EVALUATING RECYCLED WASTE PLASTIC MODIFICATION AND EXTENSION OF BITUMINOUS BINDER FOR ASPHALT

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ABSTRACT

There is increasing interest in more sustainable pavement technologies, with recycled waste plastic extension and modification of bituminous binder for asphalt production a promising opportunity. It is important to identify modification and extension of the bituminous binder with low melt-temperature plastic as being distinctly different from the extension of the aggregate in the asphalt mixture with higher melt-temperature plastics such as PET (in plastic bottles) and HDPE (in plastic bags). Three commercially available recycled plastic products for binder extension and modification were evaluated in the same stone mastic asphalt mixture in the laboratory. The recycled plastic improved the deformation and fracture resistance, had mixed and minor effect on the moisture resistance and increased the structural contribution of the asphalt to the pavement. No adverse effect was detected with regard to toxic fume generation or hazardous leachate. It is recommended that recycled low melt-temperature plastic be used as an alternate to conventional polymers for bituminous binder extension and modification, particularly in high stress areas, where resistance to deformation is important to long-term surface performance.

INTRODUCTION

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 recycled waste plastic into construction materials. At this time, the primary construction-based reuse of recycled 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, most research has focused on the replacement of the fine aggregate in concrete mixtures and only relatively recent research has considered the efficacy of recycled plastic as a extender or modifier for asphalt mixtures (Guru et al. 2014; Sojobi et al. 2016; Dalhat & Al-Adbul Wahhab 2017; White & Reid 2018; Leng et al. 2018; White & Reid 2019).

Since 2015, commercial sources of recycled waste and processed waste plastic have been developed for incorporation into asphalt for pavement surfacing (MacRebur 2017). As detailed below, some products are intended to extend the asphalt mixture and are essentially aggregate extenders. Other products are intended to melt into and extend the bituminous binder, while others are intended to extend and modify the bituminous binder (White & Reid 2019). This final category of recycled plastic is most valuable because it consumes plastic that may otherwise be sent to landfill, reduces the volume of refined bitumen required for global asphalt production and improves the performance of the resulting asphalt mixture.

This research evaluates three different commercial recycled plastic products in the laboratory. The products were all designed to extend the bituminous binder within the asphalt mixture and two of the three were developed to modify the bituminous binder in a similar manner to conventional elastomeric and plastomeric polymers for improved asphalt performance. Laboratory-measured asphalt properties indicative of resistance to deformation, resistance to fracture and moisture damage susceptibility were all considered. Environmental (leachability) and safety (fume generation) were also considered. Conclusions address the predicted field-performance benefits associated with asphalt modification using recycled plastic.

BACKGROUND

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, as long as 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 tonne less 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. It is therefore important that recycled materials provide reduced cost or improved performance, compared to otherwise similar new material use.

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 (White & Reid 2018). 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 a binder extender and modifier. This highlights the important difference between low melt-temperature waste plastic as a binder extender (and potential modifier) which is distinctly different to using higher melt-temperature waste plastic as an asphalt mixture or aggregate extender. This paper focuses on binder extension and modification using low melt-temperature recycled plastic.

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-temperature 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 recently added shredded 4 L engine oil containers to asphalt 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 extend or modify the bituminous binder and such practices 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-temperature plastics designed to digest into the asphalt binder, just like other conventional polymers for binder modification.

Commercial recycled plastic for bitumen extension

In 2015, a commercial recycled plastic venture was initiated in Scotland 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 was intended to be incorporated directly into the asphalt production plant. It is produced from 100% recycled plastic. The recycled plastics used have melt-temperature below the typical asphalt and binder production temperatures and readily melt into the bitumen 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. The original MR 6 was developed to improve deformation resistance via an increase in asphalt stiffness. 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**).

Figure 1. (a) MR6 pellets, (b) MR 8 shreddings and (c) MR10 pellets

The waste plastic sourcing, blending and processing is proprietary information but the products are manufactured from recycled waste plastic materials from both domestic and industrial origins. Suitable 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 product to be traced to a specific production batch and the associated sources of recycled plastic.

Asphalt performance and testing

Excluding functional properties, such as tyre skid resistance and visual definition, the fundamental performance requirements of asphalt are:

- Resistance to deformation.
- Resistance to fracture.
- Durability.

Resistance to deformation includes resistance to plastic flow as well as post-construction densification (Sousa et al. 1994). Good resistance to deformation reduces the risk of asphalt rutting, shoving and shearing and increases pavement smoothness, as well as preventing ponded water from inhibiting tyre skid resistance.

Resistance to fracture minimises both top-down and bottom-up fatigue cracking (Molenaar 2007). Good fracture resistance prevents moisture from entering the pavement through the surface and avoids the potential for spalling along the subsequent cracks. Good fracture resistance is important for long-term pavement surface performance, as well as protecting the underlying granular material from the detrimental effects of moisture ingress.

Durability is the capacity of the asphalt to retain its integrity and resistance to deformation/fracture over time. Asphalt durability also includes resistance to moisture damage (stripping) and resistance to surface erosion with age (ravelling) (White 2018). Ravelling resistance is complex and is affected by mixture volumetrics, aggregate properties, raw material properties and the environment (Bianchetto. et al. 2007). Stripping resistance is also complex but there are well established test methods for the measurement of the resistance to stripping of the mixture, with the modified Lottman indirect tensile strength ratio the most common (Bhasin & Little 2007).

When comparing the performance of different asphalt mixtures or different bituminous binders in the same asphalt mixture, resistance to deformation, resistance to fracture and resistance to moisture damage are often focussed on. However, with increased interest in optimisation of mechanistic-empirical pavement thickness design methods, the stiffness of modulus of pavement materials, including asphalt, has also increased (Austroads 2017).

METHODS AND RESULTS

Methods

A typical 10 mm maximum sized stone mastic asphalt (SMA) surface layer (**Table 1**) was produced with conventional (unmodified) 40/60 bitumen as well as 40/60 modified by 6% of each of the three recycled plastic products.

Table 1. Asphalt mixture properties

Property	**Target value**
Binder content (by mass)	6.3%
Maximum density	2,440 kg/m3
Combined aggregate grading (percentage passing the sieve (mm)	
14	100
10	97
8	76
6.3	45
4	38
2	24
1	17
0.500	14
0.250	13
0.125	11
0.063	9.8

Each asphalt mixture was evaluated for relative performance (compared to the 40/60 mixture) according to British SMA specification (BS EN 13108-5:2016) and using laboratory test methods indicative of asphalt mixture performance (**Table 2**). In addition, the practical concerns associated with leachability of chemicals and hazardous fume generation associated with the use of recycled plastic were also evaluated in the laboratory.

Leachability was evaluated by placing nominal 2.5 g samples of binder, with and without recycled plastic, in 50 ml of deionised water for 18 hours at 40°C. The water was then cold-evaporated under nitrogen, before the residual was dissolved in 5 ml of ethanol and analysed for mass spectrometry by gas chromatography. For the fume generation evaluation, 1 g binder samples, with and without recycled plastic, were thermally desorped at 100, 150, 180 and 200°C and analysed for mass spectrometry by gas chromatography, after each desorption temperature. The leaching and fuming evaluations were not performed to a specific British or international test method.

Rather, standard procedures and equipment were used by a specialised laboratory holding UKAS accreditation to ISO 17025 for similar test methods.

Table 2. British asphalt specification performance tests

Performance property	Test method	Indicative of
Stiffness Modulus (Indirect tension at 20°C)	EN 12697-26	Structural contribution
Moisture Damage (Indirect tensile strength ratio before/after conditioning)	BS EN 12697-12	Moisture Damage resistance
Wheel Track Rutting (Depth at 10,000 passes and rut rate at 60°C)	PD 6691-2 PD 6691-3	Rutting under traffic
Fracture Toughness (Semi circular notch propagation at 0°C)	BS EN 12697-44	Fracture resistance
Fatigue life (Stress controlled repeated indirect tension at 20°C)	BS EN 12697-24	Fracture resistance

Results

Asphalt mixture test results are in **Table 3** for all properties except for fatigue, which is in **Table 4** for each tested stress level.

Table 3. Asphalt test results, excluding fatigue life

Property	Units	Straight 40/60	6% MR6	6% MR8	6% MR10
Stiffness Modulus	MPa	1,823	5,438	4,032	6,451
Moisture Damage	%	94.8	> 100.0	85.0	86.0
Rut Depth	Mm	3.1	1.3	2.6	2.0
Rut Rate	mm/kilocycles	0.11	0.03	0.07	0.05
Fracture toughness	$N/mm^{3/2}$	23.8	29.1	25.8	27.6

Table 4. Asphalt fatigue life test results

Stress (MPa)	Straight 40/60		6% MR6		6% MR8		6% MR10	
	με(0)	N	με(0)	N	με(0)	N	με(0)	N
250	Not tested		Not tested		81	328,816	Not tested	
300	93	662,788	158	197,876	98	137,136	110	548,276
350	107	400,192	185	59,386	114	166,076	128	356,206
400	120	389,372	211	22,736	130	54,596	147	128,036
450	133	130,646	238	14,736	146	57,476	165	53,386
500	147	81,186	264	23,236	163	25,226	183	61,196
550	160	452,46	290	8,976	179	28,096	202	32,256
600	173	47,286	317	7,486	195	18,116	220	16,006
650	187	6,236	343	3,066	211	9,386	238	21,986
700	200	10,076	369	4,956	228	15,496	257	11,656
750	213	3,456	396	3,906	Not tested		275	9,836

με(0) is the initial strain at that stress level and N is the number of cycles to complete fracture.

DISCUSSION

Effect of recycled plastic on leaching and fuming

The leachability test did not indicate any leachable material in the recycled plastic or the conventional bitumen samples. The fume generation test indicated the generation of toluene and benzene, as well as the aliphatic, cyclic and aromatic hydrocarbons normally associated with bitumen. However, it was found that all harmful fumes originated from the bitumen, rather than the recycled plastic, with no significant difference between the fumes from samples with and without recycled plastic. Consequently, it was concluded that recycled plastic modification and extension of bituminous binders does not adversely impact the environment (leachate) or workplace/public safety (harmful fumes).

Effect of recycled plastic on durability

The addition of 6% MR 6 improved the moisture damage of the samples while MR 8 and MR 10 reduced the moisture damage ratio from 95% to around 85% (**Figure 2**). This parameter is 'report only' in the British specification, but in Australia and other countries it is commonly limited to not less than 80%. It is also recognised as being a variable test method. Consequently, it was concluded that recycled plastic had no substantial impact on the moisture damage resistance of the asphalt.

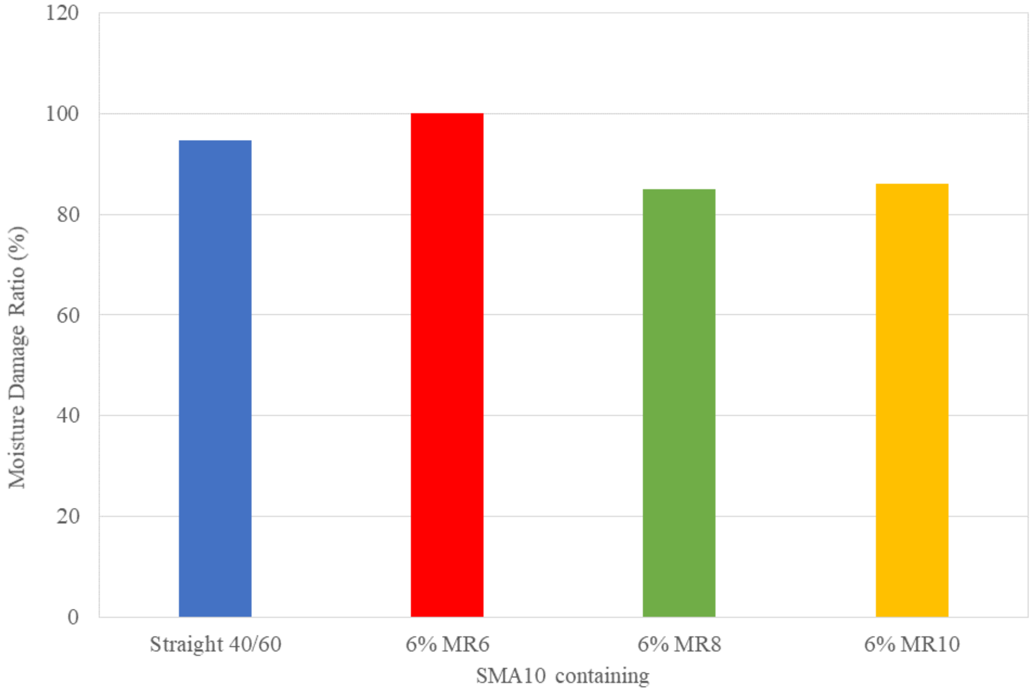

Figure 2. Asphalt moisture damage ratio for recycled plastic modified binders

Effect of recycled plastic on structural contribution

All the recycled plastic modified binders increased the stiffness modulus of the asphalt samples substantially (**Figure 3**). The increase in modulus ranged from 120% (MR 8) up to 250% (MR 10). Asphalt modulus is an important characteristic for the structural capacity of any given pavement and a higher stiffness modulus can only represent a stronger pavement, providing better protection of the underlying materials and subgrade. However, further work is required to determine the practical effects of the measured increase in asphalt stiffness modulus on overall pavement thickness reduction or longer lasting pavements. Asphalt modulus is also an indicator of asphalt deformation resistance, with a stiffer asphalt surface providing better resistance to shearing, shoving and rutting, which is discussed below.

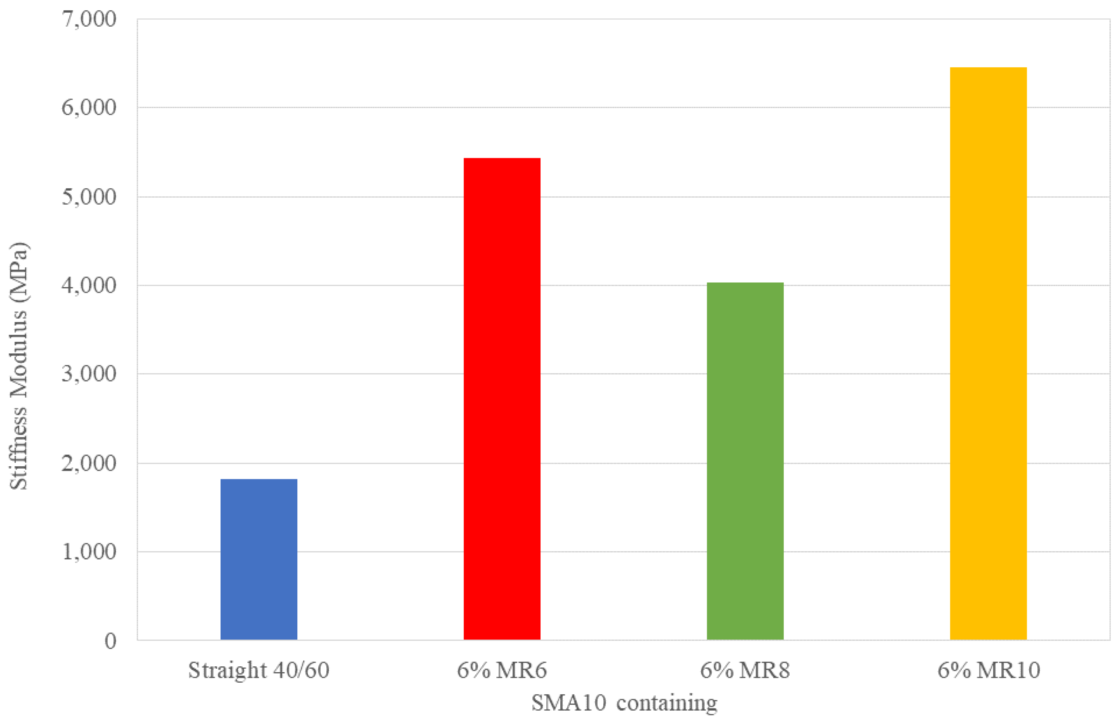

Figure 3. Asphalt stiffness modulus for recycled plastic modified binders

Effect of recycled plastic on deformation resistance

The rut depth (**Figure 4**) and rut rate (**Figure 5**) were both reduced by recycled plastic modified binders. MR 6 had the greatest effect with a 49% reduction in rut rate while MR 10 was associated with a 35% reduction. The effect on the rut rate was even greater, with a 37% to 73% reduction associated with the recycled plastic modified products. All the asphalt mixtures tested had good deformation resistance, with all rut rates well below the 1.0 mm/kilocycle maximum required by the British specification. As stated above, any increase in deformation resistance can only reduce the risk of shearing, shoving and surface rutting. Furthermore, for runway applications, greater resistance to deformation decreases the risk of groove closure. Consequently, it was concluded that recycled waste plastic had only a positive effect on asphalt deformation resistance.

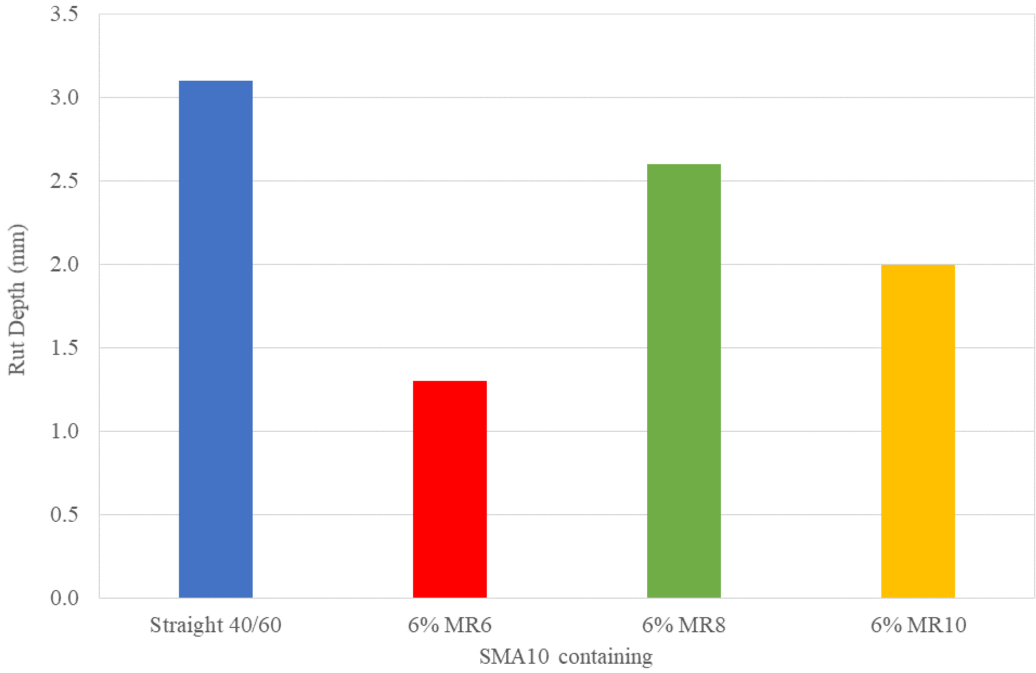

Figure 4. Asphalt rut depth for recycled plastic modified binders

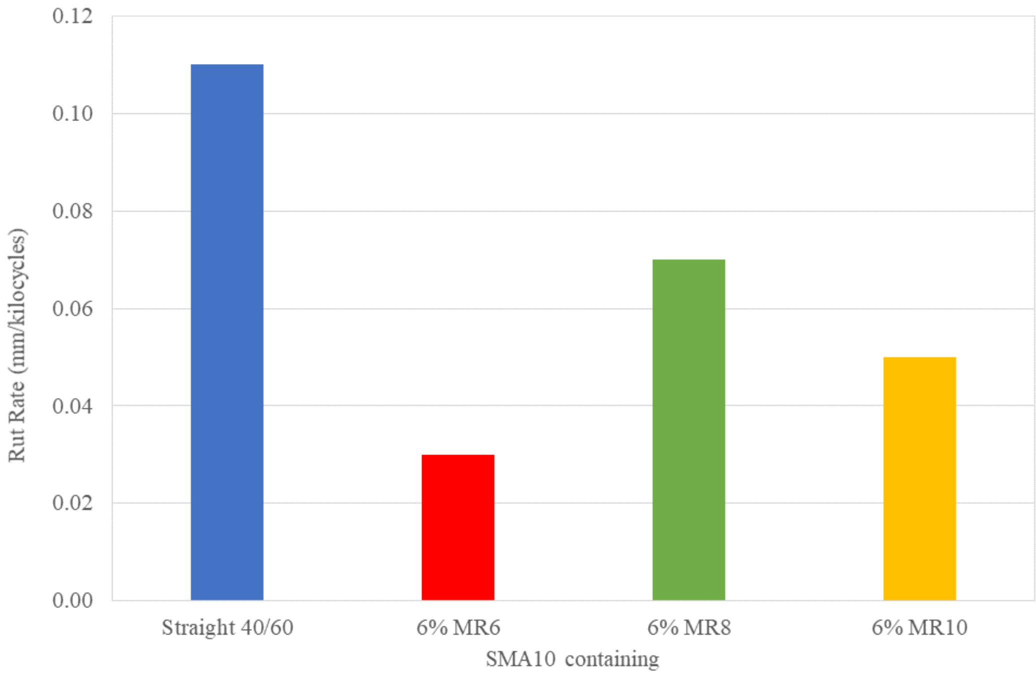

Figure 5. Asphalt rut rate for recycled plastic modified binders

Effect of recycled plastic on fracture resistance

Asphalt fracture toughness was improved by recycled plastic modification (**Figure 6**). The improvement ranged from 8% (MR 8) to 22% (MR 6). In contrast, the effect on fatigue life varied (**Figure 7**) which is clearer in a log-log (to a base of 10) space (**Figure 8**). MR 6 and MR 10 improved the measured fatigue lives while the MR 8 trendline overlapped the trendline associated with unmodified 40/60 bitumen. Interestingly, recycled plastic modification consistently reduced the slope of the trendline, meaning that the effect on fracture resistance was greatest at higher magnitudes of strain. This indicates that the benefit associated with MR 6 and MR 10 is greatest in higher stress applications.

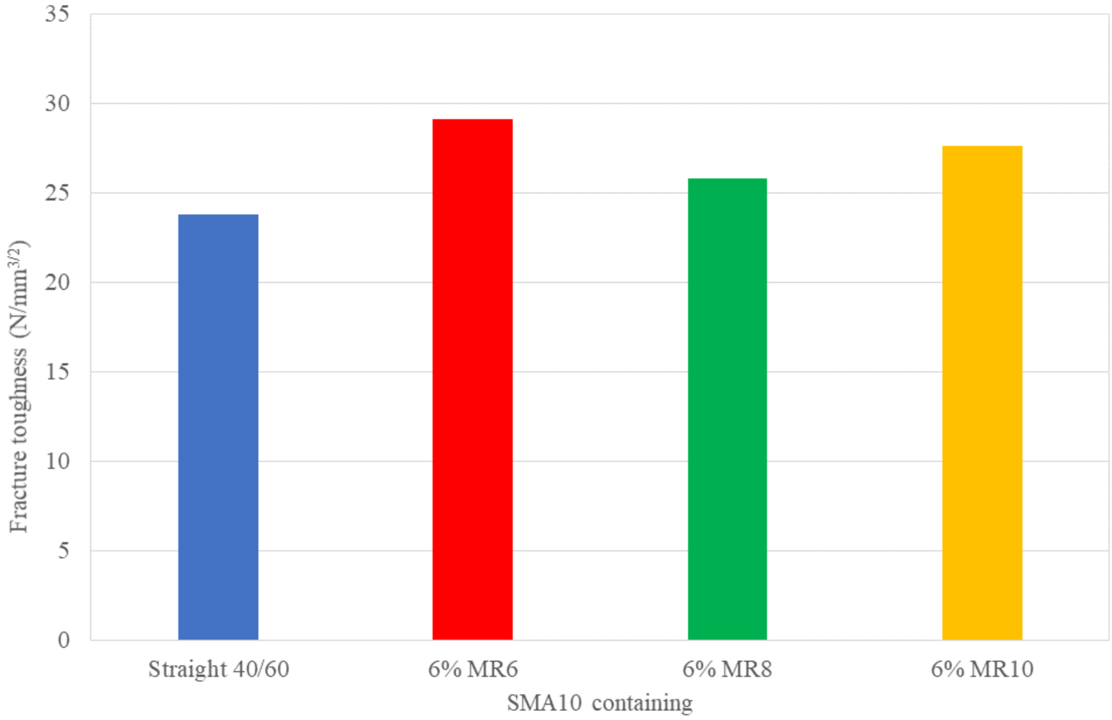

Figure 6. Asphalt fracture toughness for recycled plastic modified binders

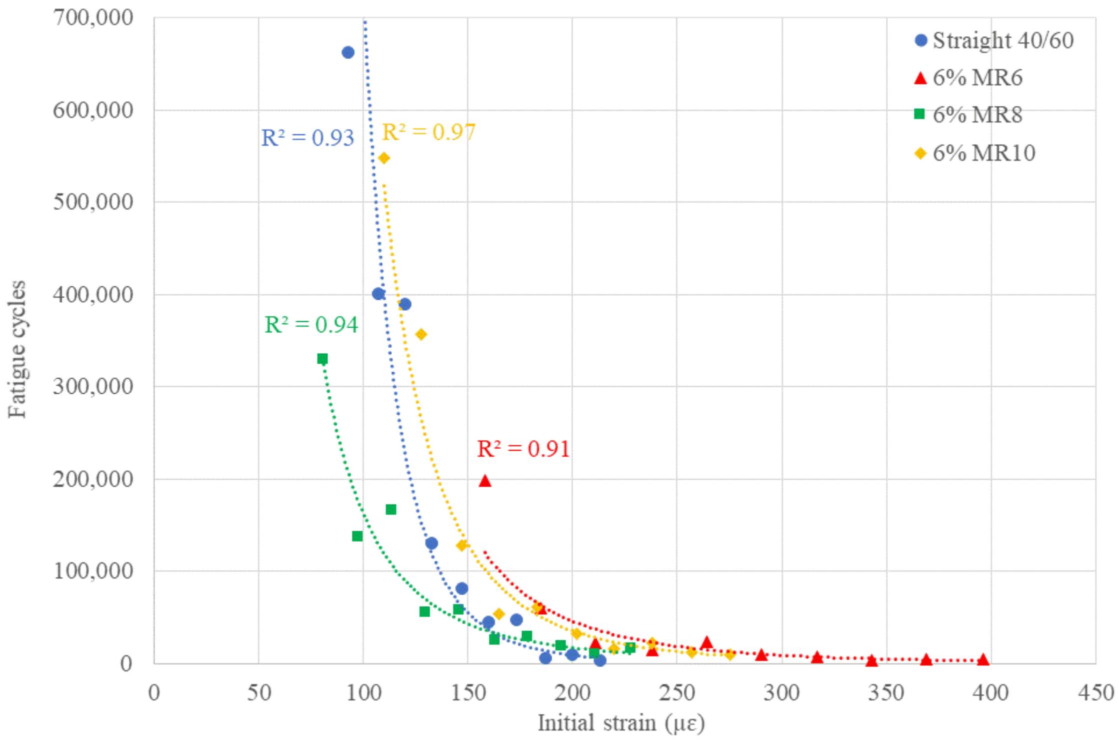

Figure 7. Asphalt fatigue life for recycled plastic modified binders at different strain

Figure 8. Asphalt fatigue life (log-log) for recycled plastic modified binders by strain

It is important to understand the interaction between stress, strain and fracture/fatigue and how it can change with different test methods. The fracture toughness test is stress controlled and reported, meaning that two materials of different stiffness require a different load to be applied to induce the same level of stress in the same sized samples. In contrast, the fatigue test is load controlled but it is reported by strain. This means that the same stress magnitude is induced in the samples, regardless of the level of strain. However, the results are reported as fatigue cycles as a function of induced strain. Consequently, a stiffer material is stressed to a higher degree at any compared level of strain. Theoretical pavement modelling in a layered elastic design tool is required to determine the difference in critical strain magnitude in the asphalt for the different asphalt modulus values This will all the effect of recycled plastic modification on the predicted asphalt fatigue life, based on the different levels of tensile strain and the different relationships between tensile strain and load cycles to fatigue failure, for the different materials.

The results indicate that MR 6 and MR 10 modified binder improved the fracture toughness and the fatigue life of the asphalt. The effect of MR 8 was less clear and depended on the level of strain. Fatigue life is accepted as being more variable than some other asphalt properties and is complicated for materials of different modulus due to the interaction between applied load (or induced stress), the resulting strain magnitude and the measured fatigue cycles.

Overall evaluation

Table 5 summarises the effects of recycled plastic modification on the asphalt performance properties for the three products evaluated. Despite MR 8 being developed as an economical bitumen extender, without necessarily improving asphalt properties, the deformation resistance and structural contribution were both improved. The moisture damage resistance was reduced, but still within common specification limits and the resistance to fracture was unclear, depending on the strain magnitude. MR 10 had the greatest effect on the structural contribution, with the highest stiffness modulus. MR 6 modification improved all performance properties and had the greatest effect on the asphalt fracture resistance and deformation resistance. This contrasts with the original intention that MR 10 be more elastomeric than MR 6, which is intended to be plastomeric. None of the recycled plastic products had any adverse effect on either toxic fume generation or hazardous leachate.

Table 5. Summary of effect of recycled plastic on asphalt performance

Performance requirement	**MR 6**	**MR 8**	**MR 10**
Resistance to deformation	Greatest improvement	Modest improvement	Significant improvement
Resistance to fracture	Greatest improvement	Depends on stress/strain level	Significant improvement
Resistance to moisture damage	Improvement	Moderate reduction	Moderate reduction
Structural contribution	Significant improvement	Moderate improvement	Greater improvement
Toxic fume generation	No effect	No effect	No effect
Hazardous leachate	No effect	No effect	No effect

CONCLUSIONS

The three recycled plastic modified binders improved the deformation resistance and structural contribution of the SMA. However, the effect on resistance to fracture depended on the recycled plastic product and the effect on moisture resistance also varied. Recycled plastic had no detectible adverse effect on either fume generation or leachability. It is recommended that recycled plastic be adopted in areas of high stress, such as intersections, round-a-bouts and heavy-duty truck route surfaces. Further work is required to better quantify the combined effect of increased stiffness on pavement asphalt tensile strain, load cycles to failure, pavement thickness and pavement/surface life.

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