VOCs in the construction sites (CRM and conventional) were low (mostly <LOR). The overall profiles of these samples were similar to those of the background samples.

Some heavy alkanes were detected during the spray of CRM bitumen while only trace level of undecane was detected in the fume of conventional PMB sprayed seal section. This is probably because of the adding of curing/cutter oil containing alkanes to the bitumen spray, with larger amount added to the CRM bitumen. The quick decrease of alkane concentrations in the air was also expected since Farshidi et al. (2013) had observed that most of the alkanes volatilize during the first hour of construction. Almost no alkane with <12 C was detected in the air 2 hours after compaction (Farshidi et al., 2013).

Naphthalene, the lightest PAH compounds, was detected only during the period of spray in both CRM and conventional treatment. However, the level of naphthalene measured in the CRM fume is almost 20-folds that of naphthalene in the polymer fume. This result is consistent with the outcome of alkane emission but did not reflect the emission of other PAHs (see the next section).

Detailed results are showed in Table 3.

Table 3. VOCs concentrations in different air samples

Chemicals / Sample name	14PW132 0-3h after polymer spray	14PW133 0-3h after CRM spray	14PW134 3-6h after CRM Spray	14PW135 6-9h after CRM Spray	14PW136 3-6h after polymer spray	14PW137 6-7h after polymer spray	14PW138 Background	14PW139 Background
Pentane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Hexane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	**1.1**	< LOR
Heptane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Octane	< LOR	**0.63**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Nonane	< LOR	**1.8**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Decane	< LOR	**4.4**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Undecane	**0.54**	**21.0**	**0.50**	< LOR	< LOR	< LOR	< LOR	< LOR
2-Methyl butane	**0.68**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
2,2,4-Trimethylpentane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Cyclohexane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,3-Butadiene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Benzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Toluene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Ethylbenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
m- & p-Xylene	< LOR	**1.0**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
o-Xylene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Styrene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
4-Ethyltoluene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,3,5-Trimethylbenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,2,4-Trimethylbenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
p-Diethylbenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Naphthalene	**0.95**	**23**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Carbon disulfide	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Ethanol	**11**	**1.4**	**1.5**	**1.1**	**1.6**	**1.1**	**2.8**	**4.7**
Isopropyl Alcohol	0.60	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Acetone	**3.7**	**1.1**	**0.93**	**1.3**	**0.92**	**0.88**	**3.0**	**1.9**
Methyl tert-butyl ether	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Methyl ethyl ketone	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Ethyl acetate	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Vinyl acetate	**1.4**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Tetrahydrofuran	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Methyl isobutyl ketone	< LOR	**0.56**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Methyl butyl ketone	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Acrolein	**1.3**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,4-Dioxane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Methyl methacrylate	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
2-Propene nitrile	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Dichlorodifluoromethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Dichlorotetrafluoroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Trichlorofluoromethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,1,2-Trichloro-1,2,2-trifluoroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR

Bromomethane	**0.52**	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Bromodichloromethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Dibromochloromethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,2-Dibromoethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Bromoform	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Chloromethane	**0.66**	**0.63**	**0.64**	**0.62**	**0.59**	**0.56**	< LOR	< LOR
Chloroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,1-Dichloroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,2-Dichloroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,1,1-Trichloroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,2-Dichloropropane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,1,2-Trichloroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,1,2,2-Tetrachloroethane	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Hexachlorobutadiene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Methylene Chide	< LOR	< LOR	< LOR	**0.92**	< LOR	< LOR	**5.0**	**9.1**
Chloroform	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Carbon tetrachide	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Vinyl bromide	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Vinyl chide	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Allyl chide	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,1-Dichloroethylene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
trans-1,2-Dichloroethylene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
cis-1,2-Dichloroethylene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Trichloroethylene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
cis-1,3-dichloropropene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
trans-1,3-dichloropropene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Tetrachloroethylene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Chlorobenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
Benzyl chide	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,3-Dichlorobenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,4-Dichlorobenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,2-Dichlorobenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
1,2,4-Trichlorobenzene	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR

TSP and PAHs

Background:
The levels of TSP and PAHs in background samples were low compared with the recently measured concentrations of PAHs in Brisbane (Wang et al., 2013). It is no surprise because the monitoring sites are in a rural area. Although it is on the roadside, the traffic is usually low and thus probably does not affect the level of PAHs in the air.

During and after construction:
Significant increase in TSP and PAH concentrations were detected in samples collected during and after the spray, in both treatments.

Fig. 2 showed that the concentration of TSP, measured using the HVS, increased more in the site of CRM treatment than the conventional one (~2.5 times higher). It is noted the level of TSP from 0-3h after spray in the CRM treatment was higher than the air quality objective of 90 μg/m^3 (average over the period of a year) set by the State of Queensland (SoQ, 2012). Even the 6-hour average value, measured by the LVS, was still at the quality objective level (94 μg/m^3). Fig. 2 showed that the concentration of TSP, measured using the HVS, increased more in the site of CRM treatment than the conventional one (~2.5 times higher). This is consistent with the conclusion of the US NIOSH health hazard evaluation report that exposures to TSP during CRM work are generally higher than during conventional work (NIOSH, 2001). Although the average concentration of TSP over longer period will decrease and thus reduce the risk for the non-occupational population, it is important to continue the study in more detailed to determine the level of occupational risk for the construction workers.

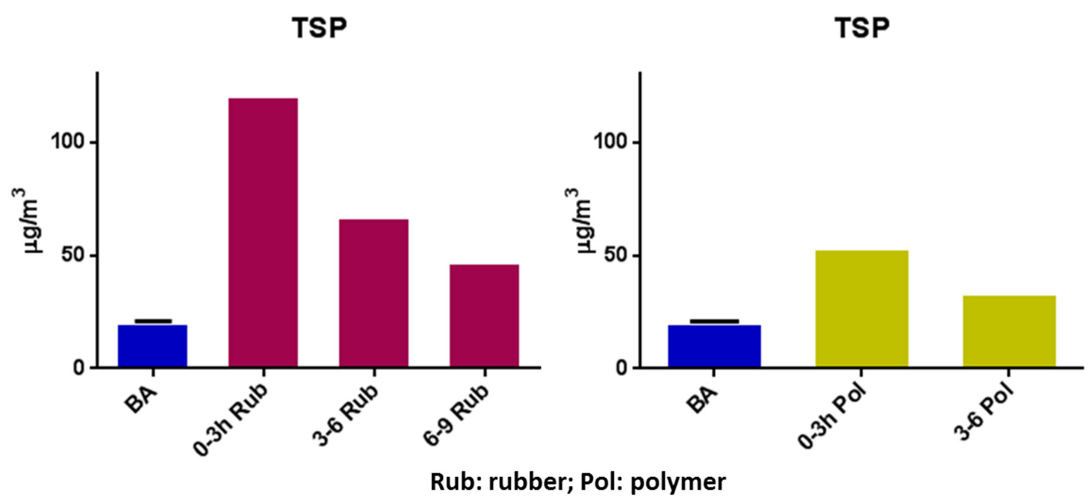

Figure 2. Total suspended particulate (TSP) before and after spray in both treatments.

Fig. 3 presented the concentrations of BaP and of total PAHs in samples before and after the sprayed sealing. Although there was an increase in the level of BaP and PAHs in the ambient air around the construction sites, the highest concentrations measured (0-3h after spray) in both treatments were still much lower than the air quality objective of 300 pg BaP/m^3 set by the State of Queensland (SoQ, 2012). Considering BaP alone, the peak concentrations measured in this study were comparable with the average BaP concentrations near a busy road in Brisbane.

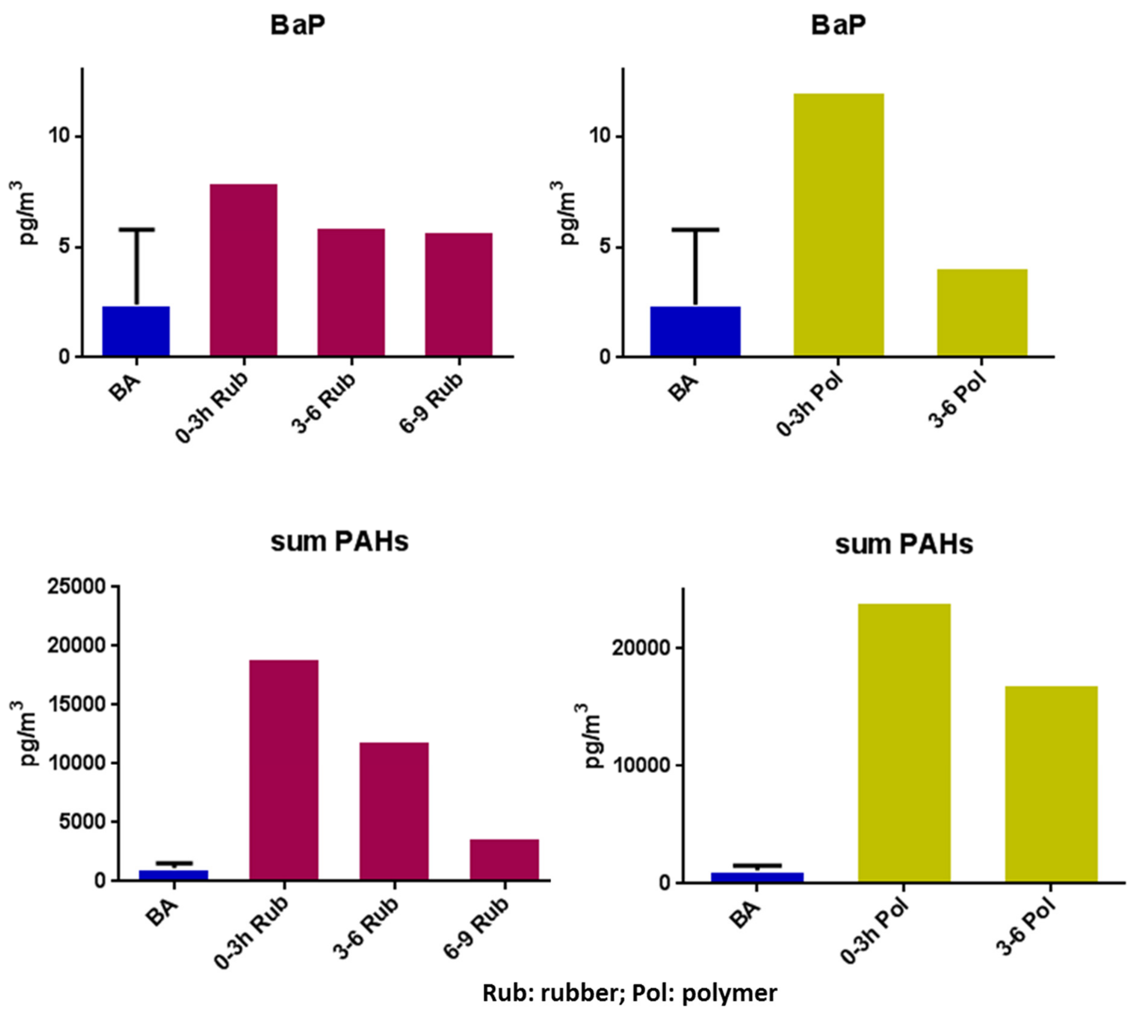

Figure 3. Concentration of BaP and total PAHs before and after spray in both treatments.

Limitations/Cautions

This study was designed to compare the levels of air pollutants in roadside locations near pavement construction. It aimed to measure the average concentrations of air pollutants in the ambient atmosphere around construction sites before, during and shortly after construction so interpretation for exposure or risk assessment should be done with caution.

It is not a study to measure emission flux or occupational exposure during pavement work.

Conclusions/Recommendations

Please sum up findings which compares emission levels for the different emission chemicals for both CRM and PMB sprayed sealing scenarios and assess these levels in relation to relevant air quality standard

Exposures to TSP, VOCs were generally higher during CRM compared to PMB sprayed sealing. Meanwhile, more PAHs were emitted from PMB scenario than the CRM one. However, the number of samples in this study is too small to conduct statistical comparison.

Although there is no exceedance of air quality guideline for any of those pollutants, there may be some concern about the level of TSP during the CRM spray that may impact the health of the workers if protective gears are not worn. More detailed study to determine the exact level of TSP and the components thereof is required to understand the extent of occupational exposure to TSP during CRM spray.

Reference

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Wang, X, Thai, P, Li, Y, Hawker, D, Gallen, M, Mueller, J. Changes in concentrations of PAHs and PCBs in Brisbane atmosphere between summer 1994/95 and 2012/13. Organohalogen Compounds Electronic (http://www.dioxin20xx.org/pdfs/2013/4311.pdf)