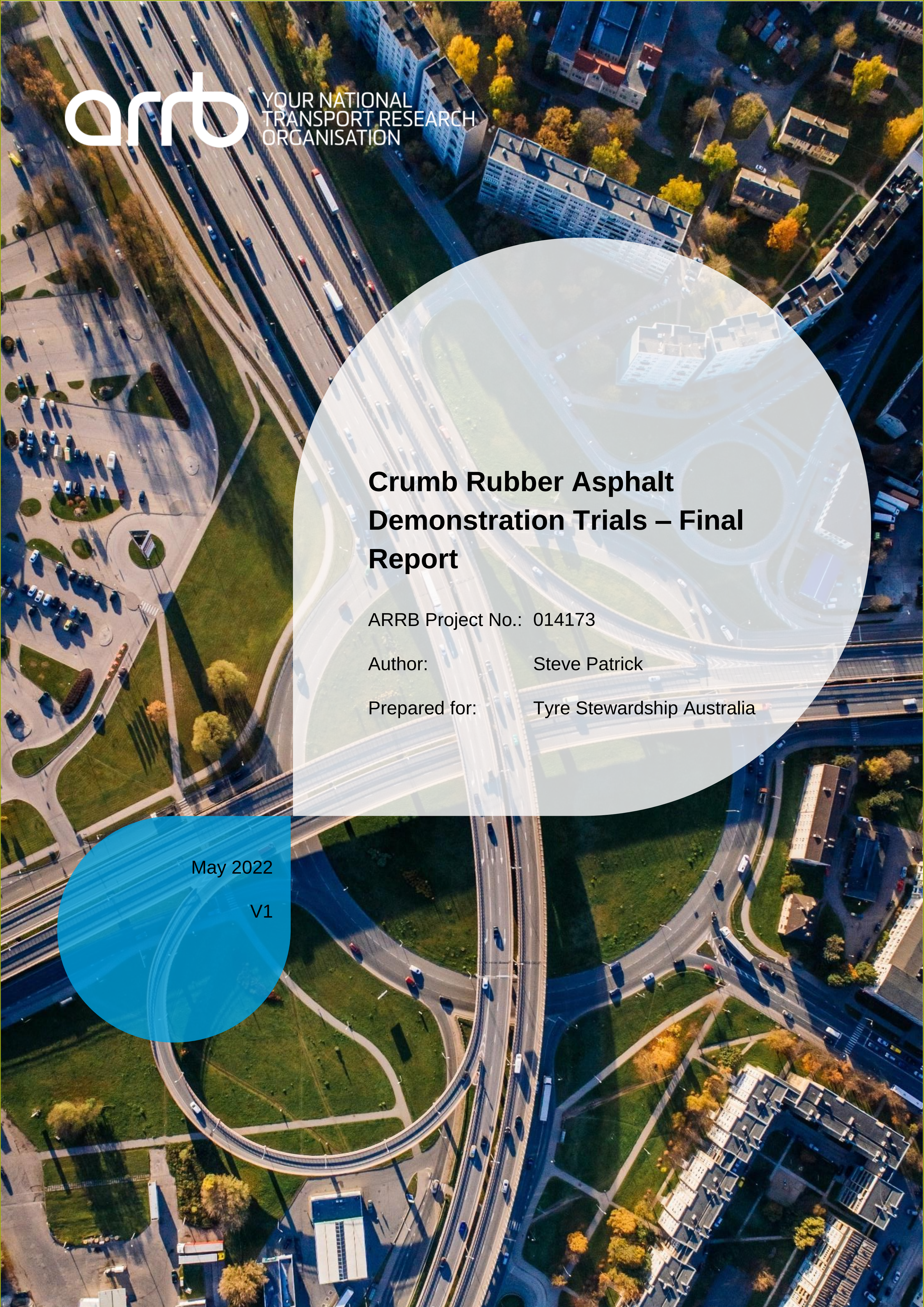

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Crumb Rubber Asphalt Demonstration Trials – Final Report

ARRB Project No.: 014173

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Summary

The crumb rubber asphalt demonstration trial was a collaborative effort organised by Tyre Stewardship Australia (TSA), Department of Transport (DoT) Victoria, and the Australian Road Research Board (ARRB). The project was undertaken with the cooperation of local asphalt manufacturers.

The goal of this project was to increase consumption of recycled tyre-derived crumb rubber and promote sustainable solutions for surfacing heavily trafficked roads. The trial was organised so that the performance of crumb rubber asphalts can be assessed in the field under real traffic and climatic conditions, compared to other asphalts under standard testing conditions, and to characterise the material properties in a laboratory. This work will inform DoT of the capabilities of crumb rubber asphalts and will assist in generating the required information for them to be included in specifications for wider use.

Additionally, the processes and outcomes of the trial may inform a framework for implementing the use of recycled and innovative materials that are not included in traditional specifications. There is a significant amount of work in designing, assuring the performance of, and implementing new products, and trials such as these enable direct collaboration between road agencies and industry in a formal and supported manner.

The trial was established at East Boundary Road, East Bentleigh, Victoria. Many samples were collected from the trial and have been tested in the laboratory to benchmark the potential performance of crumb rubber asphalt. Monitoring of the trial site was undertaken to collect data regarding the in situ performance, including cracking, roughness, rutting, texture and skid resistance. The initial results showed an improvement in condition for all measures with the new surface in place, and the ongoing monitoring has observed good performance over the two-year monitoring period of the trial. These assessments will inform DoT how these products may be incorporated into its specifications, which will encourage their widespread use and an improvement in sustainable road building practice.

A study of the environmental emissions during the asphalt paving was undertaken to measure the potential fuming exposure of crumb rubber asphalts, and to provide a comparison to control mixes. The analysis found no significant fuming exposure to volatile organic compounds. Detected values of total suspended solids, bitumen fumes, and polycyclic aromatic hydrocarbons were below recommended guidelines, and were lower for the crumb rubber asphalts compared to the control asphalts. Benzothiazole was measured in higher quantities for the crumb rubber mixes compared to control asphalts, but this was not correlated to any reported symptoms of irritation.

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1. Introduction

The crumb rubber asphalt demonstration trial was a collaborative effort organised by Tyre Stewardship Australia (TSA), Department of Transport (DoT) Victoria, and the Australian Road Research Board (ARRB). The project was undertaken with the cooperation of local asphalt manufacturers.

Whilst asphalt manufacturers have developed crumb rubber asphalt products, many do not comply with current DoT specifications, and thus cannot be widely used. The trial provided an opportunity to test crumb rubber asphalts both in the laboratory and in the field under real traffic and climatic conditions, so that DoT can assure that the products will perform to a certain standard, and subsequently be included in their specifications to encourage the adoption of these products.

This project will promote sustainable solutions for surfacing heavily trafficked roads. The goal is to increase consumption of tyre-derived crumb rubber, a recycled product.

Additionally, the processes and outcomes of the trial may inform a framework for implementing the use of recycled and innovative materials that are not included in traditional specifications. There is a significant amount of work in designing, assuring the performance of, and implementing new products, and trials such as these enable direct collaboration between road agencies and industry in a formal and supported manner.

The trial was established at East Boundary Road, East Bentleigh, Victoria, and included four different crumb rubber asphalt mixes, and two control sections to provide a basis for comparison of the new mixes (Figure 1.1).

This project report forms part of Milestone 6 requirements for the crumb rubber asphalt demonstration trial project, and describes the state of the trials two years after construction, including:

- summary of trial site
- field-testing results
- emissions monitoring results
- laboratory testing results of plant asphalt mixes
- condition monitoring outcomes
- record of site inspections.

Figure 1.1: Crumb rubber asphalt at East Boundary Road

2. Trial Site Construction

2.1 Site Description

The trial site was located at East Boundary Road, East Bentleigh, Victoria, between Centre Road and South Road. East Boundary Road features a parking lane, and two through lanes in each direction, separated by a median.

The trial encompassed all three lanes of the southbound direction of East Boundary Road. This section is straight and flat.

2.2 Section Details

A summary of the trial site sections and locations is provided in Table 2.1. The zero-chainage location was 30 m north of Omeo Court. A map view of the trial site sections is provided in Figure 2.1.

Table 2.1: Summary of trial sections

Section number	Chainage		Product
	Start (m)	End (m)	
1	0	200	10 mm dense graded crumb rubber asphalt
2	200	447	10 mm stone mastic asphalt (type H) A10E (control)
3	447	647	14 mm gap graded crumb rubber asphalt
4	647	847	10 mm stone mastic crumb rubber (wet mix) asphalt (type N)
5	847	1,200	10 mm stone mastic asphalt (type N) A20E (control)
6	1,200	1,450	10 mm stone mastic crumb rubber (dry mix) asphalt (type N)

Figure 2.1: Map of trial site sections

Source: Google Maps (2020), 'East Bentleigh, Victoria', map data, Google, CA, USA.

2.2.1 Section 1: 10 mm DGA (Crumb Rubber)

Section 1 of the trial was laid on 15 March 2020, with a crumb rubber asphalt. The mix is a 10 mm dense graded asphalt, utilising C320 binder modified with 20% crumb rubber. An inspection after three months of trafficking found the asphalt to be performing well (Figure 2.2).

Figure 2.2: Section 1 at 3 months

2.2.2 Section 2: 10 mm SMA-H (Control)

Section 2 of the trial was laid on 16 March 2020, as a control mix. The mix is a 10 mm stone mastic asphalt, type H, utilising A10E binder. An inspection after three months of trafficking found the asphalt to be performing well (Figure 2.3 and Figure 2.4).

Figure 2.3: Section 2 at 3 months

Figure 2.4: Section 2 – close-up of surface at 3 months

2.2.3 Section 3: 14 mm GGA (Crumb Rubber)

Section 3 of the trial was laid on 17 March 2020, with a crumb rubber asphalt. The mix is a 14 mm gap graded asphalt, utilising C170 binder modified with 18% crumb rubber. An inspection after three months of trafficking found the asphalt to be performing well (Figure 2.5 and Figure 2.6).

Figure 2.5: Section 3 at 3 months

Figure 2.6: Section 3 – close-up of surface at 3 months

2.2.4 Section 4: 10 mm SMA-N (Crumb Rubber)

Section 4 of the trial was laid on 18 March 2020, with a crumb rubber asphalt. The mix is a 10 mm stone mastic asphalt, type N, utilising A20E binder that contains 10% crumb rubber. An inspection after three months of trafficking found the asphalt performing well (Figure 2.7 and Figure 2.8).

Figure 2.7: Section 4 at 3 months

Figure 2.8: Section 4 – close-up of surface at 3 months

2.2.5 Section 5: 10 mm SMA-N (Control)

Section 5 of the trial was laid on 22 March 2020, as a control mix (Figure 2.9). The mix is a 10 mm stone mastic asphalt, type N, utilising A20E binder. An inspection after three months of trafficking found the asphalt performing well, with some evidence of dragging from construction early in the section (Figure 2.10).

Figure 2.9: Section 5 at 3 months

Figure 2.10: Section 5 – close-up of surface at 3 months

2.2.6 Section 6: 10 mm SMA-N (Crumb Rubber Dry Mix)

Section 6 of the trial was laid on 23 March 2020, with a crumb rubber asphalt (Figure 2.11). The mix is a 10 mm stone mastic asphalt, type N, utilising A20E binder. This asphalt is a dry mix crumb rubber, with 1% of crumb rubber by mass of mix added. An inspection after three months of trafficking found the asphalt performing mostly well, but with some flushing and loss of texture in the wheelpaths (Figure 2.12).

Figure 2.11: Section 6 at 3 months

Figure 2.12: Section 6 – close-up of surface at 3 months

3. Environmental Emissions Monitoring

In order to assess the potential fuming exposure from crumb rubber asphalt mixes, emissions monitoring was undertaken by personal sampling for several airborne contaminants in the breathing zones of operators involved in the paving, including paving operators, screed operators, and rake hands.

The monitoring devices were assembled into small backpacks that were worn for the extent of the paving operations by the nominated members of the paving crew (Figure 3.1). The devices were used to collect samples for all the asphalts paved, both crumb rubber asphalts and control mixes, allowing comparison.

Figure 3.1: Emissions monitoring equipment loaded into backpacks

The results of the monitoring are compared against established workplace exposure standards and guidelines, such as those published by SafeWork Australia and the American Conference of Governmental Industrial Hygienists (ACGIH), as applicable. The complete emissions monitoring data are presented in Appendix A.

3.1 Volatile Organic Compounds

Volatile Organic Compounds (VOC) include numerous human-made and naturally occurring chemical compounds, and some are dangerous to human health or can harm to the environment. The results of the VOC monitoring are displayed in Table 3.1.

Table 3.1: VOC result comparison

Section	VOC	Spotter	Level hand	Paver driver
1	Aliphatic hydrocarbons (mg/m^3)	< 0.17	< 0.24	< 0.21
	Aromatic hydrocarbons (mg/m^3)	< 0.03	< 0.05	< 0.04
	Total VOC's (mg/m^3)	< 1.7	< 2.3	< 2.1
2	Aliphatic hydrocarbons (mg/m^3)	< 0.24	< 0.28	< 0.28
	Aromatic hydrocarbons (mg/m^3)	< 0.05	< 0.06	< 0.06
	Total VOC's (mg/m^3)	< 2.4	< 2.8	< 2.8

Section	VOC	Spotter	Level hand	Paver driver
3	Aliphatic hydrocarbons (mg/m^3)	< 0.24	< 0.28	< 0.28
	Aromatic hydrocarbons (mg/m^3)	< 0.05	< 0.06	< 0.06
	Total VOC's (mg/m^3)	< 2.4	< 2.8	< 2.8
4	Aliphatic hydrocarbons (mg/m^3)	< 0.25	< 0.19	< 0.22
	Aromatic hydrocarbons (mg/m^3)	< 0.01	< 0.08	< 0.04
	Total VOC's (mg/m^3)	< 2.5	< 1.9	< 2.2
5	Aliphatic hydrocarbons (mg/m^3)	< 0.19	< 0.20	< 0.15
	Aromatic hydrocarbons (mg/m^3)	< 0.04	< 0.04	< 0.03
	Total VOC's (mg/m^3)	< 1.9	< 2.0	< 1.5
6	Aliphatic hydrocarbons (mg/m^3)	< 0.22	< 0.23	< 0.17
	Aromatic hydrocarbons (mg/m^3)	< 0.04	< 0.05	< 0.03
	Total VOC's (mg/m^3)	< 2.2	< 2.3	< 1.7

There were no significant amounts of volatile organic compounds detected in any of the samples, for all asphalt mixes. All the detected levels were well below the time weighted average SafeWork Australia workplace exposure standards (Table A.1).

3.2 Benzothiazole

Benzothiazole is an aromatic heterocyclic compound, and many of its derivatives are found in commercial products and nature. There are no exposure standards set for Benzothiazole (BZ) in the working environment in Australia or in most other nations. Benzothiazole is classified under the Globally Harmonised System of Classification and Labelling of Chemicals (GHS) as a Category 2 Eye Irritant. There is limited evidence from overseas studies on asphalt crews, that the breathing zone levels of Benzothiazole are higher when laying crumb rubber modified asphalt (CRA) compared with conventional (stone mastic) asphalt. There is also some evidence that benzothiazole levels are positively correlated with symptoms of eye and respiratory tract irritation, but it has not been established whether the correlation is causal.

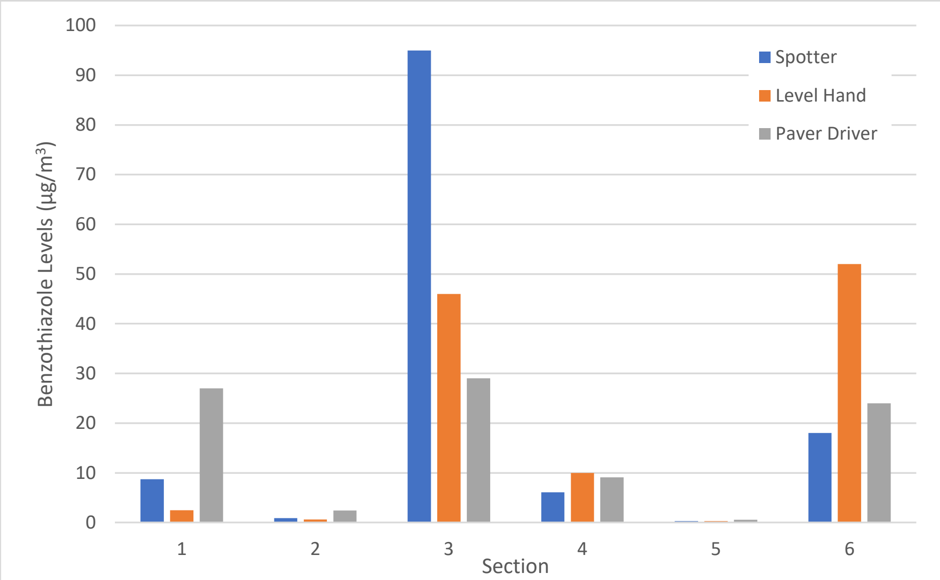
The results of the benzothiazole monitoring are listed in Table 3.2, and displayed in a chart in Figure 3.2.

Table 3.2: Benzothiazole result comparison

Section	Breathing zone Benzothiazole concentration (µg/m3)			Comment
	Spotter	Level hand	Paver driver	
1	8.7	2.5	27	Low visible fume. Paver pedestal fans on. Operators wearing A1P2 respirators. No symptoms reported.
2	0.9	0.6	2.4	Moderate Visible Fume Paver pedestal fans off. No respirators worn. Level hand described dry/stinging eyes.
3	95	46	29	Paver pedestal fans on. No respirators worn. Moderate fuming. Rubber odour evident. Level hand described light-headedness and sore throat which persisted into the next day.
4	6.1	10	9.1	Paver pedestal fans on. No respirators worn. Moderate fume level. Level hand described light-headedness.
5	0.29	0.3	0.56	Paver pedestal fans off No respirators worn. High visible fume level. Paver driver described sore throat.

Section	Breathing zone Benzothiazole concentration (µg/m3)			Comment
	Spotter	Level hand	Paver driver	
6	18	52	24	Paver pedestal fans off No respirators worn. Moderate fume level. No symptoms reported.

Figure 3.2: Benzothiazole result comparison



Operators' breathing zone concentrations of Benzothiazole were significantly higher when laying CRA (Sections 1, 3, 4, 6) than control SMA mixes (Sections 2 and 5). The results are consistent with those of overseas studies where measurement of benzothiazole exposures have been undertaken on crews undertaking CRA paving, both in terms of exposure patterns (i.e. CRA resulting in approximately 10 times higher exposures to benzothiazole) and the magnitude of the exposures.

The highest breathing zone benzothiazole levels were measured in Section 2 with the spotter having the highest exposure of the three operators monitored. This coincided with reported symptoms of light-headedness and sore throat from the level hand when questioned. The spotter did not report symptoms. The Section 3 CRA had a distinct rubber odour, which was not evident with other CRA mixes.

It is difficult to interpret the results of the monitoring in terms of reported symptoms due to the varied use of respiratory protection, variations in the amount of mix from night-to-night, weather conditions on each night such as air temperature, wind speed and direction, the use of the paver-mounted pedestal fans for some mixes and not others, and the side of the paver that the level hand was operating from (e.g. the level hand operated from the right-hand side of the Paver on 18/3/2020 and on the left-hand side on other nights). However, as symptoms of sore throat and stinging eyes were reported for both the control stone mastic mixes (where benzothiazole levels were low) and some of the trial CRA mixes (with elevated benzothiazole exposures) and no symptoms for other CRA mixes where benzothiazole levels were similar, there did not appear to be a correlation between benzothiazole levels and symptoms in this study.

3.3 Total Suspended Particulates

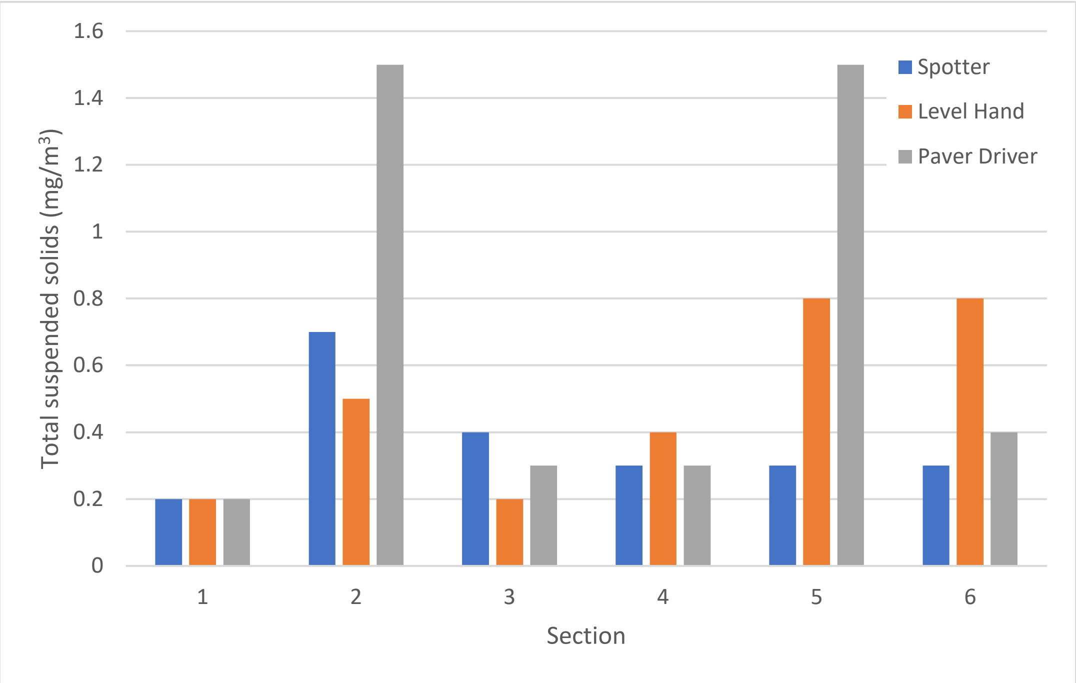
Total Suspended Particulates (TSP) can be made up of aerosols consisting of solids (e.g. dust) and condensed liquids (e.g. mineral oils and other semi-volatile organic compounds) suspended in air. Because the composition of TSP can vary greatly, depending on its source, there are no specific exposure standards set in the working environment in Australia. SafeWork Australia recommends that, where no specific exposure standard has been assigned and the substance is both of inherently low toxicity and free from toxic impurities, exposure to dusts (not otherwise classified (DNOC) should be maintained below 10 mg/m^3, measured as inhalable dust (8-hour TWA). Inhalable dust is that size range which can be inhaled and is nominally composed of particles of a size range 50% of which are less than 100 microns in mean equivalent aerodynamic diameter. TSP is of a wide range of particle sizes, some of which are in the inhalable range, and includes particles too large to be inhaled. The Australian Institute of Occupational Hygienists (AIOH) recommends a ‘Dusts Not Otherwise Specified’ (DNOS) trigger value of 5 mg/m^3 (inhalable fraction) be adopted to protect workers from potentially serious health effects due to insoluble or poorly water-soluble dusts of inherently low toxicity and free from toxic impurities and for which there is no other applicable Workplace Exposure Standard specified.

The results of the total suspended solids monitoring are listed in Table 3.3, and displayed in a chart in Figure 3.3.

Table 3.3: Total suspended solids comparison

Section	Total suspended solids (mg/m^3)		
	Spotter	Level hand	Paver driver
1	0.2	0.2	0.2
2	0.7	0.5	1.5
3	0.4	0.2	0.3
4	0.3	0.4	0.3
5	0.3	0.8	1.5
6	0.3	0.8	0.4

Figure 3.3: Benzothiazole result comparison



All TSP levels were below the SafeWork Australia recommended guideline value for Dusts Not Otherwise Classified (DNOS) of 10 mg/m^3 and the AIOH trigger value for DNOS of 5 mg/m^3.

The results indicate that the TSP exposure of the three members of the asphalting crew were significantly higher for the two control conventional stone mastic asphalt mixes (range 0.3 mg/m^3 to 1.5 mg/m^3) than for any of the CRA trail mixes (range 0.2 mg/m^3 to 0.8 mg/m^3). Previous overseas studies have shown no significant differences in the total particulate exposure levels between crews undertaking conventional SMA and CRA paving operations.

The highest TSP exposure levels were for the paver driver for the control mixes (1.5 mg/m^3 for both mixes). Observations indicated that the paver driver sits elevated above the hot asphalt and is consistently in the plume of bitumen fume from both the hopper and screed board. Additionally, the roof of the Paver acts to trap fumes in the breathing zone of the driver who is fixed in position whilst the level hand and spotter are free to move away from the plume.

3.4 Bitumen Fumes

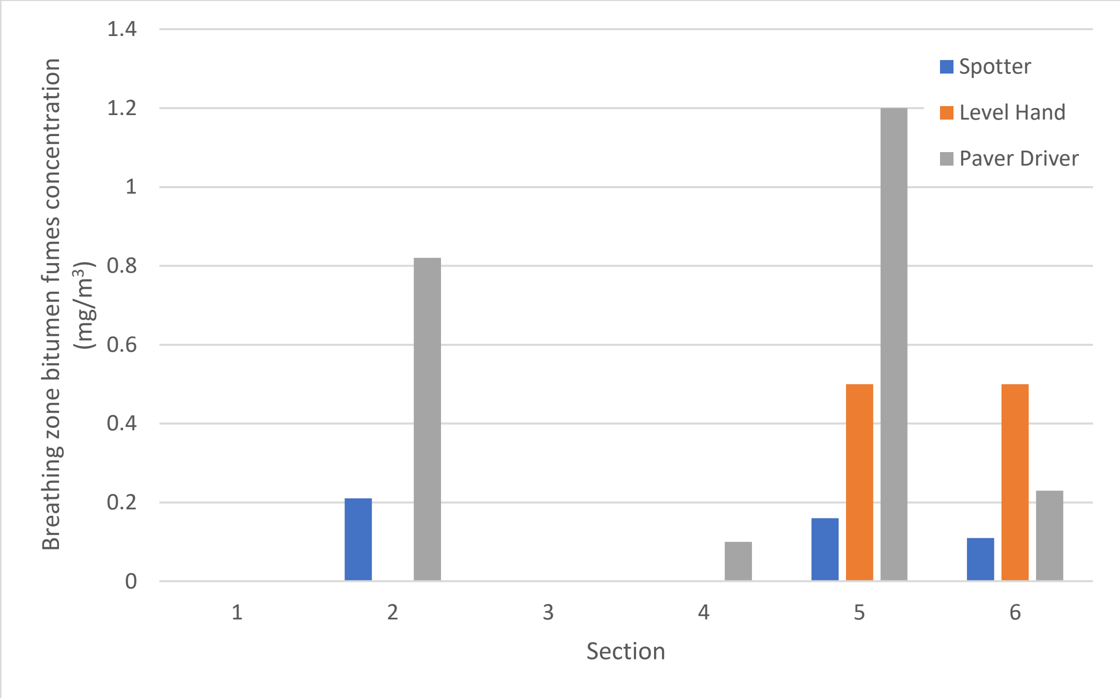
Studies of asphalt working populations suggest that bitumen fumes are irritating to mucous membranes and that these symptoms increase with increasing temperature of the asphalt. Safe Work Australia has set a time-weighted average workplace exposure standard for bitumen fume of 5 mg/m^3.

The results of the bitumen fumes monitoring are listed in Table 3.4, and displayed in a chart in Figure 3.4.

Table 3.4: Bitumen fumes comparison

	Breathing zone bitumen fumes concentration (mg/m^3)		
	Spotter	Level hand	Paver driver
1	< 0.1	< 0.1	< 0.1
2	0.21	< 0.2	0.82
3	< 0.1	< 0.1	< 0.1
4	< 0.1	< 0.1	0.1
5	0.16	0.5	1.2
6	0.11	0.5	0.23

Figure 3.4: Bitumen fumes comparison



The results indicate that the bitumen fume exposure monitoring of the three members of the asphalting crew were generally higher for the two control SAM mixes (Sections 2 and 5) (range 0.16 mg/m^3 to 1.2 mg/m^3) than for any of the CRA trial mixes (Sections 1, 3, 4, 6) (range < 0.1 mg/m^3 to 0.5 mg/m^3). Overseas studies have found no significant differences in bitumen fume exposure levels between crews paving with conventional SMA compared with CRA.

Similarly, to the TSP results, the highest bitumen exposure levels were for the paver driver for the control SMA mixes (0.82 to 1.2 mg/m^3). This most likely indicates that bitumen fume particles constitute a significant portion of the TSP. Laying of most of the CRA trial mixes had nondetectable to barely detectable levels of bitumen fume exposure, except for Section 6, which showed exposure levels between 0.11 mg/m^3 to 0.5 mg/m^3. All bitumen fume levels were well below the SafeWork Australia bitumen fume workplace exposure standard over the monitoring period and, when calculated as 8-hour time-weighted average exposures, would be below approximately 10% of the standard.

3.5 Polycyclic Aromatic Hydrocarbons

Polycyclic Aromatic Hydrocarbons compounds (PAHs) are molecules containing fused benzene ring systems. This structure includes the most basic two-ring naphthalene or four-ring pyrene and higher five-ring benzo(a)pyrene (B[a]P) and six-ring dibenzo(a,e)pyrene molecular compounds which are found in hundreds of PAH compounds. PAHs are widespread in the environment and exposure may occur due to combustion processes such as bushfires, volcanic activity, automobile exhaust, cooking and cigarette smoking.

PAHs are present in crude oils and crude oil products in low concentrations. Bitumen consists of a complex mixture of organic compounds, including polycyclic aromatic hydrocarbons (PAHs), which may vary in characteristics depending on the origin of the crude oil, refinery process, and additives. PAHs present in bitumen may become airborne and result in exposure to crews during paving operations. Measurement of PAHs is undertaken by quantifying 16 PAHs identified by the US EPA as posing the greatest concern, several of which are known to be potentially carcinogenic to humans.

Some overseas studies of asphalting crews have generally indicated that PAH exposure during conventional SMA paving are similar to those during CRA paving, whilst others have indicated that CRA paving results in slightly higher PAH exposures to crews compared with SMA paving.

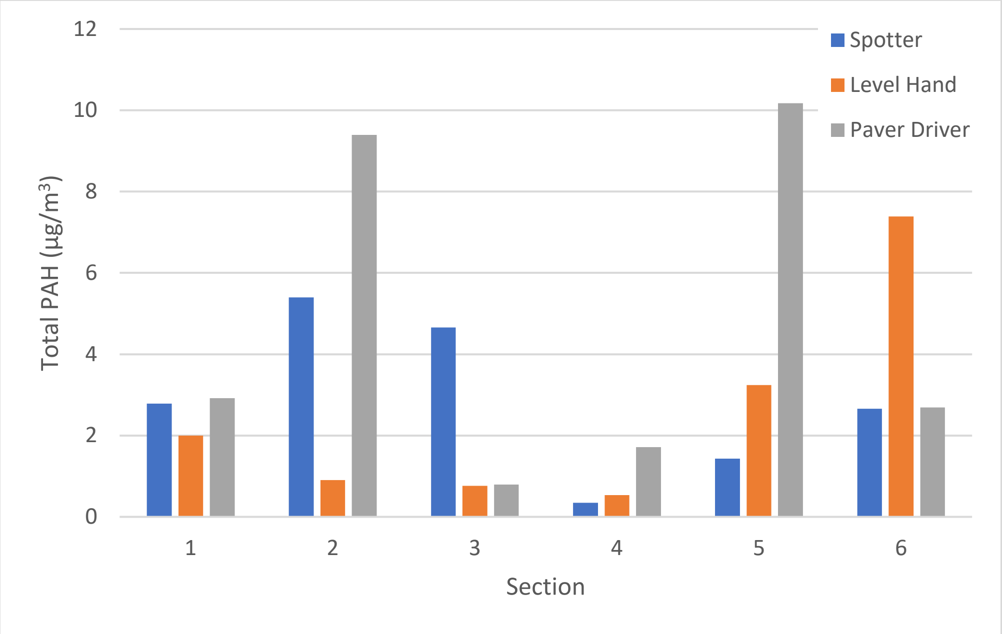
SafeWork Australia has set a workplace exposure standard for only one PAH, naphthalene – the simplest PAH – at 52 mg/m³ (10 ppm) as an 8-hour time weighted average concentration in the breathing zone. The Australian Institute of Occupational Hygienists (AIOH) recommends that a workplace exposure standard for benzo(a)pyrene (the most potent carcinogenic PAH) be set at 0.2 µg/m³ as an 8-hour time weighted average breathing zone concentration.

The results of the total PAH detected is displayed in Table 3.5, and displayed in a chart in Figure 3.5. A more detailed breakdown of individual PAH results is provided in Table A.2.

Table 3.5: Total polycyclic aromatic hydrocarbons comparison

Section	Total of 16 ESEPA priority PAHs (µg/m³)		
	Spotter	Level hand	Paver driver
1	2.78	2	2.92
2	5.4	0.9	9.4
3	4.66	0.76	0.79
4	0.34	0.53	1.71
5	1.43	3.24	10.18
6	2.66	7.39	2.69

Figure 3.5: Total polycyclic aromatic hydrocarbons comparison



The results of PAH monitoring indicate that the exposure of the three members of the asphalting crew to total 16 USEPA Priority PAHs were generally higher for the SMA mixes (Section 2 and 5) (range 0.9 µg/m³ to 10.18 µg/m³) than for any of the CRA trial mixes (Sections 1, 3, 4, 6) (range 0.34 µg/m³ to 7.39 µg/m³). This contrasts with the results of previous studies, and may reflect the slightly higher average temperatures of the control SMA mixes compared with the CRA trial mixes and the variations on weather conditions. The paver driver showed the highest median PAH exposures over all the trials of the three crew members tested, followed by the spotter and then level hand. It should be noted that all three operators were smokers and therefore there is a potential contribution of PAH exposures from smoking in addition to that from asphalt fume exposure.

Naphthalene (a non-carcinogenic and the most volatile PAH) was the most prominent PAH with the highest levels measured being 6.6 µg/m³ for the paver driver during laying of Section 2, and 3.2µg/m³ for Section 6. All levels of naphthalene were well below the SafeWork Australia workplace exposure standard of 52 mg/m³

(52,000 µg/m^3). The major PAHs compounds detected were naphthalene, fluorene, phenanthrene, anthracene and pyrene, none of which are classified as carcinogenic PAHs. Three samples showed detectable levels of benz(a)anthracene (a carcinogenic PAH) being Section 2 – paver driver 0.32 µg/m^3; Section 5 – paver driver 0.38 µg/m^3 and Section 3 – spotter 0.13 µg/m^3. Benz(a)pyrene (the most carcinogenically potent PAH) was not detected in any of the samples for either the SMA control or CRA trial mixes.

3.6 Discussion

The emissions study has explored the potential fuming exposure from CRA mixes, and a comparison to exposure from paving the control SMA asphalt mixes, for several operators involved in the paving.

Some VOCs are dangerous to humans and the environment, but there were no significant amounts of VOC detected in any of the CRA or SMA mixes.

Benzothiazole has been linked with symptoms of eye and respiratory tract infection, however a direct correlation has not been established. Limited overseas studies have indicated that benzothiazole levels are higher in the breathing zones of asphalt crews laying CRA compared to SMA. The results of this study support this observation, with benzothiazole levels being detected as significantly higher for the CRA mixes. However, the symptoms of irritation reported by the paving crew throughout this trial were not linked to the detected benzothiazole levels. Sore throats and stinging eyes were reported for both the SMA mixes that do not contain crumb rubber and had low benzothiazole levels, and symptoms were reported for some of the CRA mixes but not others where benzothiazole levels were comparable.

TSP, which can be made up of aerosols consisting of solids and condensed liquids, were measured at levels below SafeWork Australia guidelines and AIOH trigger values for all asphalt mixes. The TSP were significantly higher for the control SMA mixes compared to the CRA, which contrasts with some overseas studies which showed no significant differences.

Bitumen fumes were monitored as they may be irritating to mucous membranes, with symptoms increasing with increasing temperatures of asphalt. The study found that bitumen fume exposure was higher for the control SAM mixes than the CRA mixes, which contrasts with some overseas studies that found no significant difference. However, all bitumen fume levels detected were well below SafeWork Australia standard over the monitoring period, equivalent to below approximately 10% of the standard when calculated as 8-hour time-weighted average exposure.

PAHs are widespread in the environment, and several are known to be potential carcinogens. PAHs present in bitumen may be exposed to crews during paving. The study found that PAHs were generally higher for the SMA mixes than for the CRA mixes. This contrasts to previous studies that have found similar or higher levels of PAH for CRA compared to SMA, and may reflect the slightly higher paving temperatures of the SMA and variations in weather conditions. The most prominent PAH detected was naphthalene, but at a level well below SafeWork Australia standards. The major PAH compounds detected are not classified as carcinogenic. Both SMA sections and one CRA section showed detectable levels of benz(a)anthracene (a carcinogenic PAH), however the most carcinogenically potent PAH benz(a)pyrene was not detected in any of the samples for either the SMA control or CRA trial mixes.

4. Laboratory Testing Program

Many asphalt and material samples were collected from each of the suppliers during the trial, to conduct a series of laboratory tests to assure that the asphalt products conform to the expected performance requirements.

4.1 Binder Testing

Samples of all bituminous binders used in the crumb rubber asphalt trial, including control mixes, were collected at the asphalt mixing plant to check their adherence to their relevant specifications.

4.1.1 Section 1: 10 mm DGA (Crumb Rubber)

The Section 1 binder is a C320 bitumen. The binder has been tested for conformance to AS 2008 *Bitumen for Pavements*, with the results shown in Table 4.1. The binder satisfies all requirements of the standard.

Table 4.1: Section 1 binder testing results, C320

Test	Test method	Units	Result	AS 2008 specification limits	
				Min.	Max.
Viscosity at 60 °C	AS/NZS 2341.2	Pa.s	302	260	380
Viscosity at 135 °C	AS/NZS 2341.4	Pa.s	0.47	0.40	0.65
Penetration at 25 °C	AS/NZS 2341.12	0.1 mm	60	40	–
Insoluble material in toluene	AS/NZS 2341.8	%	0.0	–	1.0
Per cent increase in viscosity at 60 °C after RTFO treatment	AS/NZS 2341.2 AS/NZS 2341.10	%	233	–	300

4.1.2 Section 2: 10 mm SMA-H (Control)

The Section 2 binder is a A10E PMB. The binder has been tested for conformance to the Austroads PMB specification framework (AGPT/T190), with the results shown in Table 4.2. The binder satisfies all requirements of the specification.

Table 4.2: Section 2 binder testing results, A10E

Test	Test method	Units	Result	AGPT/T190 specification limits	
				Min.	Max.
Viscosity at 135 °C	AS/NZS 2341.4	Pa.s	0.71	–	1.1
Torsional recovery	ATM 122	%	76	60	86
Softening point	AS 2341.18	°C	90.5	88	110
Stress ratio at 10 °C	AGPT/T125	N/A	2.47	Record	
Consistency at 6%	AGPT/T121	Pa.s	1720	1000	–
Stiffness at 25 °C	AGPT/T121	kPa	20	–	30
Segregation – softening point top	AS 2341.18	°C	88.5	–	8
Segregation – softening point bottom	AS 2341.18	°C	87.5		
Segregation	AGPT/T108	%	1.0		

4.1.3 Section 3: 14 mm GGA (Crumb Rubber)

The Section 3 binder is a C170 bitumen with 18% crumb rubber, and 0.5% evotherm warm mix asphalt additive. The binder has been tested for conformance to an S45R binder in the Austroads PMB specification framework (AGPT/T190), with the results shown in Table 4.3. The asphalt production document notes that this binder was aiming to satisfy the requirements of the AAPA *Crumb Rubber Modified Open Graded and Gap Graded Asphalt Pilot Specification* (AAPA 2018) after 60 minutes of digestion, however instead compared to AP-T296-15 it satisfies the requirements except for consistency at 6%, segregation and compressive limit.

Table 4.3: Section 3 binder testing results, S45R (with evotherm)

Test	Test method	Units	Result	AGPT/T190 specification limits	
				Min.	Max.
Viscosity at 135 °C	AS/NZS 2341.4	Pa.s	0.86	–	4.5
Torsional recovery	ATM 122	%	31	25	55
Softening point	AS 2341.18	°C	55.4	55	65
Stress ratio at 10 °C	AGPT/T125	N/A	1.53	Record	
Consistency at 6%	AGPT/T121	Pa.s	491	800	–
Stiffness at 25 °C	AGPT/T121	kPa	112	–	180
Segregation – softening point top	AS 2341.18	°C	54.8	–	8
Segregation – softening point bottom	AS 2341.18	°C	60.8		
Segregation	AGPT/T108	%	–10.5		
Compressive limit 70 °C	AGPT/T132	mm	0.1	0.2	–

4.1.4 Section 4: 10 mm SMA-N (Crumb Rubber)

The Section 4 binder is a A20E PMB utilising 10% crumb rubber. The binder has been tested for conformance to the Austroads PMB specification framework (AGPT/T190), with the results shown in Table 4.4. The binder satisfies all requirements of the specification.

Table 4.4: Section 4 binder testing results, A20E

Test	Test method	Units	Result	AGPT/T190 specification limits	
				Min.	Max.
Viscosity at 135 °C	AS/NZS 2341.4	Pa.s	0.50	–	0.6
Torsional recovery	ATM 122	%	61	38	70
Softening point	AS 2341.18	°C	89.0	65	95
Stress ratio at 10 °C	AGPT/T125	N/A	2.07	Record	
Consistency at 6%	AGPT/T121	Pa.s	1663	500	–
Stiffness at 25 °C	AGPT/T121	kPa	16	–	35
Segregation – softening point top	AS 2341.18	°C	89.0	–	8
Segregation – softening point bottom	AS 2341.18	°C	88.0		
Segregation	AGPT/T108	%	1.0		
Compressive limit 70 °C	AGPT/T132	mm	0.1	–	–

4.1.5 Section 5: 10 mm SMA-N (Control)

The Section 5 binder is a A20E PMB with sasobit warm mix additive. The binder has been tested for conformance to the Austroads PMB specification framework (AGPT/T190), with the results shown in Table 4.5. The binder satisfies all requirements of the specification.

Table 4.5: Section 5 binder testing results, A20E (with sasobit)

Test	Test method	Units	Result	AGPT/T190 specification limits	
				Min.	Max.
Viscosity at 135 °C	AS/NZS 2341.4	Pa.s	0.26	–	0.6
Torsional recovery	ATM 122	%	54	38	70
Softening point	AS 2341.18	°C	82.5	65	95
Stress ratio at 10 °C	AGPT/T125	N/A	2.12	Record	
Consistency at 6%	AGPT/T121	Pa.s	2075	500	–
Stiffness at 25 °C	AGPT/T121	kPa	24	–	35
Segregation – softening point top	AS 2341.18	°C	77.2	–	8
Segregation – softening point bottom	AS 2341.18	°C	77.4		
Segregation	AGPT/T108	%	0.0		

4.1.6 Section 6: 10 mm SMA-N (Crumb Rubber Dry Mix)

The Section 6 binder is a A20E PMB. The binder has been tested for conformance to the Austroads PMB specification framework (AGPT/T190), with the results shown in Table 4.6. The binder satisfies all requirements of the specification.

Table 4.6: Section 6 binder testing results, A20E

Test	Test method	Units	Result	AGPT/T190 specification limits	
				Min.	Max.
Viscosity at 135 °C	AS/NZS 2341.4	Pa.s	0.47	–	0.6
Torsional recovery	ATM 122	%	66	38	70
Softening point	AS 2341.18	°C	88.0	65	95
Stress ratio at 10 °C	AGPT/T125	N/A	2.32	Record	
Consistency at 6%	AGPT/T121	Pa.s	1124	500	–
Stiffness at 25 °C	AGPT/T121	kPa	20	–	35
Segregation – softening point top	AS 2341.18	°C	86.5	–	8
Segregation – softening point bottom	AS 2341.18	°C	86.0		
Segregation	AGPT/T108	%	0.5		

4.2 Plant Mix Testing

Samples of each trial asphalt mix were collected at the plants from the delivery truck at the time of production, as they were being prepared for delivery (Figure 4.1).

Figure 4.1: Collecting crumb rubber asphalt samples

The samples were prepared and tested in the laboratory in order to verify the manufacturer-supplied designs for bulk density, average maximum density, and air voids by either the Marshall method (Table 4.7) or Gyratory method (Table 4.8).

The results indicate some differences (calculated as 'design' minus 'test') between the design and laboratory tested samples, most likely caused by derivations of binder content, aggregate gradings or segregation of the mix.

Table 4.7: Bulk density and air voids – Marshall method

Section	1		2		4		5		6	
Result	Design	Test	Design	Test	Design	Test	Design	Test	Design	Test
Bulk density (t/m^3) 50 blows	2.484	2.498	2.302	2.291	2.302	2.355	2.311	2.333	2.245	2.317
Difference	–0.014		0.011		–0.053		–0.022		–0.072	
Average maximum density (t/m^3)	2.588	2.583	2.428	2.433	2.419	2.422	2.423	2.456	2.363	2.369
Difference	0.005		–0.005		–0.003		–0.033		–0.006	
Average air voids (%) 50 blows	4	3.3	5.2	5.8	4.8	2.8	4.6	5	5	2.2
Difference	0.7		–0.6		2.0		–0.4		2.8	

Table 4.8: Bulk density and air voids – Gyratory method

Section	3	
Result	Design	Test
Bulk density (t/m^3) 50 cycles	2.284	2.359
Difference	–0.075	
Average bulk density (t/m^3) 150 cycles	2.364	2.389
Difference	–0.025	
Average maximum density (t/m^3)	2.394	2.399
Difference	–0.005	
Average air voids (%) 50 cycles	4.6	1.7
Difference	2.9	
Average air voids (%) 150 cycles	1.3	0.4
Difference	0.9	

4.3 Core Testing

Asphalt cores were collected (Figure 4.2) from the paved asphalt sections to verify layer thickness and test the strength capabilities in situ.

Figure 4.2: Extracting cores from completed trial sections

4.3.1 Asphalt Layer Thickness

The layer thickness measured on the cores extracted in each section (Table 4.9) showed there was variation from the target layer thickness of 40 mm in some sections, most notably core A of Section 1 and core B of Section 5 which were 28 mm.

Table 4.9: Asphalt layer thickness: field cores data

Section	1			2		3		4		5		6	
Sample number	A	B	C	A	B	A	B	A	B	A	B	A	B
Chainage (m)	44	165	165	165	340	540	600	760	820	960	1,000	1,210	1,250
Diameter (mm) nearest mm	100	100	101	100	101	100	101	100	Sample too small to test	100	100	101	101
Layer thickness (mm) nearest mm	28	36	36	32	36	40	40	43		43	28	37	40

4.3.2 Asphalt Resilient Modulus

The modulus testing (AS/NZS 2891.13.1) results (Table 4.10) show that the crumb rubber asphalts (Sections 1, 3, 4, 6) had a higher average resilient modulus than the two control sections (Sections 2 and 5), in all cases.

Table 4.10: Field core modulus testing results

Section	1			2		3		4		5		6	
Sample number	A	B	C	A	B	A	B	A	B	A	B	A	B
Mean height (mm)	24.1	35.8	37.3	27.8	31.9	39.7	41.1	39.8	33.1	33.1	Fracture during strength testing	36.6	39.6
Bulk density (t/m^3)	2.385	2.407	2.412	2.214	2.290	2.220	2.261	2.315	2.216	2.247		2.176	2.270
Air voids (%)	7.7	6.8	6.6	9.0	5.9	7.5	5.8	4.4	8.5	8.5		8.1	4.2
Resilient modulus (MPa)	2,990	2,890	3,260	913	589	1,140	1,140	715	961	783		985	1,210
Average resilient modulus (MPa)	3,100			750		1,100		840		780		1,100	

4.3.3 Assessment of the Bonding to the Existing Pavement

The evaluation of the strength of the bond between the new surfacing and the existing pavement provides additional information related to the durability of the surfacing. Lack of bonding at the asphalt interface would accelerate the damage of the surfacing. DoT in Victoria has been collecting data on bond strength, utilising the shear bond test (prEN 12697-48 2013) to understand its influence, and will be able to compare the results from the crumb rubber trial with its available data. The results of the bond strength testing are provided in Table 4.11.

Table 4.11: Bond strength testing results

Section	1			2		3		4		5		6	
Sample number	A	B	C	A	B	A	B	A	B	A	B	A	B
Chainage (m)	44	165	165	165	340	540	600	760	820	960	1,000	1,210	1,250
Diameter (mm) nearest mm	100	100	101	100	101	100	101	100	Sample bottom layer too small to be tested	100	100	101	101
Layer thickness (mm) nearest mm	28	36	36	32	36	40	40	43		43	28	37	40
Maximum load (kN) to the nearest 0.1 kN	12.6	11.8	14.3	10.0	8.7	8.6	8.1	14.2		12.5	14.1	10.8	15.2
Displacement at peak shear stress (δSBT, max.) to the nearest 0.1	2.2	4.4	4.0	2.8	2.7	3.4	2.6	4.1		4.1	5.7	5.6	4.6
Peak shear stress (τSBT, max.) to the nearest 0.01 MPa	1.61	1.50	1.78	1.28	1.09	1.10	1.01	1.80		1.60	1.79	1.35	1.90
Maximum shear stiffness modulus (kSBT, max.) to the nearest 0.01 MPa/mm	1.77	0.87	1.37	0.75	1.13	0.66	0.76	1.24		1.00	0.63	0.75	1.16

5. Condition Monitoring

5.1 Pre-trial Condition Assessment

A detailed condition assessment of the trial site was completed before construction. Investigations of the existing pavement structure, and the behaviour of the existing surface were undertaken to identify factors that may influence the ongoing performance of the trial asphalt mixes, and to guide the required site preparations.

The trial site was assessed by the following methods:

- Pavement strength evaluation – the DoT PaSE vehicle evaluated the pavement strength and found consistent and sound pavement throughout the site.
- Ground penetrating radar (GPR) – GPR testing was completed in order to determine the structure of the existing pavement, in particular the asphalt layer thickness. This testing showed sufficient asphalt thickness to complete a 'remove and replace' (thin layer of surface asphalt is removed and replaced by the new asphalt), however there were some areas where the results were inconclusive, and the type of underlying material could not be determined. Coring was therefore recommended.
- Coring was completed at seven locations across the site. The extracted cores showed there was sufficient asphalt to remove approximately 20 mm to be replaced with 40 mm of the trial crumb rubber asphalts.
- Crack detection using the ARRB Network Survey Vehicle (NSV). The data showed that the cracking was consistent across the site and consists mostly of environmental cracking. Roughness, rutting and texture data was also collected as part of this process.
- Visual assessment of cracking and rutting to identify areas for patching.

5.2 Post-trial Condition Assessment

A survey of the trial site was conducted by an ARRB NSV one month after construction on 14 April 2020, and again at 6 and 24 months.

5.2.1 Cracking

Surface cracking throughout the site was measured by the ARRB NSV. Results for Lane 1 are shown in Figure 5.1, and Lane 2 in Figure 5.2.

Pre-trial, the cracking was consistent throughout the site. At one month after the trial, the new surface has eradicated the surface cracking, however the automatic crack detection software reported small, isolated areas of cracking, which is mostly noise due to surface changes, and drainage access and other facilities that have made a blemish on the regularity of the surface. The 6- and 24-month surveys returned similar results, with minimal cracks, later confirmed during the site inspection to be noise from other features that the automatic crack detection software mistook as cracking.

Figure 5.1: Cracking (Lane 1)

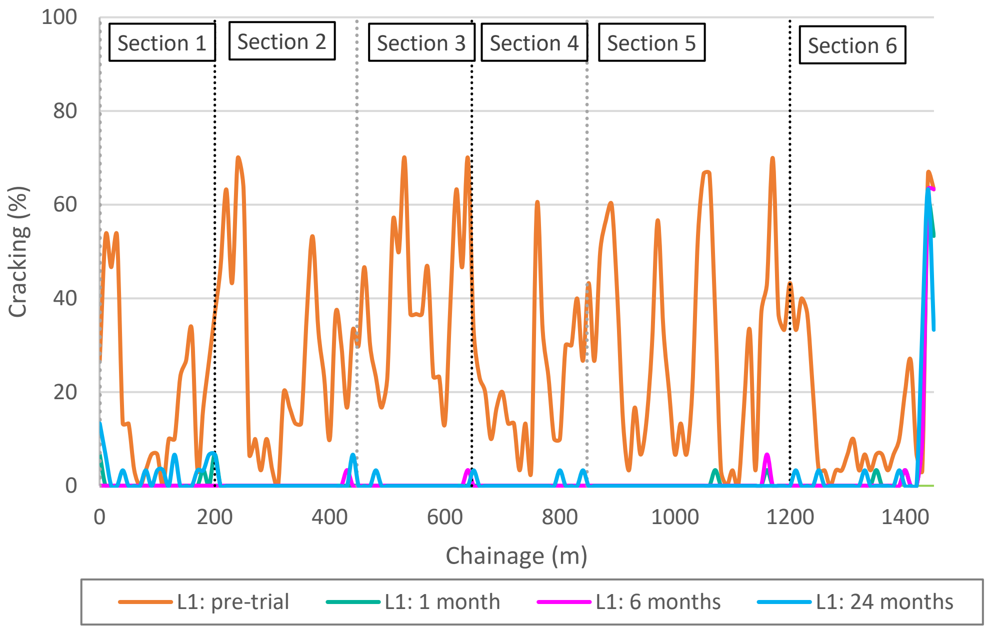
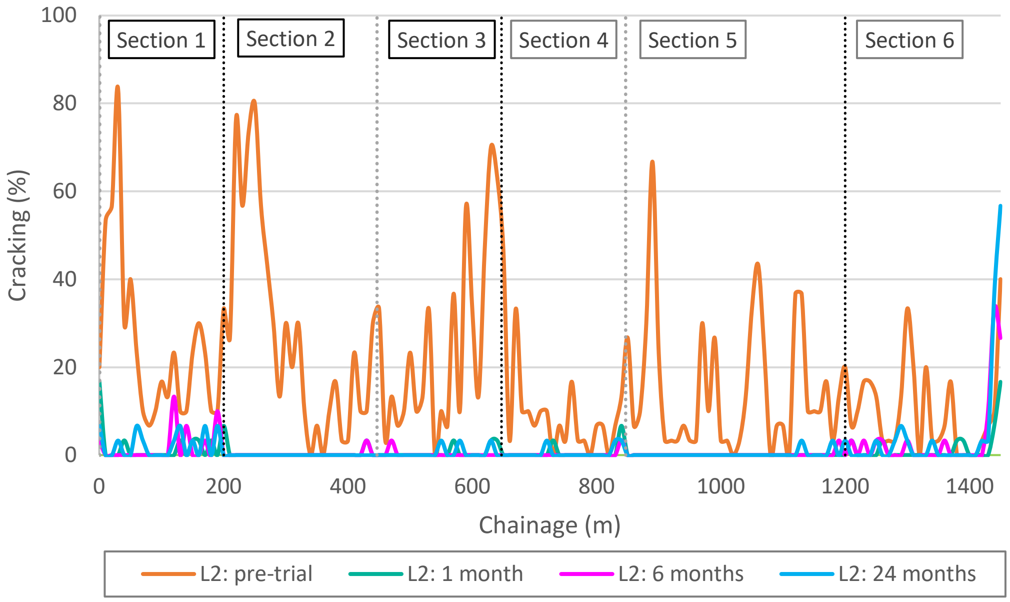


Figure 5.2: Cracking (Lane 2)



5.2.2 Roughness

Roughness is as an expression of pavement surface irregularities that adversely affect the ride quality of a vehicle and is measured by the ARRB NSV and expressed in terms of the International Roughness Index (IRI). Results are provided for Lane 1 (Figure 5.3) and Lane 2 (Figure 5.4).

The roughness has reduced with the new surface, as a result of improved ride quality of the fresh asphalt and has remained very stable between the 1 and 24-month surveys.

Figure 5.3: Roughness (Lane 1)

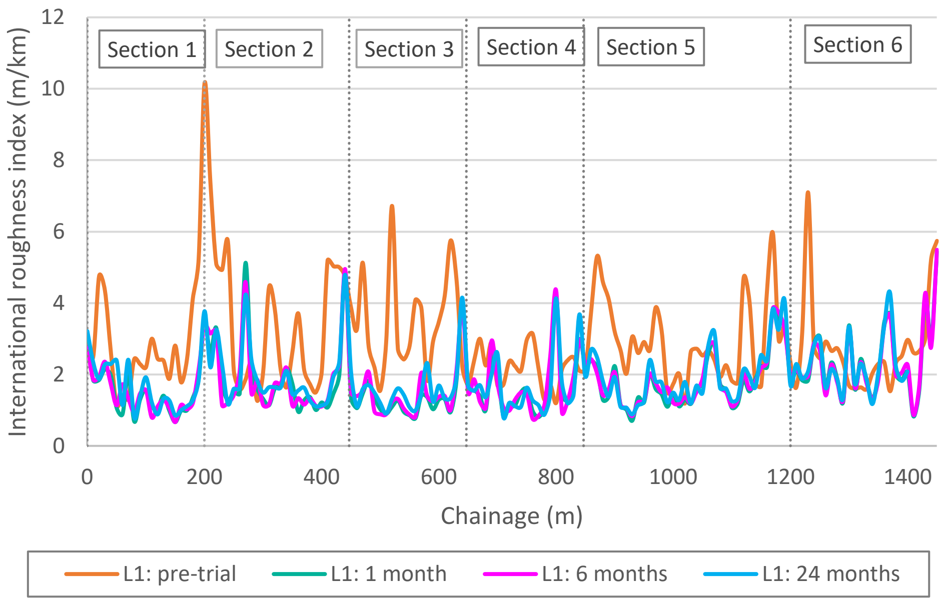
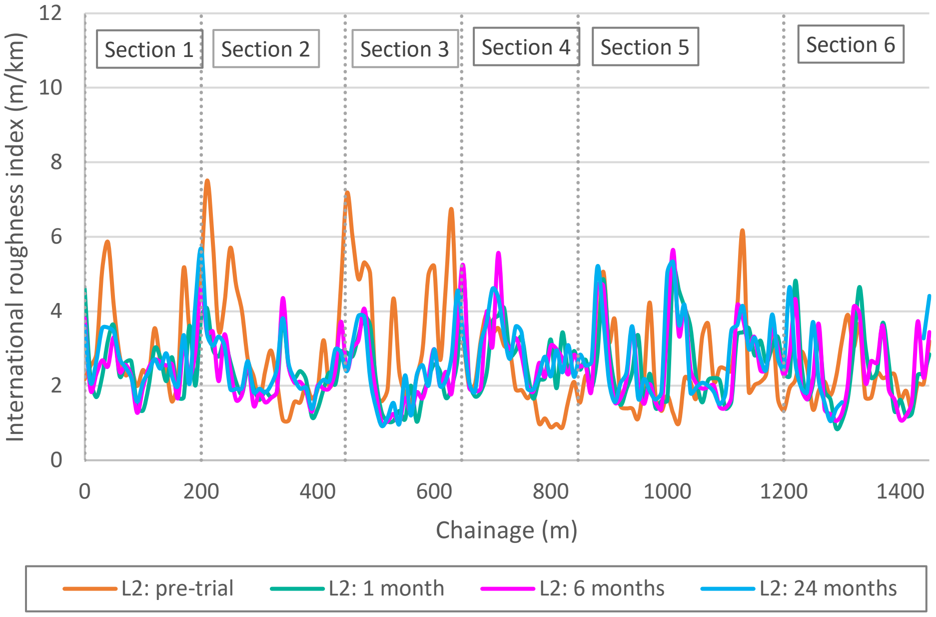


Figure 5.4: Roughness (Lane 2)



5.2.3 Rutting

The rutting (left wheelpath) is measured by the ARRB NSV. Results for Lane 1 (Figure 5.5) and Lane 2 (Figure 5.6) are shown.

The new surface has considerably reduced the amount of rutting throughout the extent of the trial sections and has not progressed between the 1 and 24-month surveys, excepting in Section 3 where small ruts appear to be developing, more so in Lane 1, where the inspection noted flushing at the surface (Section 5.3.3).

Figure 5.5: Rutting (Lane 1)

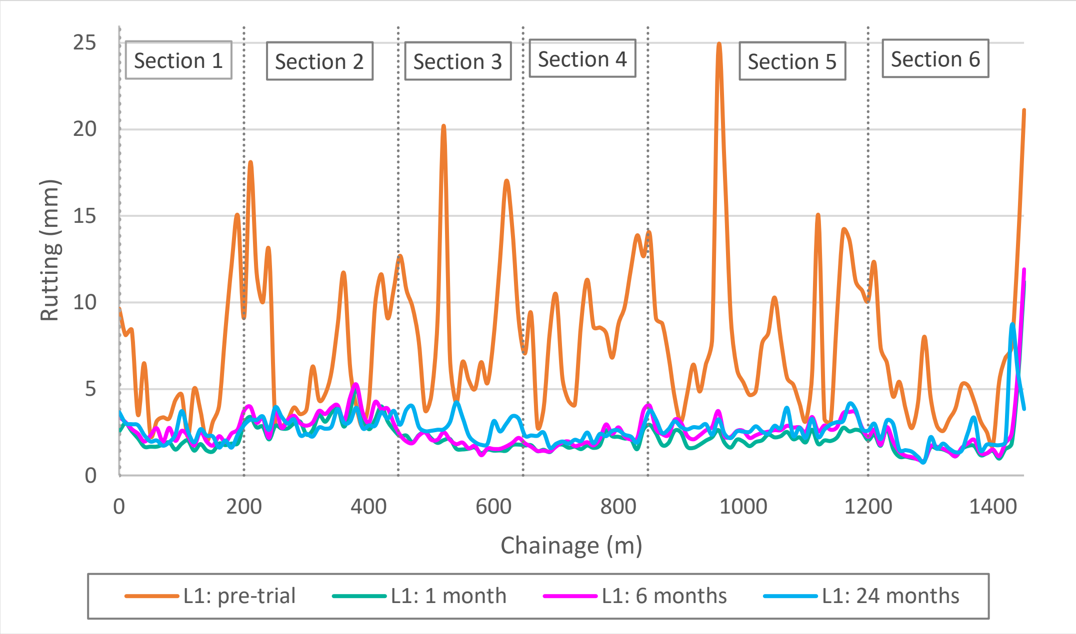
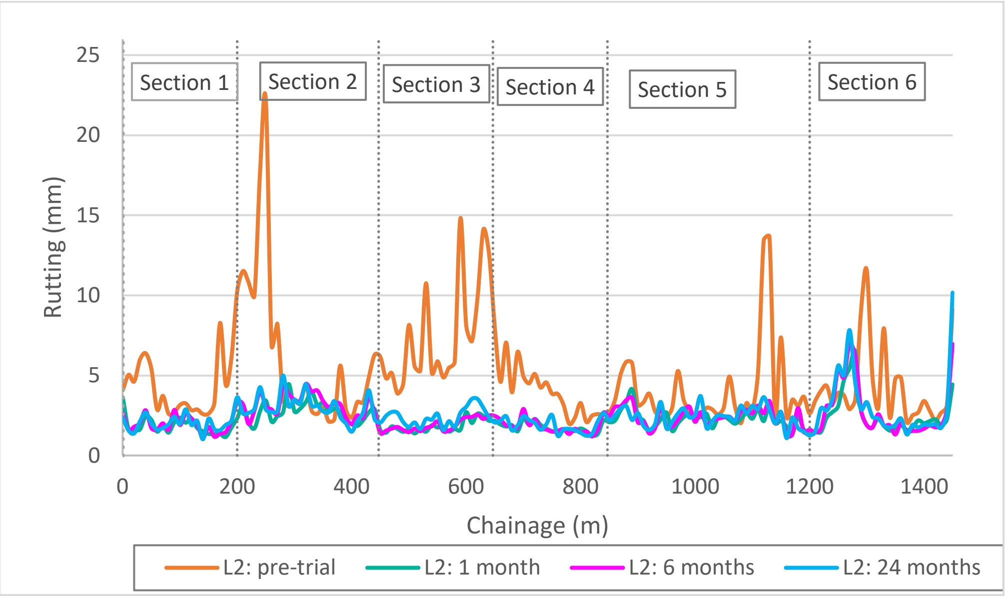


Figure 5.6: Rutting (Lane 2)



5.2.4 Texture

The texture of the surface was measured by the ARRB NSV, and is expressed in terms of sensor measured texture depth (SMTD), and is displayed for the left wheel paths in Lane 1 (Figure 5.7) and Lane 2 (Figure 5.8).

The new surfaces restored texture to similar levels as the old surfaces for Sections 1, 3 and 6, and have increased texture considerably in Sections 2, 4 and 5. Texture has progressively reduced in small increments between the 1, 6 and 24-month surveys, as the asphalt surfaces has settled under traffic.

Figure 5.7: Texture (Lane 1)

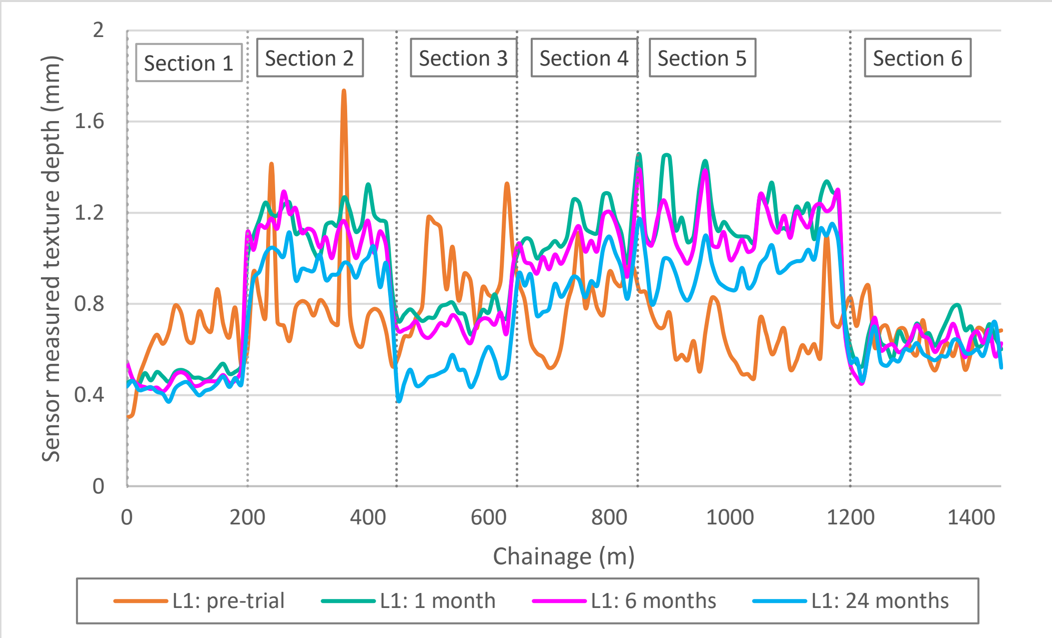
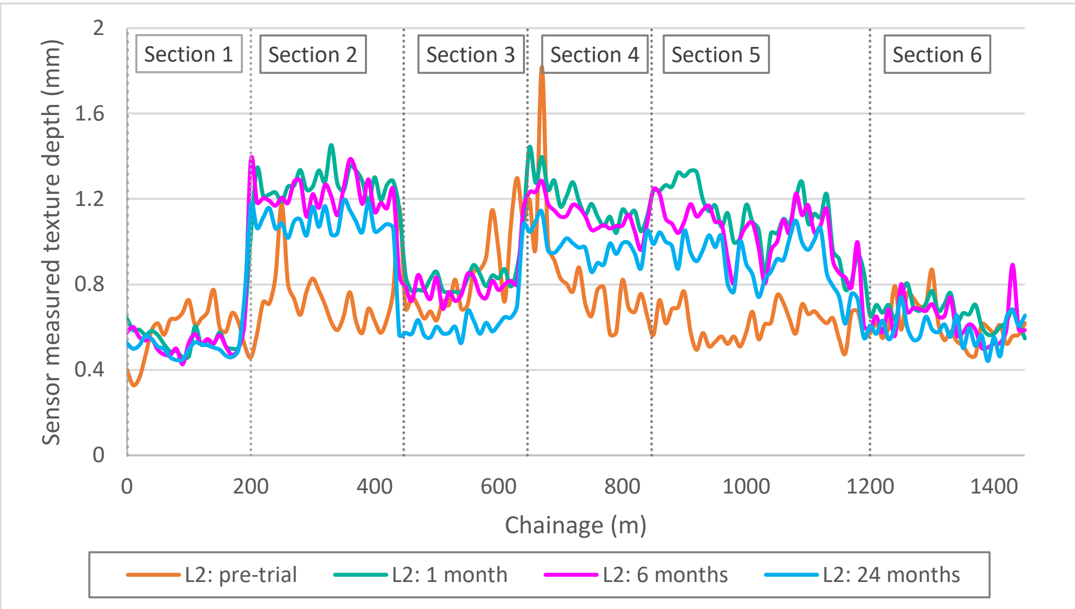


Figure 5.8: Texture (Lane 2)



5.2.5 Skid Resistance

The skid resistance capabilities of the trial asphalts have been measured by the DoT Sideways-force Coefficient Routine Investigation Machine (SCRIM) immediately after the trial, and again after 1 and 2 months. The results for Lane 1 are displayed in Figure 5.9, and Lane 2 in Figure 5.10.

The results show some settling of the asphalt surface over its initial life. In trial Sections 1 through 4, the skid resistance has slightly increased after 2 months, likely due to binder film over aggregate particles on the surface being removed by the scrubbing effect of passing vehicle tyres, which improves the ability of tyres to grip to the surface. After 24 months, the skid resistance has reduced a little throughout Section 1 and Section 3. The skid resistance dips below the DoT investigatory level at the beginning of Section 3, where the inspection noted flushing at the surface (Section 5.3.3).

After 1 month, the skid resistance reduced considerably in Section 5 and 6 but was somewhat restored after 2 months. It is unclear what caused this, but may be due to some flushing of binder from the asphalt to the surface, which in turn was removed by the scrubbing effect of passing vehicle tyres, which has seen the skid resistance increase again after 2 months. At 24 months the skid resistance had continued to increase in Section 5, and has settled in Section 6.

After 24 months, the measured skid resistance exceeds the DoT investigatory level throughout the entire section excepting the small region at the beginning of Section 3, indicating good performance.

Figure 5.9: SCRIM results (Lane 1)

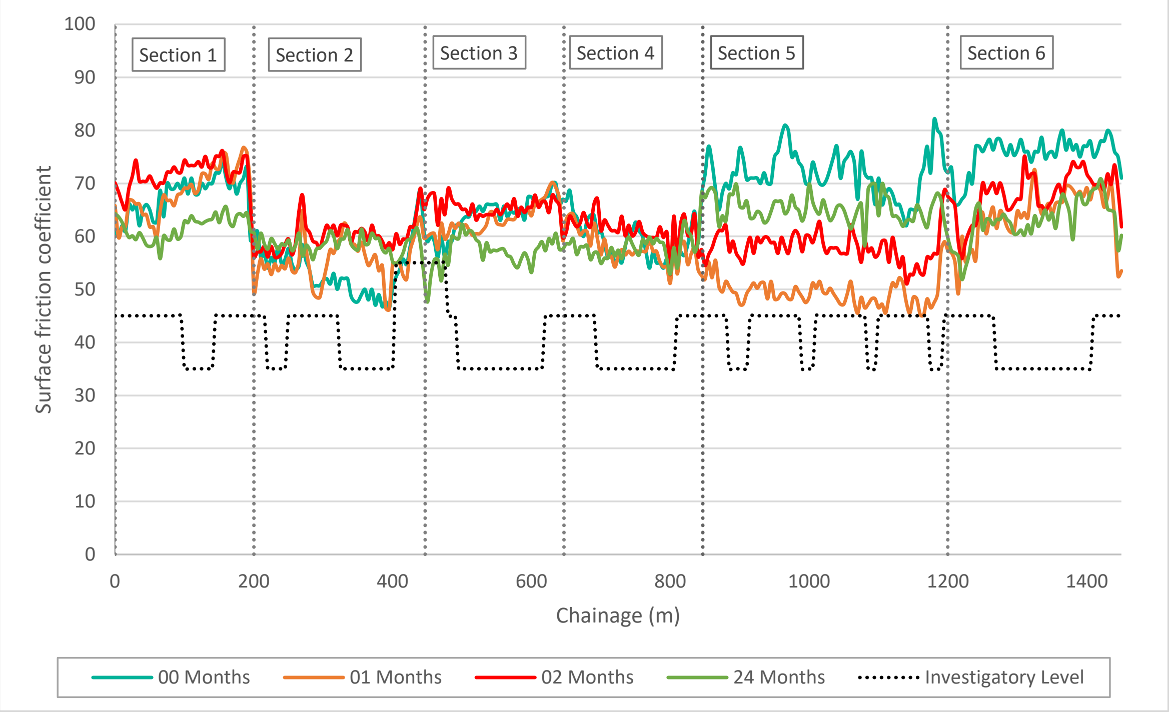
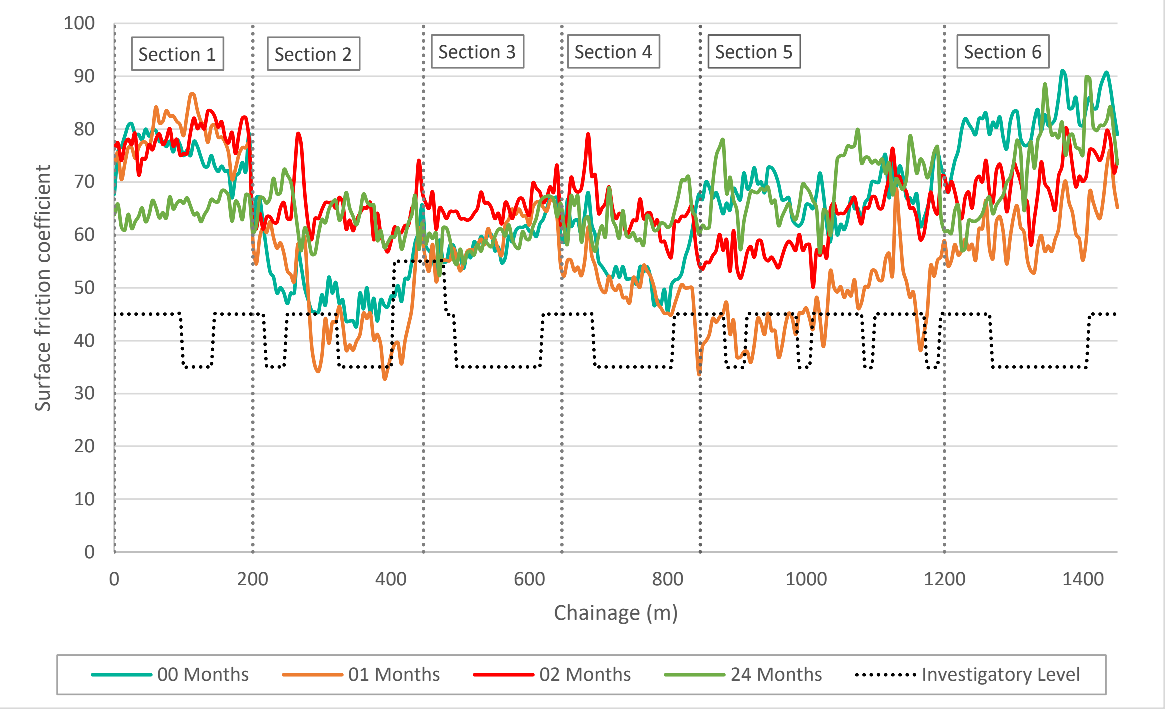


Figure 5.10: SCRIM results (Lane 2)



5.3 Site Inspection

A visual site inspection of the trial asphalts was conducted after 24 months of service life, by representatives of DoT and ARRB.

5.3.1 Section 1

Section 1 was observed to be performing well. In general, the surface appearance is typical of a DGA, albeit slightly coarse (Figure 5.11). There are isolated areas where the texture is bonier, or open, mostly occurring in Lane 2, with Lane 1 in general with a more complete smooth finish (Figure 5.12). There was no apparent ravelling or shape loss.

Figure 5.11: Section 1 at 24 months

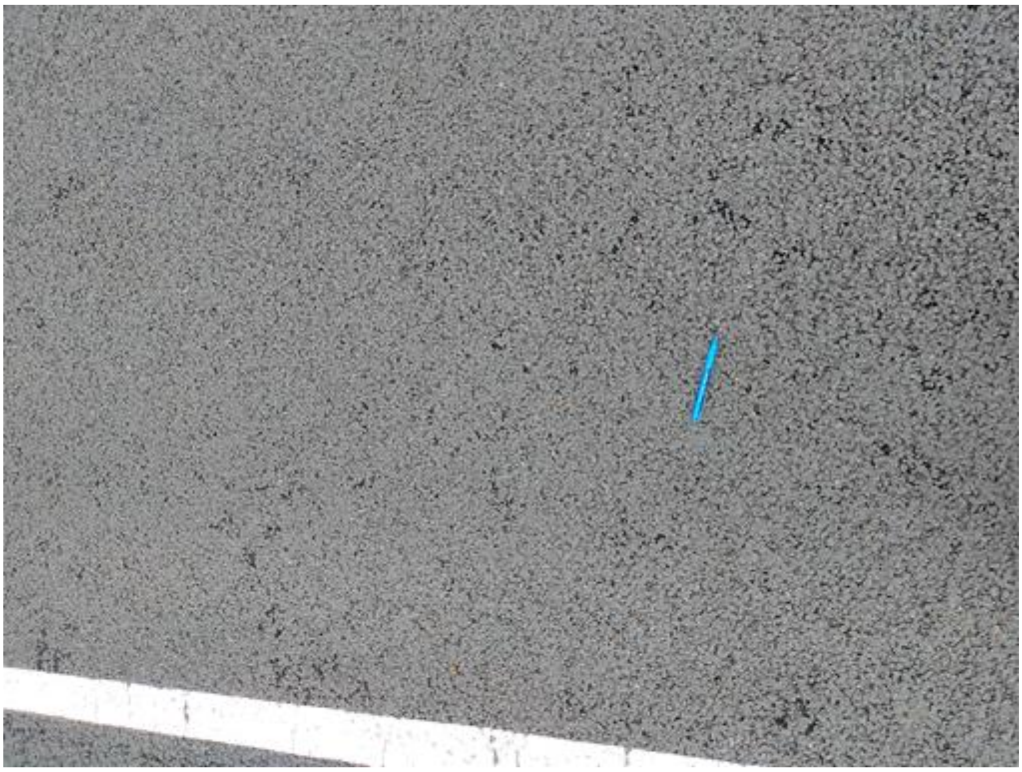
Figure 5.12: Section 1, Lane 1 texture at 24 months

5.3.2 Section 2

Section 2 was observed to be performing well (Figure 5.13), with a reasonable texture and an appearance typical of an SMA-H asphalt (Figure 5.14). There was no apparent ravelling or shape loss.

Figure 5.13: Section 2 at 24 months

Figure 5.14: Section 2, Lane 1 texture at 24 months



5.3.3 Section 3

Section 3 was observed to have a good appearance in general (Figure 5.15), with a tight texture appropriate for a GGA. There is flushing developing in the braking and acceleration zone surrounding the pedestrian operated signals, which is worse in Lane 1 (Figure 5.16) but also present in Lane 2. This area of flushing aligns with the small amount of rutting that was measured in the NSV survey at 24 months (Figure 5.5 and Figure 5.6). The rutting had not progressed to a point where it was detectable during the visual inspection. No ravelling was observed.

Figure 5.15: Section 3 at 24 months

Figure 5.16: Section 3, Lane 1 texture at 24 months

5.3.4 Section 4

Section 4 was observed to be performing well with a good appearance, typical of a SMA (Figure 5.17). The texture is consistent throughout (Figure 5.18), and there is no evidence of ravelling or shape loss.

Figure 5.17: Section 4 at 24 months

Figure 5.18: Section 4, Lane 1 texture at 24 months

5.3.5 Section 5

Section 5 was observed to have a good overall appearance (Figure 5.19), typical of an SMA, with isolated areas of open texture in the outer wheelpath of Lane 2. The texture is otherwise consistent throughout (Figure 5.20). There was no ravelling or shape loss detected.

Figure 5.19: Section 5 at 24 months

Figure 5.20: Section 5, Lane 1 texture at 24 months

5.3.6 Section 6

Section 6 was observed to have a generally good appearance (Figure 5.21). The texture was judged to be a little tighter than is typical for an SMA (Figure 5.22), with some more open areas at the start of the section, becoming more consistent towards the end. There was no ravelling or shape loss detected.

Figure 5.21: Section 6 at 24 months

Figure 5.22: Section 6, Lane 1 texture at 24 months

6. Conclusion

The crumb rubber asphalt demonstration trial was a collaborative effort organised by Tyre Stewardship Australia (TSA), Department of Transport (DoT) Victoria, and the Australian Road Research Board (ARRB), undertaken with the cooperation of local asphalt manufacturers.

The project aimed to increase consumption of recycled tyre-derived crumb rubber and promote sustainable solutions for surfacing heavily trafficked roads. The trial was organised so that the performance of crumb rubber asphalts could be assessed in the field under real traffic and climatic conditions, compared to other asphalts under standard testing conditions, and to characterise the material properties in a laboratory.

A study of the environmental emissions during the asphalt paving was undertaken to measure the potential fuming exposure of crumb rubber asphalts, and to provide a comparison to control mixes. The analysis found no significant fuming exposure to volatile organic compounds. Detected values of total suspended solids, bitumen fumes, and polycyclic aromatic hydrocarbons were below recommended guidelines, and were lower for the crumb rubber asphalts compared to the control asphalts. Benzothiazole was measured in higher quantities for the crumb rubber mixes compared to control asphalts, but this was not correlated to any reported symptoms of irritation.

Many samples were collected from the trial at East Boundary Road and have been tested in the laboratory to benchmark the potential performance of crumb rubber asphalt. Monitoring of the trial site was undertaken to collect data regarding the in situ performance, including cracking, roughness, rutting, texture and skid resistance. The trial surfaces are performing well after two years and are comparable to the control sections.

The assessment of the inherent properties of the crumb rubber asphalt mixes in the laboratory, and their performance in the field, will inform the Department of Transport as to how the mixes may be implemented in its specifications. Incorporating these mixes into the specifications will allow their use alongside, and potentially in place of traditional mixes, to maximise the use of innovative recycled materials and improve the sustainability of road building.

References

AAPA 2018, *Crumb rubber modified open graded and gap graded asphalt pilot specification*, v1.0, Australian Asphalt Pavement Association, Port Melbourne, Vic.

Australian and New Zealand Standards

AS 2008:2013, *Bitumen for pavements.*

AS 2341.12:2020, *Methods of testing bitumen and related roadmaking products: determination of penetration.*

AS 2341.18:2020, *Methods of testing bitumen and related roadmaking products: determination of softening point (ring and ball method).*

AS/NZS 2341.2:2015, *Methods of testing bitumen and related roadmaking products: determination of dynamic viscosity by vacuum capillary viscometer.*

AS/NZS 2341.4:2015, *Methods of testing bitumen and related roadmaking products: determination of dynamic viscosity by rotational viscometer.*

AS/NZS 2341.8:2016, *Methods of testing bitumen and related roadmaking products: determination of matter insoluble in toluene.*

AS/NZS 2341.10:2015, *Methods of testing bitumen and related roadmaking products: determination of the effect of heat and air on a moving film of bitumen (rolling thin film oven (RTFO) test).*

AS/NZS 2891.13.1:2013, *Methods of sampling and testing asphalt: determination of the resilient modulus of asphalt: indirect tensile method.*

Austroads Test Methods

AGPT-T108-21, *Segregation of polymer modified binders.*

AGPT-T121-14, *Shear properties of polymer modified binders (ARRB Elastometer).*

AGPT-T125-18, *Stress ratio of bituminous binders using the dynamic shear rheometer.*

AGPT-T132-06, *Compressive limit of polymer modified binders.*

AGPT-T190-19, *Specification framework for polymer modified binders.*

ATM 122-22, *Torsional recovery of polymer modified binders.*

European Committee for Standardization (CEN)

prEN 12697-48 2013, *Bituminous mixtures: test methods for hot mix asphalt: part 48: interlayer bonding*.

Appendix A Emissions Monitoring Data

A.1 VOC Standards

Table A.1: SafeWork Australia Workplace Exposure Standards for selected VOCs

Chemical	Time-weighted average (TWA)* Workplace Exposure Standard (mg/m^3)
Pentane	1,770
Hexanes	1,760
n-hexane	72
Cyclohexane	350
Methyl Cyclohexane	1,610
n-heptane	1,640
Octane	1,400
Nonane	1,050
Benzene	3.2
Toluene	191
Xylene	350
Ethylbenzene	434
Styrene	213
Cumene	125
Trimethylbenzene	123
Total VOC (as White Spirit)	790

*TWA = Average concentration over an 8-hour shift.

A.2 Complete PAH Results

Table A.2: Polycyclic aromatic hydrocarbons comparison

Section	Chemical	Spotter	Level hand	Paver driver
1	Naphthalene	1.8	1.1	1.5
	Acenaphthylene	< 1.1	< 1.1	< 1.1
	Acenaphthene	< 1.1	< 1.1	< 1.1
	Anthracene	< 0.1	< 0.1	0.2
	Pyrene	< 0.1	< 0.1	< 0.1
	Benz(a)anthracene	< 0.1	< 0.1	< 0.1
	Chrysene	< 0.1	< 0.1	< 0.1
	Other PAHs	ND	ND	ND
	TOTAL PAHs	**2.78**	**2**	**2.92**

Section	Chemical	Spotter	Level hand	Paver driver
2	Naphthalene	3.4	< 2.0	6.5
	Acenaphthylene	< 1.5	< 2.0	< 1.5
	Acenaphthene	< 1.5	< 2.0	< 1.5
	Fluorene	0.4	0.51	1.4
	Phenanthrene	1.6	0.39	1.5
	Anthracene	0.18	< 0.2	0.41
	Pyrene	< 0.2	< 0.2	< 0.2
	Benz(a)anthracene	< 0.2	< 0.2	0.32
	Chrysene	< 0.2	< 0.2	< 0.2
	Other PAHs	ND	ND	ND
	TOTAL PAHs	**5.4**	**0.9**	**9.4**
3	Naphthalene	1.3	< 1.3	< 1.3
	Acenaphthylene	< 1.3	< 1.3	< 1.3
	Acenaphthene	< 1.3	< 1.3	< 1.3
	Fluorene	1.4	0.47	0.57
	Phenanthrene	1.4	0.29	0.22
	Anthracene	0.28	< 0.1	< 0.1
	Pyrene	0.15	< 0.1	< 0.1
	Benz(a)anthracene	0.13	< 0.1	< 0.1
	Chrysene	< 0.1	< 0.1	< 0.1
	Other PAHs	ND	ND	ND
	TOTAL PAHs	**4.66**	**0.76**	**0.79**
4	Naphthalene	< 1.2	< 1.1	1.3
	Acenaphthylene	< 1.2	< 1.1	< 1.1
	Acenaphthene	< 1.2	< 1.1	< 1.1
	Fluorene	< 0.12	< 0.11	< 0.11
	Phenanthrene	0.34	0.33	0.26
	Anthracene	< 0.12	0.2	0.15
	Pyrene	< 0.12	< 0.11	< 0.11
	Benz(a)anthracene	< 0.12	< 0.11	< 0.11
	Chrysene	< 0.12	< 0.11	< 0.11
	Other PAHs	ND	ND	ND
	TOTAL PAHs	**0.34**	**0.53**	**1.71**

Section	Chemical	Spotter	Level hand	Paver driver
5	Naphthalene	1.1	2.3	4.2
	Acenaphthylene	< 0.9	< 0.9	2.4
	Acenaphthene	< 0.9	< 0.9	< 0.9
	Fluorene	0.26	< 0.09	2.4
	Phenanthrene	0.21	0.69	1.7
	Anthracene	0.12	0.25	0.62
	Pyrene	< 0.09	< 0.09	0.09
	Benz(a)anthracene	< 0.09	0.16	0.38
	Chrysene	< 0.09	< 0.09	0.09
	Other PAHs	ND	ND	ND
	TOTAL PAHs	**1.43**	**3.24**	**10.18**
6	Naphthalene	2.1	3.2	1.9
	Acenaphthylene	< 0.9	< 1.1	< 1.0
	Acenaphthene	< 0.9	1.9	< 1.0
	Fluorene	< 0.09	0.21	< 0.1
	Phenanthrene	0.41	1.4	0.62
	Anthracene	0.15	0.38	0.17
	Pyrene	< 0.09	0.15	< 0.1
	Benz(a)anthracene	< 0.09	0.15	< 0.1
	Chrysene	< 0.09	< 0.11	< 0.1
	Other PAHs	ND	ND	ND
	TOTAL PAHs	**2.66**	**7.39**	**2.69**

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