Recycled waste plastic modification of bituminous binder

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ABSTRACT: Two waste plastic products for asphalt binder modification and extension, known as MR 6 and MR 10, were added to penetration-grade bitumen in the laboratory. The samples were tested for the index properties contained in the British modified binder specification, as well as high temperature Performance Grading. The investigation included 50/70 and 100/150 penetration grade bitumen with 4-8% (by mass) waste plastic content, tested at 52-82°C. Waste plastic modification significantly improved the high temperature Performance Grading. The harder 50/70 penetration grade bitumen produced a harder modified binder and the difference between 4% and 6% waste plastic content was significantly greater than the difference between 6% and 8%. The MR 6 modified binder was more elastomeric and had greater resistance to deformation than MR 10. Further research is recommended to compare the properties of wet blended and dry mixed production methods.

1 INTRODUCTION

Sustainable and cost-effective pavement solutions present a significant opportunity to reduce the cost of infrastructure management through the productive consumption of reused and recycled products, as well as reducing the demand on new natural resources.

Waste plastic is a significant and growing environmental challenge and includes industrial plastics, plastic bags and plastic bottles. As a result, there has been an increased interest in the incorporation of processed and recycled waste plastic into construction materials (White & Reid 2018). At this time, the primary construction-based reuse of processed waste plastic has been in concrete and masonry products, such as low-cost bricks for dwellings in developing countries and concrete for non-structural works (Shoubi et al. 2013; Ganesh Prabhu et al. 2014; Sharma 2017; Saikia & de Brito 2014). Furthermore, research has focused on the replacement of the fine aggregate in concrete mixtures and only limited research into the efficacy of recycled plastic as a binder extender or modifier for asphalt mixtures has been reported (Guru et al. 2014; Dalhat & Al-Adbul Wahhab 2017).

This paper evaluates a source of recycled waste plastic from the United Kingdom (UK) as a partial bitumen replacement and modifier. Recycled plastic processing and production is summarised before the results of comparative laboratory binder testing of UK index properties and the USA Performance Grading (PG) parameters are compared for different base bitumen grades, modified with different waste plastic products, at different waste plastic dosages. The improvement in binder properties associated with waste plastic extension and modification is determined. Finally, further work is recommended to better understand waste plastic modification of asphalt binders.

2 BACKGROUND

2.1 *Recycling in asphalt*

The primary material recycled into asphalt mixtures is recycled asphalt. Reclaimed Asphalt Pavement (RAP) is commonly stockpiled, crushed, tested and recycled back into new asphalt at the production plant (Austroads 2015). Typically, 10-20% of RAP is incorporated, with higher RAP percentages also considered when the RAP is available in greater quantities (Pires et al. 2017).

In more recent times, other recycled materials have been incorporated into asphalt mixtures. Waste printer toner (Yildirim et al. 2003), crushed (gullet) glass (Jamshidi et al. 2017), incinerator waste, municipal waste refuse and coal mine overburden (Kandhal 1992) have all been reported. In general, there is a desire to increase recycled material use in asphalt mixtures, where surface performance is not adversely affected. Every tonne of recycled waste material is one tonne less of new aggregate and/or bituminous binder required to be produced from finite natural resources, as well as one less tonne of material that might otherwise become landfill. However, if 20% waste recycling results in a 50% pavement or surface life reduction, the benefits of recycling are not justified and the long-term cost and environmental impact are actually worse than not using recycled materials. Similarly, the cost of sorting, processing and reincorporating recycled materials is often high compared to the saving associated with the reduction of new material consumption (White & Reid 2018). It is therefore important that recycled materials provide at least comparable performance, at no greater cost, than new material use.

2.2 *Waste plastic*

Plastics are synthetic materials derived primarily from refined crude oil petroleum products. The high melting temperature, high decomposition temperature and resistance to UV radiation provides many benefits, but also means that waste plastic remains in the environment for hundreds of years (Guru et al. 2014) creating an increasing environmental challenge. Furthermore, the toxic chemicals within many plastics are bio-cumulative, presenting a health and safety risk throughout the food chain, including humans.

Two of the main sources of waste plastic in the environment are plastic drink bottles and single-use plastic bags. However, plastic bags are made from high density polyethylene (HDPE) and plastic bottles are manufactured from polyethylene terephthalate (PET). PET has a melting point of around 260°C and HDPE has a melting point of up to 270°C, which are both higher than typical bituminous binder and asphalt production and storage temperatures. Consequently, PET and HDPE can not be used as binder extenders and modifiers. This highlights the important difference between low melt point waste plastic as a binder extender (and potential modifier) compared to the use of higher melt point waste plastic as an asphalt mixture or aggregate extender. This paper focuses on binder extension and modification, using two low melt point processed waste plastics.

2.3 *Waste plastic in asphalt mixtures*

As discussed above, there is a distinct difference between asphalt binder extension and asphalt mixture extension. The difference is primarily characterised by the melt point of the waste plastic being used. Many countries have reported the use of waste plastic in asphalt production. For example, Vancouver (Canada) incorporated plastic crate waste as a warm mixed asphalt wax additive in 2012 (Ridden 2012) and Rotterdam (The Netherlands) announced a plan to produce recycled plastic segments in a factory for road construction in 2015 (Saini 2015). Also, Janshedpur (India) recently reduced bitumen usage by 7% by dry-mixing shredded recycled plastic into asphalt production (PTI 2015). More recently, a New Zealand asphalt contractor added shredded 4 L engine oil containers to asphalt used at Christchurch Airport (Parkes 2018).

It is likely that the unsophisticated incorporation of shredded plastic products into asphalt production did not melt the plastic. Consequently, these efforts extend the asphalt mixture, but do not necessarily extend or modify the bituminous binder and have led to terms such as ‘trash-phalt’ and negative statements regarding ‘the stench of burning plastic’. However, this is distinctly different from bituminous binder extension and modification with low melt point plastics, designed to be digested into the asphalt binder.

In 2015 a commercial plastic waste recycling venture was initiated in Scotland (UK), aiming to (MacRebur 2017):

- Productively consume a portion of the waste plastic otherwise destined for landfill.
- Reduce the cost of new road construction and maintenance.
- Increase the strength and durability of local roads.

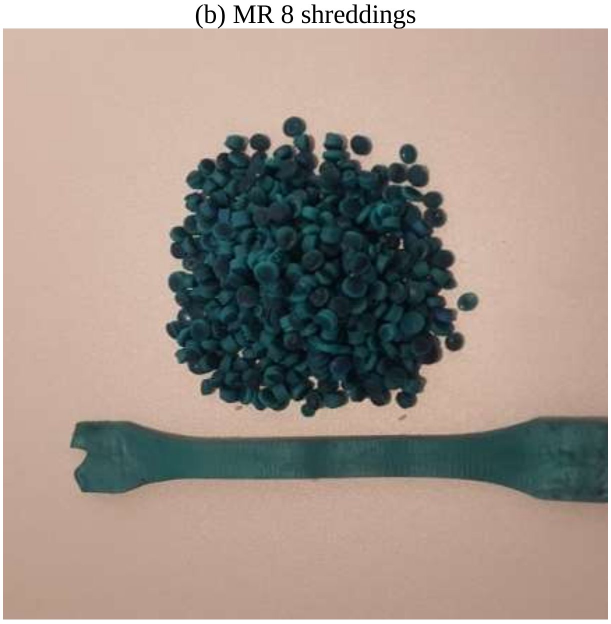
The recycled plastic extender/modifier, now known as MR 6 was developed. MR 6 comes in pellet form and is intended to be incorporated directly into the asphalt production plant. It is produced from 100% recycled waste plastic. The waste plastics used have a melting point below the typical asphalt and binder production temperatures and readily melt into the binder to extend and modify it (White & Reid 2018).

Other products, known as MR 8 and MR 10, soon followed with different target applications. MR 8 was developed as an economical bitumen extender without performance enhancement, while MR 10 was developed to provide a more crack resistant binder. Only MR 6 and MR 10 are considered in this research. Each of the three products comes in a different colour and form, with MR 8 a shredded plastic, while MR 6 and MR 10 are produced as pellets (Figure 1).

The waste plastic sourcing, blending and processing is proprietary information but the products are produced from recycled or reused waste materials from both domestic and industrial origins. Suitable waste plastics are cleaned, melted and extruded into high density pellet form for transportation. Various pellets are then blended together to provide the desired performance properties and bagged for transportation. The process is controlled by an accredited quality system allowing each package of finished modifier to be traced to a specific production batch and the associated sources of recycled waste plastic.

(a) MR 6 pellets

(b) MR 8 shreddings



(c) MR 10 pellets

Figure 1. Processed waste plastic products.

2.4 *Testing and grading bituminous binders*

Different jurisdictions take different approaches to bitumen and asphalt performance and compliance testing. In the UK, the performance of asphalt surfaces generally relies on asphalt mixture volumetric properties and asphalt testing intended to be indicative of performance (BS EN 13108). Consequently, only production or index properties are specified (BS EN 14023) for bituminous binders. However, some binder index properties can be related to characteristics that are indicative of the relative asphalt performance, such as (White 2015):

- Force ductility at 25°C. Indicative of relative resistance to cracking.
- Penetration at 25°C. Indicative of relative resistance to deformation.
- Softening point. Indicative of relative temperature susceptibility.

This approach contrasts with Australian practice, where grades of binder with particular performance characteristics are explicitly specified by index property brackets, and asphalt mixture testing is generally confined to volumetrics and Marshall properties (White 2015). It also contrasts with practice in the USA, where PG rating of binder is common, in addition to performance testing of asphalt mixtures under the USA Superpave system (Tredrea 2007).

The Superpave project was initiated in the USA in 1987 with one of its many aims being to provide better performing asphalt surfaces. The original Superpave rut resistance parameter for bituminous binder rating was the Dynamic Shear Rheometer (DSR) derived $|G^*|/\sin \delta$. The PG system also assesses fatigue cracking (intermediate temperature) and brittle fracture (low temperature). However, for most bitumen supplies, these other requirements are easily exceeded and it's the high temperature grading that is critical (Holleran et al. 2014).

Subsequent work in the USA resulted in the development of the Multiple Stress Creep Recovery (MSCR) protocol which was demonstrated to be easy to perform in the laboratory using the same DSR equipment (D'Angelo 2009a) and takes only around 15 minutes to complete (DuBois et al. 2014). The primary output from the MSCR test is termed the creep compliance (Jnr) which is related to an upper service temperature, depending on the assigned level of traffic severity (D'Angelo 2009b). The $|G^*|/\sin \delta$ and MSCR parameters represent best practice for objectively comparing deformation resistance of different bituminous binders for asphalt production.

3 METHODS AND RESULTS

Various unmodified and waste plastic modified bituminous binders were tested for the UK binder specification properties, as well as the high temperature USA PG gradings by the DSR based |G*|/sin δ (ASTM D6373) and MSCR protocol (ASTM D7405).

The UK specification testing was performed on unmodified 100/150 penetration grade bitumen, as well as the same base bitumen with the standard 6% dosage of MR 6 and 6% of MR 10 (Table 1).

Table 1. Index test results.

Parameter	Sample		
	Unmodified	6% MR 6	6% MR 10
Force ductility (J/cm^2)	0.03	0.69	2.35
Penetration (d.mm)	134	90	94
Softening point (°C)	41	51	47

The |G*|/sin δ and the MSCR parameters were determined:

- Over a range of temperatures, generally from 52°C to 82°C, to cover the range of likely PG high temperature ratings.
- For unmodified, MR 6 modified and MR 10 modified binders.
- Using a base of 50/70 and 100/150 penetration bitumen grades.
- At waste plastic dosages of 4%, 6% and 8% of the bitumen mass.

The |G*|/sin δ and MSCR results are in Appendix 1. In all cases, the MR 6 and MR 10 modified products were prepared by heating the base bitumen to 170°C, adding the required mass of waste plastic pellets and mixing in a Silverson laboratory high-sheer mixer for 30 seconds, followed by immediate testing. In all cases, the |G*|/sin δ was measured on unaged binder and the MSCR parameters were measured on binder aged by the Rolling Thin Film Oven (RTFO) protocol (BS EN 12591).

A summary of the high temperature PG results, based on the |G*|/sin δ, and the MSCR Jnr for Extreme traffic (E) and for Standard traffic (S), are in Figure 2 (for the 100/150 penetration grade base bitumen) and in Figure 3 (for the harder 50/70 base bitumen).

As stated above, the PG testing was only performed over the temperature range 52-82°C. Any result outside of this range was only determined to be ‘88°C or more’ or to be ‘46°C or less’. That is, the actual PG rating was not determined, just the upper or lower limit of the rating. Consequently, any GP rating exceeding 82°C was recorded as 88°C and any result lower than 52°C was recorded at 46°C.

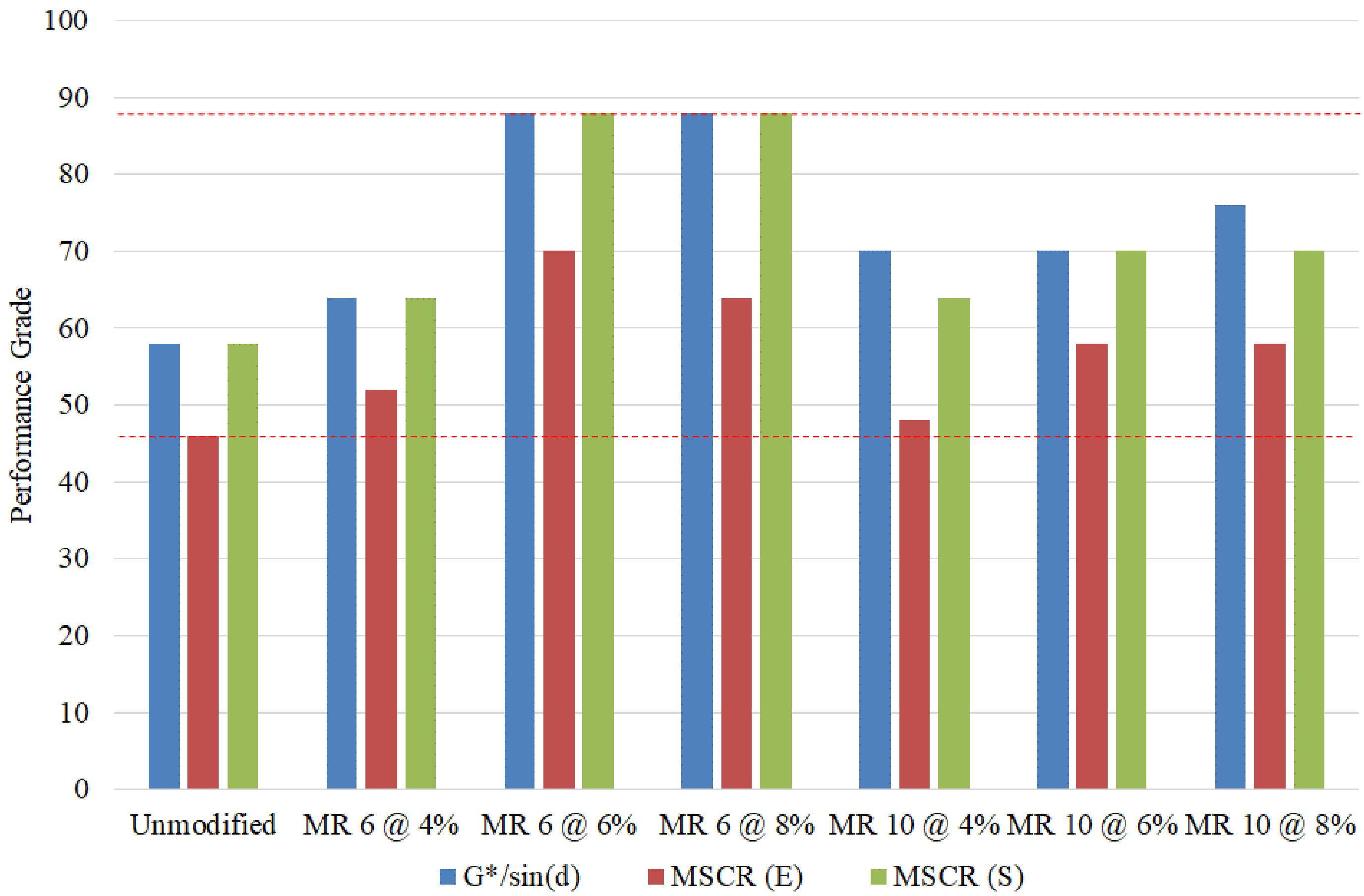


Figure 2. Summary of PG results for 100/150 base bitumen.

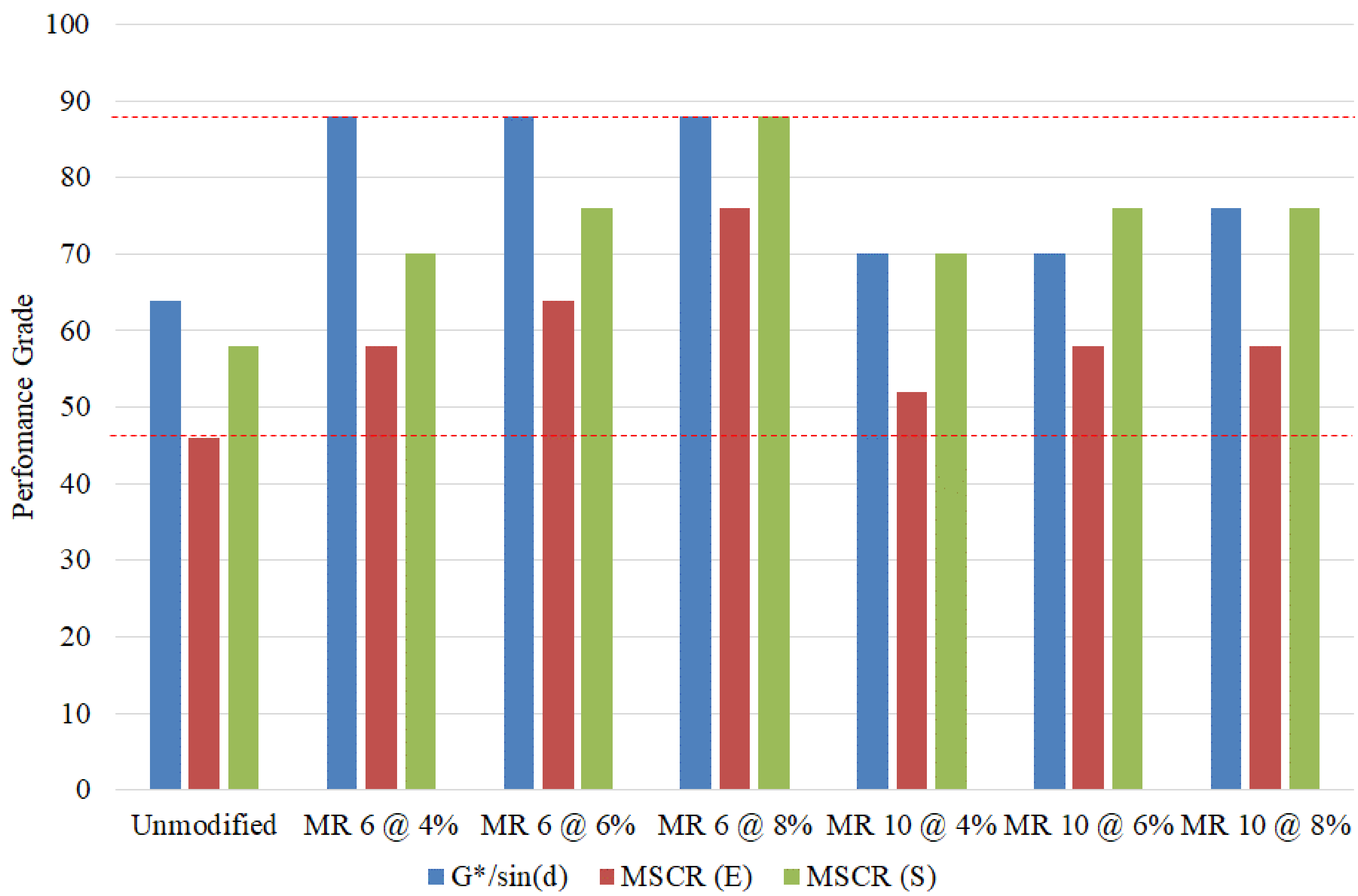


Figure 3. Summary of PG results for 50/70 base bitumen.

4 ANALYSIS

The unmodified bitumen grades were PG rated as 58°C and 64°C, for 100/150 and 50/70 penetration grade, respectively, based on the |G*|/sin δ parameter. Based on the MSCR protocol, the 100/150 penetration grade bitumen was PG rated at less than 52°C (for Extreme traffic) and 58°C (for Standard traffic). The 50/70 penetration grade bitumen rated the same as the 100/150 penetration grade by MSCR.

4.1 *Impact of MR 6 and MR 10 on index properties*

The impact of waste plastic modification is clear (Table 1). At the standard 6% MR dosage, both MR 6 and MR 10 reduced the penetration of the 100/150 penetration grade bitumen significantly, from 134 to 90-94. This reflects the increased resistance to penetration and deformation associated with modified binders. Similarly, the addition of waste plastic increased the softening point from 41°C to 47°C (for MR 10) and 51°C (for MR 6).

The most significant difference associated with the index properties was for the force ductility. This increased by one order of magnitude for MR 6 and two orders of magnitude for MR 10. This indicates a significant increase in the crack resistance associated with MR 10 modified binders, similar to that expected for conventional SBS polymer modified binder.

4.2 *Impact of MR 6 and MR 10 on PG rating*

The additional of MR 6 and MR 10 waste plastic resulted in a significant improvement in the PG rating of the binders. For example:

- 100/150 penetration bitumen increased in |G*|/sin δ PG rating from 58°C to more than 82°C with the addition of 6% MR 6 and to 70°C with the addition of 6% of MR 10.
- 50/70 penetration bitumen increased in |G*|/sin δ PG rating from 64°C to more than 82°C with the addition of 6% MR 6 and to 70°C with the addition of 6% of MR 10.

Consequently, it was concluded that MR 6 and MR 10 improved unmodified penetration-grade bitumen in a similar manner to conventional polymer modification of bitumen for asphalt production.

4.3 *Impact of plastic dosage on binder properties*

Using the standard 6% (by mass of bitumen) as the reference, it is logical that higher waste plastic dosage would provide greater improvement. On average the PG rating of the binder increased by only 4% for 8% of waste plastic, while the average PG rating decreased by 12% when only 4% of waste plastic was added (Figure 4). Consequently, it was concluded that 6% (by mass of bitumen) is likely to the be the optimum dosage, with only minimal additional benefit at 8%, while the increased improvement compared to 4% was significant.

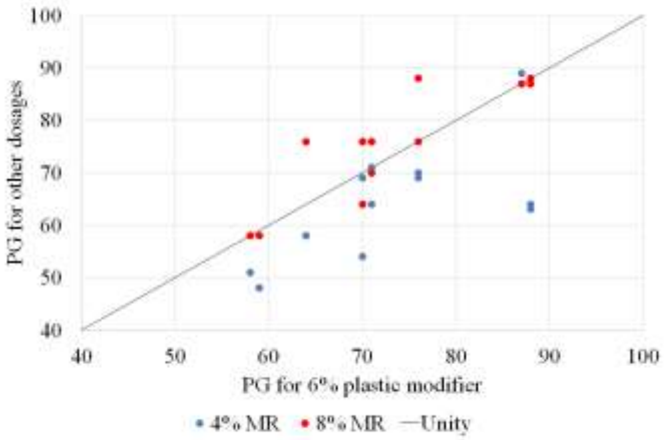


Figure 4. Impact of plastic dosage on binder PG rating.
Note: Some results have been adjusted by 1°C to allow all data-points to be visible.

4.4 *Impact of base bitumen on binder properties*

It is logical that a harder base bitumen would result in a harder modified bitumen, when otherwise similarly modified. On average, this was the case, with the PG rating associated with the 50/70 penetration grade base bitumen 7%, 4% and 3%, higher than for 100/150 penetration grade bitumen when assessment by |G*|/sin δ, MSCR at Extreme traffic and MSCR at Standard traffic, respectively (Figure 5).

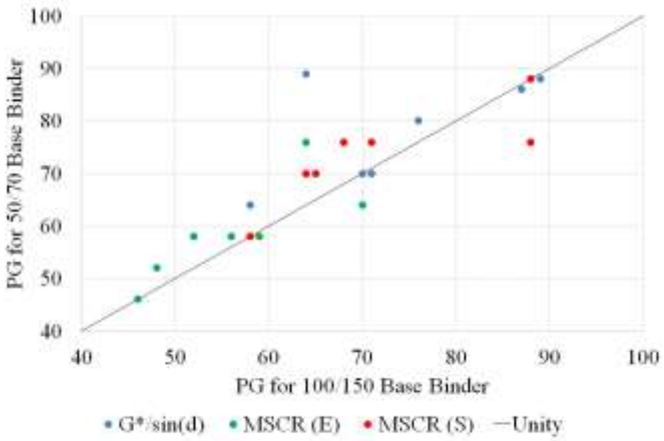


Figure 5. Impact of base bitumen on binder PG rating.
Note: Some results have been adjusted by 1°C to allow all data-points to be visible.

4.5 *Comparing MR 6 and MR 10 modification*

MR 6 is intended to be a plastomeric modifier, meaning that MR 6 modified binder is expected to be stiff and have only limited recovery capacity. Furthermore, MR 10 is intended to be elastomeric, so is expected to have increased recovery capacity, but less resistance to deformation than MR 6.

Figure 6 indicates that MR 6 generally resulted in a higher PG rating than MR 10. The difference was greatest when the PG rating was based on the MSCR for Extreme traffic conditions.

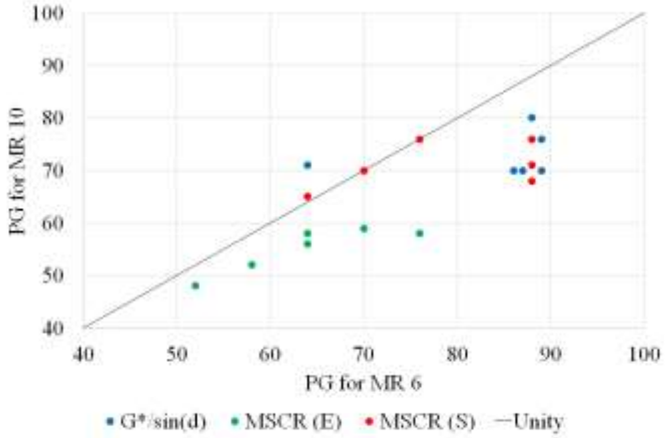


Figure 6. Impact of plastic modifier type on binder PG rating.
Note: Some results have been adjusted by 1°C to allow all data-points to be visible.

A greater difference between MR 6 and MR 10 modified binder was evident in the MSCR percentage recovery results, as an indicator of elasticity. These are shown in Figure 7 (for the 100/150 penetration grade base bitumen) and Figure 8 (for the 50/70 base bitumen).

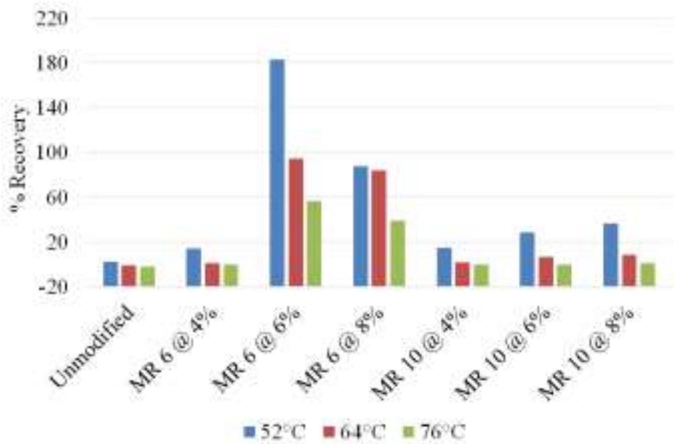


Figure 7. Summary of MSCR percentage recovery results for 100/150 base bitumen.

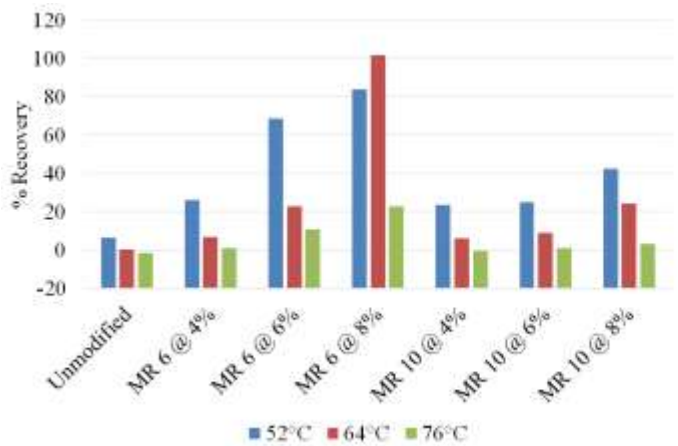


Figure 8. Summary of MSCR percentage recovery results for 50/70 base bitumen.

On average, the percentage recovery of MR 10 modified binder was only 45% of that for MR 6 modified binder. This is clearly shown in Figure 9 and contrasts with the intention that MR 10 is elastomeric modified, while MR 6 is intended to be a plastomeric modifier. This finding is consistent with separately reported asphalt testing results, which indicated that asphalt made with MR 6 had a higher fracture toughness than nominally identical asphalt made with MR 10 (White & Reid 2018). Further research is required to understand the contradiction between different binder and asphalt indicators of fracture resistance for waste plastic modified binders.

It was hypothesized that a change in binder properties with regard to temperature may be a significant factor. The influence of MSCR test temperature on binder Jnr (Figure 10) and MSCR elastic recovery (Figure 11) is clear. In both cases, common Australian modified binders (M1000, A10E and A35P) are compared from previously published data (White 2017). The general reduction in performance at increasing temperature of all binders is clear. However, the fact that some lines cross-over indicates that different conclusions are possible depending on the test temperature, and by extension the test method. Furthermore, it appears that MR 10 is generally more sensitive to temperature than MR 6 and the other conventional polymer modifiers.

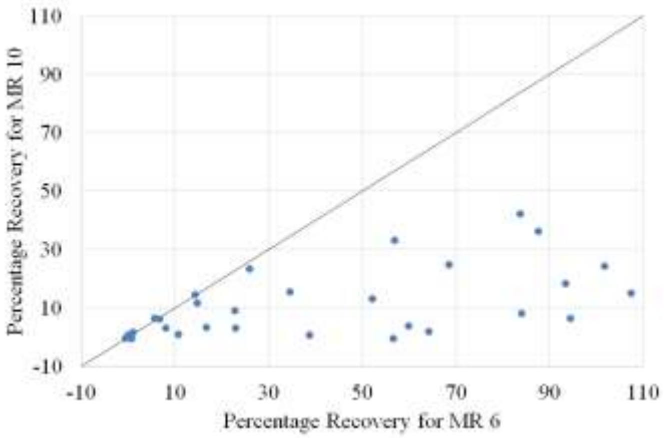


Figure 9. Impact of plastic modifier type on binder MSCR percentage recovery.

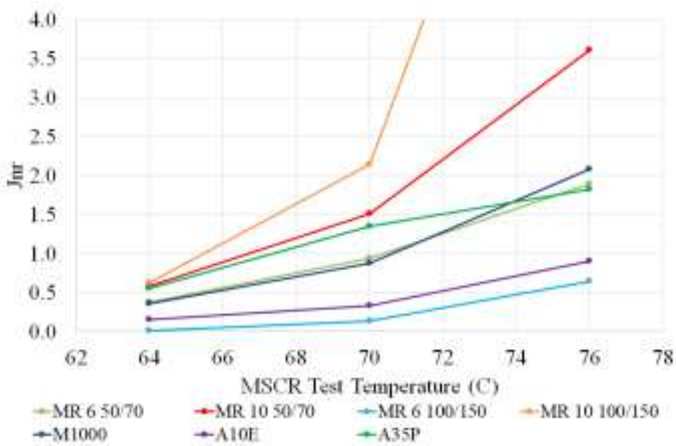


Figure 10. MSCR creep compliance versus test temperature.

At a more fundamental level, the cumulative strain during the MSCR test indicates the different response to load for different binders (Figure 12). In this example, the reduced deformation associated with the waste plastic modified binder is clear, as is the higher deformation associated with the softer 100/150 penetration grade bitumen compared to the 50/70 penetration grade. Furthermore, by isolating a single strain cycle (Figure 13) the different response to load of MR 6 and MR 10 is clear. In this example, MR 6 experienced less deformation and exhibited significant recovery, while the recovery of MR 10 modified binder was minimal. This is consistent with the higher MSCR PG rating of MR 6 than MR 10, as well as the higher elastic recovery associated with MR 6 compared to MR 10.

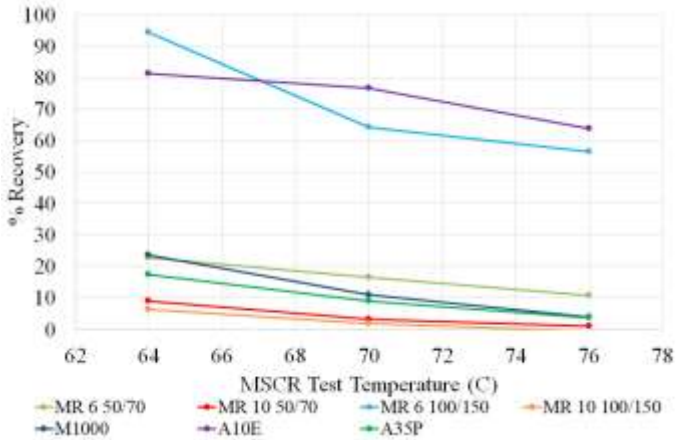


Figure 11. MSCR elastic recovery versus test temperature.

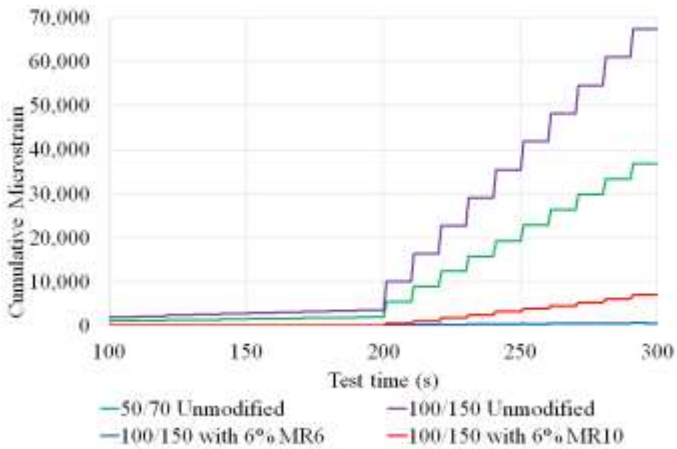


Figure 12. Example MSCR cumulative deformation.

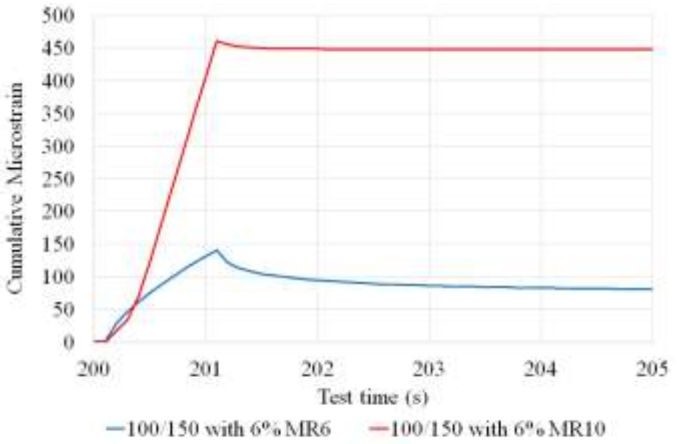


Figure 13. Example comparison of MR 6 and MR 10 response to single MSCR stress and recovery cycle.

4.6 *Comparison to other modified binders*

Under the USA's PG system for rating binders, comparison of binder modifiers is challenging because the type and dosage of polymer or another modifier is not necessarily described or reported. However, in Australia, the polymer modified and multigrade binders are defined in terms of modifier type. Furthermore, White (2015) graded various Australian binders my the MSCR protocol, allowing a comparison of waste plastic modified binders to conventional polymer and other modifiers commonly used in Australia.

A single MSCR (at 70°C) stress and recovery cycle is reproduced in Figure 14. Comparing Figure 14 to Figure 13, it was concluded that 6% of MR 10 produces a binder with maximum strain comparable to SBS modified A10E but with minimal recovery, more comparable to acid modified multigrade M1000. Furthermore, 6% of MR 6 produced a binder with comparable response to EVA modified A35P, with regard to both maximum strain and subsequent recovery.

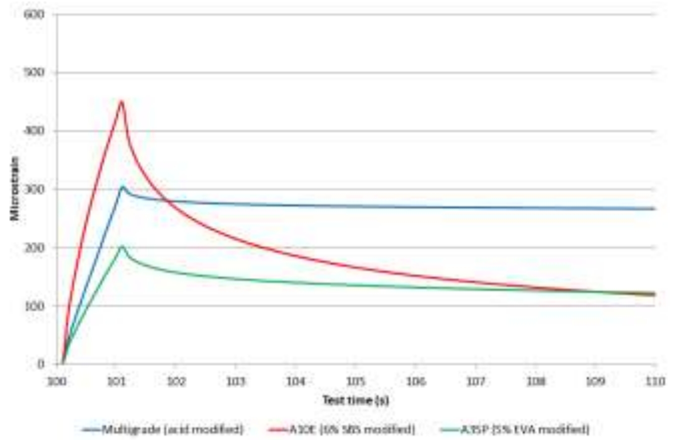


Figure 14. Australian modified binder response to single MSCR stress and recovery cycle (White 2015).

The MSCR based PG rating of these Australian modified binders is summarised in Table 2. These PG ratings are again comparable to 6% MR 6, which was rated by the MSCR protocol from PG 64 to greater than PG 82, for Extreme and Standard traffic, for both 100/150 an 50/70 penetration grade bitumen. Furthermore, 6% MR 10 was rated by MSCR as PG 58 to PG 76 over the range of traffic categories. The waste plastic modified binder results were better than the Australian polymer modified binder results for PG rating, indicating that plastic waste modified binders are likely to perform in a comparable or better manner than typical conventional polymer modified binders.

Table 2. Summary of Australian MSCR PG ratings.

Binder	MSCR PG rating	
	Extreme traffic	Standard traffic
Multigrade M1000	64°C	76°C
SBS modified A10E	64°C	76°C
EVA modified A35P	<64°C	70°C

5 FURTHER RESEARCH

The waste plastic source investigated was developed to be added directly into the asphalt production plant. This contrasts with most bitumen modifiers, which are intended to be pre-blended into bitumen prior to asphalt production. The two production methods may return different results and further research is recommended to compare asphalt and binder properties produced by wet blending into bitumen and dry mixing into asphalt.

It would also be beneficial to understand why MR 10, which is designed to be more elastomeric, responds to load in a more plastomeric manner and why MR 6 appears to be significantly more elastomeric than MR 10.

Some of the results in Appendix 1 appear to exhibit high variability. This likely reflects some incomplete digestion or post-mixing partial segregation of some samples, which was also observed during testing. This contrasts with separately reported waste plastic modified binder segregation testing which indicated that waste plastic was no more susceptible to segregation than other polymer modifiers. Further research is recommended to understand the risk of waste plastic modifier segregation and/or incomplete digestion and whether smaller and less dense waste plastic pellets produce more consistent results than the MR 6 and MR 10 pellets shown in Figure 1. It is also recommended that asphalt property consistence testing evaluate whether digestion during dry mixing is more consistent than for wet blending.

Finally, properties indicative of asphalt performance should be compared between otherwise nominally identical samples of asphalt produced with waste plastic modified binder and other common modified binders. In Australia, this would include plastomeric A35P, elastomeric A10E and multigrade M1000.

6 CONCLUSIONS

The improvement in binder properties associated with waste plastic modification was significant, with two or more PG increases or ‘grade-bumps’ common. Although all waste plastic contents and both waste plastic types improved the binder, a 6% (of binder mass) dosage was optimum and MR 6 provided greater improvement than MR 10.

It was concluded that MR 6 and MR 10 modified bitumen exhibited properties similar to common Australian multigrade and polymer modified binders, but MR 6 exhibited more elastic response to load than MR 10, which contrasts with the manufacturers advertised intent for the two products.

Further research is recommended to better understand the propensity for wet blended waste plastic modified to not fully digest or to segregate after mixing, and to determine if more consistent results are achieved from different waste plastic pellet size, shape and density. Furthermore, additional research is recommended to compare waste plastic modified asphalt properties to properties of otherwise comparable asphalt produced with polymer modified and multigrade binders, and to compare asphalt and binder properties when waste plastic is wet blended compared to when it is dry mixed.

The benefits of waste plastic as an alternate modifiers of asphalt binder was significant and an objective evaluation of the economic and environmental benefit for products producing comparable performance is required.

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Appendix 1 – Dynamic shear rheometer test results
Note: not all samples were tested at all temperatures, depending on the PG rating of the binder.

Unmodified binder results

Base bitumen	Parameter	Test temperature					
		52	58	64	70	76	82
50/70	|G*|/Sin(δ)	7.83	3.13	1.33	0.58	0.28	
	Jnr	0.57	1.69	4.37	10.85	28.00	
	% Rec	6.35	0.90	<0.01	-0.78	-1.72	
100/150	|G*|/Sin(δ)	4.42	1.92	0.87	0.42	0.22	
	Jnr	1.46	4.00	9.07	19.86	39.79	
	% Rec	1.96	0.06	-0.76	-1.20	-2.07	

MR6 modified binder results

Base bitumen and MR dosage	Parameter	Test temperature					
		52	58	64	70	76	82
50/70 4%	|G*|/Sin(δ)	79.96	60.36	49.78	3.70	2.39	1.65
	Jnr	0.09	0.28	0.87	1.97	5.99	10.97
	% Rec	25.91	14.74	6.69	8.05	0.72	-0.64
50/70 6%	|G*|/Sin(δ)	105.60	64.36	47.84	40.20	34.70	29.30
	Jnr	0.01	0.12	0.37	0.94	1.89	6.39
	% Rec	68.45	34.47	22.71	16.61	10.75	6.39
50/70 8%	|G*|/Sin(δ)	234.30	141.50	94.91	67.72	49.82	37.64
	Jnr	<0.01	0.03	<0.01	0.01	0.05	1.88
	% Rec	83.65	56.82	101.70	52.11	22.88	28.20
100/150 4%	|G*|/Sin(δ)	10.51	4.51	2.05	0.99	0.51	0.29
	Jnr	0.32	0.89	2.10	5.60	11.43	23.85
	% Rec	14.22	5.61	1.02	-0.03	-0.66	-1.71
100/150 6%	|G*|/Sin(δ)	31.97	17.38	10.52	7.04	5.11	4.00
	Jnr	<0.01	<0.01	<0.01	0.13	0.64	1.31
	% Rec	182.70	107.4	94.42	64.16	56.58	44.23
100/150 8%	|G*|/Sin(δ)	73.09	42.45	27.47	19.20	14.22	11.21
	Jnr	<0.01	<0.01	0.02	0.58	0.76	1.80
	% Rec	87.64	93.4	84.01	59.89	38.69	24.16

MR10 modified binder results

Base bitumen and MR dosage	Parameter	Test temperature					
		52	58	64	70	76	82
50/70 4%	|G*|/Sin(δ)	11.41	4.94	2.25	1.07	0.52	
	Jnr	0.22	0.81	1.98	3.91	11.92	
	% Rec	23.27	11.70	6.14	2.99	-0.44	
50/70 6%	|G*|/Sin(δ)	15.90	7.02	3.26	1.58	0.78	0.39
	Jnr	0.07	0.21	0.58	1.51	3.61	7.61
	% Rec	24.83	15.46	9.03	3.34	0.99	-0.12
50/70 8%	|G*|/Sin(δ)	19.71	8.86	4.13	2.02	1.03	0.52
	Jnr	0.09	0.26	0.69	1.92	3.88	8.38
	% Rec	42.29	33.17	24.26	13.01	3.09	0.01
100/150 4%	|G*|/Sin(δ)	11.43	5.66	3.03	1.78	0.95	0.84
	Jnr	0.63	1.52	3.90	8.11	12.53	
	% Rec	14.52	6.28	1.52	0.69	-0.59	
100/150 6%	|G*|/Sin(δ)	8.88	4.26	2.08	0.93	0.54	0.30
	Jnr	0.12	0.34	0.63	2.15	9.70	26.40
	% Rec	27.97	14.99	6.33	1.79	-0.44	-1.45
100/150 8%	|G*|/Sin(δ)	16.39	8.42	4.53	2.58	1.55	0.98
	Jnr	0.18	0.22	1.26	3.45	8.97	26.82
	% Rec	36.26	18.24	8.13	3.76	0.77	-1.44