Sustainability & Environment

Recycled Plastic as an Alternate to Conventional Polymers for Bituminous Binder

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Abstract

Some recycled soft plastics have been reported to improve the deformation (rutting) resistance and fracture (cracking) resistance of asphalt mixtures by beneficial modification of the bituminous binder. This research evaluates recycled soft plastic for bituminous bitumen modification with a focus on bituminous binder testing, rather than asphalt mixture testing. Elastomeric and plastomeric commercially available waste plastic products for bitumen modification and extension were evaluated in the laboratory, using bituminous binder tests commonly used in the United Kingdom and Australia, as well as the Performance Grading methods developed in the United States. The effect of recycled plastic modification was determined by comparison to the unmodified bitumen properties. The results indicate that both recycled plastic products significantly improved the bituminous binder properties commonly associated with asphalt mixture deformation resistance and temperature resistance. However, the greatest improvement was associated with the indicators of elasticity and mixture fracture resistance. These improvements were consistent across the test methods specified by all three countries. It was concluded that recycled plastic products have the potential to improve bituminous binder products in a similar manner to conventional polymers such as SBS and EVA. Further work is recommended to directly compare the recycled plastic modified products to otherwise similar SBS and EVA modified binders.

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1. INTRODUCTION

Waste plastic is a significant and growing environmental challenge and includes industrial plastics, plastic bags and plastic bottles [1]. As a result, there is an increased interest in recycling waste plastic [2] including into construction materials [3]. For some time, the primary construction-based reuse of recycled plastic was in concrete and masonry products, such as low-cost bricks for dwellings in developing countries and concrete for non-structural works [4-7]. However, in recent years recycled plastic has also been used as an aggregate extender, a bitumen extender and as a binder modifier in asphalt mixtures for pavement construction [1,3,8-11]. The differences between aggregate extension, bitumen extension and binder modification are important. Although aggregate and bitumen extension offer a means of disposing of plastics otherwise destined for landfill and reducing the rate of consumption of new constituent materials, binder modification also provides the potential to improve the performance of the asphalt and consequently the associated pavement.

Since 2015, commercial sources of recycled plastic have been developed for incorporation into asphalt for pavement surfacing and construction [12]. Some of these products are specifically intended to melt into, extend and modify the bituminous binder for improved asphalt performance through binder property modification [13]. These recycled plastic products, often referred to as 'soft plastics', are the most valuable because they not only consume plastic that may otherwise be sent to landfill and reduce the virgin bitumen content, but they also improve the performance of the resulting asphalt mixture in a similar manner to convention polymer modified binders [11].

This paper evaluates two commercially available recycled plastic products as bituminous binder modifiers. Binder properties were compared using typical test methods used in the United Kingdom (UK), Australia and the United States (US). Australian and UK test methods are generally index properties while the US testing is based on Performance Grade (PG) rating. Different unmodified penetration grade base bitumens were considered, as well as a range of recycled plastic contents.

2. BACKGROUND

2.1. Sustainable asphalt

The primary material recycled into asphalt mixtures is recycled asphalt. Reclaimed asphalt (RA) is commonly stockpiled, crushed, tested and recycled back into new asphalt at the production plant [14]. Typically, 10-20% RAP is incorporated, with higher RA percentages also considered when the RA is available in greater quantities [15].

In more recent times, other recycled materials have been incorporated into asphalt mixtures. Waste printer toner [16], crushed (gullet) glass [17], incinerator waste, municipal waste refuse and coal mine overburden [18] have all been reported. In general, there is a desire to increase recycled material use in asphalt mixtures, as long as the performance of the asphalt is not adversely impacted.

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 either reduced cost or improved performance, compared to otherwise similar new material use.

2.2. Waste plastic in asphalt

Many countries have now reported the use of recycled plastic in asphalt production, either as an aggregate extender, a bitumen extender or a binder modifier, including Canada, New Zealand, Australia and the UK [11]. Some of these field trials have been supported or complemented by laboratory investigations into the effects associated with adding various recycled plastics to bituminous binders and asphalt mixtures. Some laboratory trials of recycled PET (eg. plastic drink bottles) depolymerised the PET with acids and glycols and the residual was chemically recycled [10-19]. In contrast, Ziari et al. [20] investigated the effect of unprocessed and un-melted PET on asphalt rutting performance and Sojobi et al. [3] investigated PET modification of asphalt by heating and melting the PET using a portable gas cooker, well above normal binder and asphalt production temperatures. Although these approaches allow high melt-point plastics, such as PET, to be recycled, the cost of processing is expected to be high and the economic practicality is questioned.

Other researchers have more practically concentrated on soft plastics with melting points below normal modified binder blending and asphalt production temperatures. Dalhat & Wahhub [9] shredded and ground low and high density polyethylene, as well as polypropylene, and wet mixed the recycled plastic products into bitumen prior to asphalt manufacture in the laboratory. The viscosity of the binder increased, as did the PG [21] high temperature rating. Asphalt modulus increased and when a typical asphalt pavement was modelled in a pavement management model, the predicted rut depth and top-down longitudinal cracking both reduced significantly [9]. Acrylonitrile butadiene styrene (ABS) also melts at lower temperatures and was wet and dry mixed at 4-12% of the binder content, into otherwise similar asphalt mixtures [22]. Compared to the control samples, the high temperature PG rating of the binder increased from 64°C up to 82°C, while the low temperature rating was unaffected. Binder viscosity and Marshall Stability both increased, but the Marshall Flow also increased [22]. White & Reid [1] reported asphalt mixture modification with three recycled plastics designed to melt during dry mixing at normal asphalt production temperatures. Mixture modulus increased by 120-250%, wheel track rutting reduced by 0.5-1.8 mm and fracture toughness increased moderately. In related work, White [11] reported comparable moisture damage resistance and an improved fatigue life for asphalt mixtures produced with the same recycled plastic products.

2.3. Bituminous binder characterisation

Different jurisdictions use different specifications for the grading and production of bituminous binder for asphalt production. Because this research focussed on binder grading using the UK, Australian and US systems, the following descriptions are limited to the binder grading systems in those jurisdictions.

In the UK, the performance of asphalt surfaces generally relies on asphalt mixture volumetric properties and asphalt testing intended to be indicative of performance as detailed in BS EN 13108. Important performance-indicating asphalt properties include indirect tensile strength for moisture damage resistance, abrasion value for studded tyre resistance, wheel track rutting for deformation resistance and fatigue for cracking resistance. Consequently, only production or index properties are specified for bituminous binders. However, because modified bitumen and polymer modified binders have significantly different properties, there are two different binder specifications, BS EN 15291 for unmodified paving grade bitumen and BS EN 14023 for polymer modified binders. For modified binders, the index properties that can be related to characteristics that are indicative of the relative asphalt performance [13] are:

- force ductility at 25°C, an indicator of relative resistance to cracking,
- penetration at 25°C, an indicator of relative resistance to deformation
- softening point, an indicator of relative temperature susceptibility.

However, rather than a specifier selecting a specific grade or class of modified binder, each binder supplier simply reports the class (1-11) of each property measured for the particular binder. Although this system is informative, it complicates the selection of a particular class of polymer modified binder with a particular combination of properties.

Australia also uses two grading systems for bituminous binder for asphalt production. The first is viscosity based and applies to unmodified or conventional bitumen, while the second system includes categorical grades of polymer modified binder. The viscosity-based system uses viscosity at 60°C as the primary basis of grading, supplemented by properties including penetration, as detailed in AS 2008. For example, C320 has a viscosity of between 260 and 380 Pa.s, which is a band around the 320 Pa.s grade. The PMB categorisation is based on production properties that are indicative of polymer type and content. The primary properties are softening point, torsional recovery at 25°C and viscosity at 165°C, a typical asphalt paving temperature [23]. For example, A10E is a grade of polymer modified binder, with the 'A' indicating the intended use is in asphalt production and the 'E' indicating an elastomeric polymer, usually SBS. The '10' is an arbitrary designation. For a particular PMB to be considered as A10E, all its properties must be within the specified limits, For example, the torsional recovery of A10E must be between 60% and 86%.

In the US, the Superpave project, initiated in 1987, developed a parameter for high temperature grading of bituminous binder based on the dynamic shear rheometer (DSR), known as $|G^*|/\sin\delta$. The PG system also assesses fatigue cracking (intermediate temperature) and brittle fracture (low temperature). However, for most binder supplies, these requirements are easily exceeded [24] meaning the high temperature rating is usually the most important parameter for binder design and development. Subsequently, the multiple stress creep recovery (MSCR) protocol, also DSR-based, was developed as an improvement over the $|G^*|/\sin\delta$ parameter for high temperature PG rating. The MSCR was developed to be performance-based and easy to conduct in the laboratory [21]. The MSCR is blind to modification and site in the non-linear response domain, which made it an attractive replacement for the $|G^*|/\sin\delta$ [25]. Although not all States in the US have implemented the MSCR system for binder characterisation, it represents the most advanced basis for relative contribution of binders to deformation resistance of asphalt mixtures [26].

3. MATERIALS AND METHODS

Bitumen samples were modified in the laboratory with various recycled plastic modifiers and the modified binders were characterised using the test methods routinely used in the UK, Australia and the US binder grading systems.

The recycled plastic products are commercially available modifiers and extenders of bitumen, referred to in this paper as recycled plastic-plastomeric (RP-P) and recycled plastic-elastomeric (RP-E). Both products were supplied in extruded pellet form (Figure 1) and the supplier recommends a dosage of 6% by mass of the unmodified bitumen.

The UK binder testing included force ductility, penetration and softening point (Table 1). Samples were prepared with 6% of the recycled plastic modifiers added to a 100-150 penetration bitumen, which was also tested as the control. The Australian testing also included the softening point, but the fracture resistance was evaluated by torsional recovery and deformation resistance was evaluated by viscosity (Table 2). The two recycled plastic products were added at 3%, 4.5% and 6% (by mass of bitumen) to C170 bitumen. C170 is commonly used in Australia for modified binder production but not for asphalt production. Consequently, the results were compared to C320, which is the most common grade of unmodified bitumen for asphalt production in Australia. For the US testing, a 50-70 penetration bitumen and a 100-150 penetration bitumen were both modified with the two recycled plastic products at 4%, 6% and 8% by mass of the bitumen. The samples were tested for the original (|G*|/sin δ) and newer (MSCR) high temperature PG rating using the DSR (Table 3). The samples were tested over the temperature range 52-82°C.

(a) Pelletised RP-P

(b) Pelletised RP-E

Figure 1: Recycle plastic polymers

Table 1. UK binder test methods

Test	Units	Method
Force ductility at 25°C	J/cm^2	BS EN 13703
Penetration at 25°C	d.mm	BS EN 1426
Softening point	°C	BS EN 1427

Table 2. Australian binder test methods

Test	Units	Method
Viscosity at 60°C	Pa.s	AS 2341.2
Softening point	°C	AG:PT/T131
Torsional recovery at 25°C	%	AG:PT/T122

Table 3. US binder test methods

Test	Parameter	Method
PG by |G*|/sin δ	PG temperature (°C)	ASTM D6373
PG by MSCR	Various, including high PG temperature (°C) creep compliance (Jnr) and elastic recovery (%) at various temperatures	ASTM D7405

All samples were prepared by heating the unmodified bitumen to 170°C, adding the required mass of recycled plastic and mixing with a Silverson laboratory high-sheer mixer for 30 seconds, followed by immediate testing. An unmodified (control) sample of bitumen was also retained. For the US testing, the samples were pre-treated in the rolling thin film oven (BS EN 12591) intended to replicate the ageing effects associated with asphalt production.

4. UNITED KINGDOM GRADING

The typical 100-150 penetration grade of unmodified bitumen was sub-sampled and sub-samples were modified with 6% of RP-P and 6% of RP-E. Sub-samples were further split for testing. The results demonstrate the change in binder properties associated with waste plastic modification (Table 4).

Table 4. UK test results

Parameter	Unmodified	6% RP-P	6% RP-E
Force ductility	0.03	0.69	2.35
Penetration	134	90	94
Softening point	41	51	47

Compared to the unmodified 100-150 penetration bitumen, the plastic modified binders showed an approximately 30% reduction in penetration (Figure 2) as well as an approximately 20% increase in softening point (Figure 3). These results indicate a modest stiffening of the 100-150 penetration bitumen associated with both recycled plastic products, as is commonly expected with conventional polymer modification of bitumen. However, the greatest effect was on force ductility at 25°C. The increase in force ductility was 22 fold for RP-P and 78 fold for RP-E, introducing significant ductility, indicating a likely reduction in fatigue cracking susceptibility of asphalt mixtures. This is also consistent with conventional polymer modifiers, with plastomeric modified binders (such as EVA) often providing a significant improvement in mixture fatigue life, but not as great an increase as that associated with elastomeric modified binders (such as SBS).

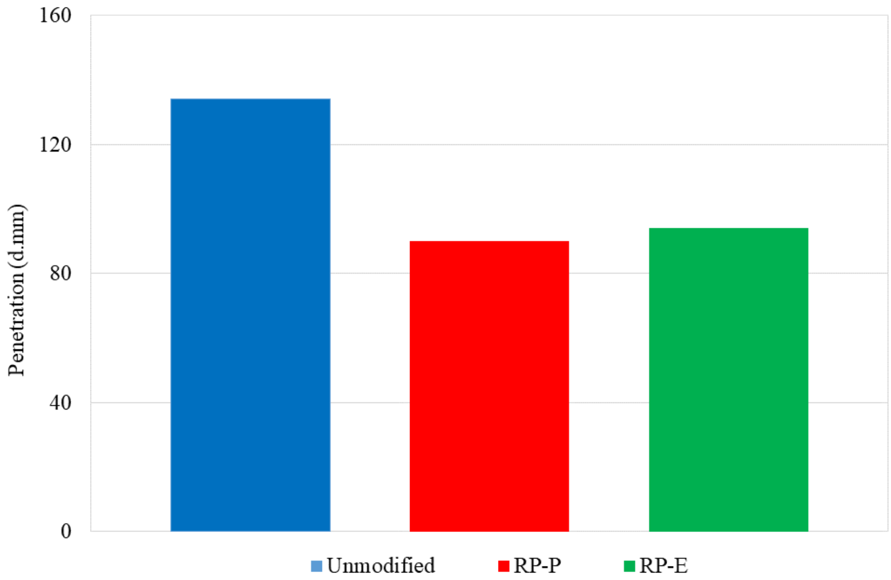

Figure 2: Effect of 6% recycled plastic on UK penetration

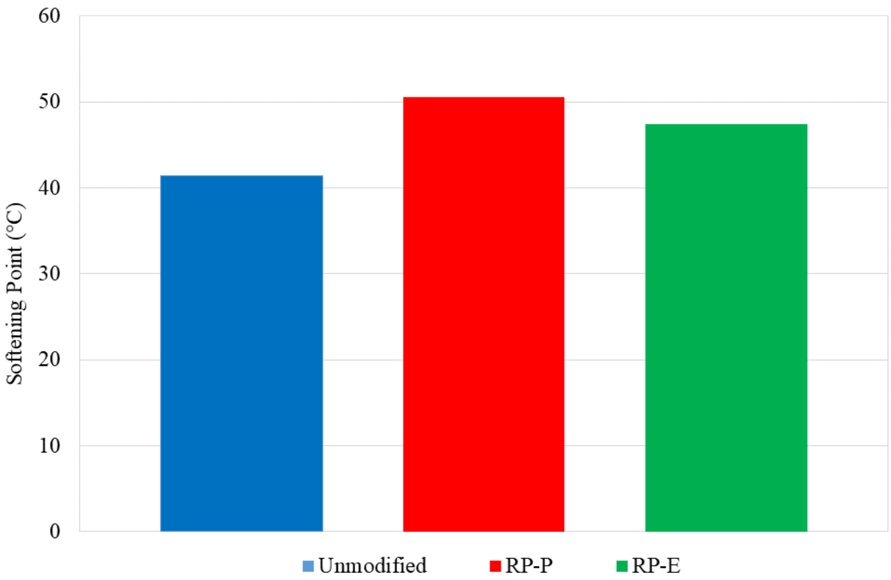

Figure 3: Effect of 6% recycled plastic on UK softening point

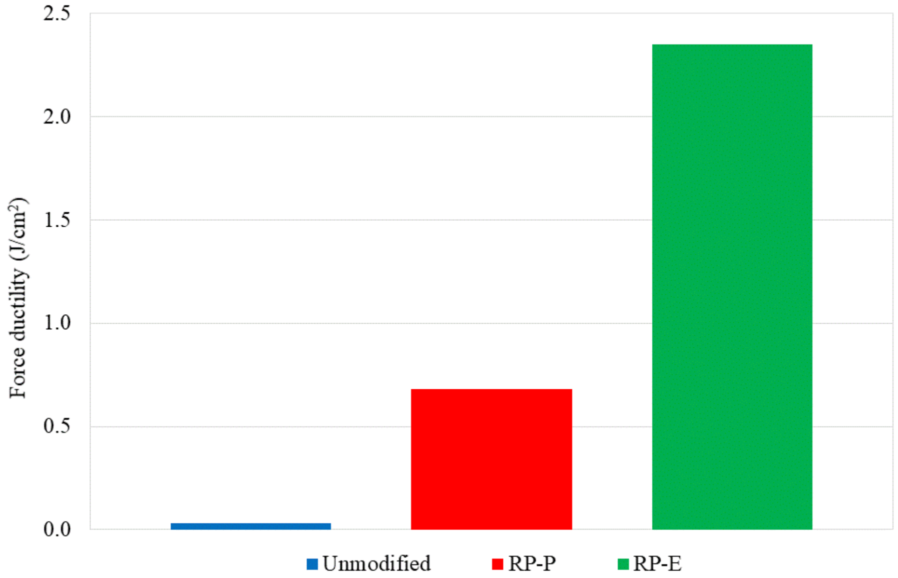

Figure 4: Effect of 6% recycled plastic on UK force ductility

5. AUSTRALIAN GRADING

The C170 viscosity grade of unmodified bitumen was sub-sampled and sub-samples were modified with various amounts of RP-P and RP-E. Sub-samples were further split for testing. The results demonstrate the change in binder properties associated with waste plastic modification (Table 5). The modification with 6% recycled plastic approximately doubled the viscosity, increased the softening point by an average 45% and increased the torsional recovery by ten fold for RP-P and over twenty fold for RP-E. This is consistent with the UK test results, with a modest increase in the stiffness of the binder and a significant increase in the elasticity, particularly for the elastomeric RP-E. Similar to conventional polymer modifiers, the effect of the recycled plastic generally increased as the dosage increased. However, the rate of increase was different for the different properties and recycled plastic type. For example, the torsional recovery increased consistently with increasing recycled plastic content (Figure 5). In contrast, the softening point increased consistently with increasing RP-P content but was insensitive to RP-E content (Figure 6). Furthermore, Figure 7 shows that 3% recycled plastic had modest effect on the viscosity, but a significant increase occurred between 3% and 6%.

Table 5. Australian test results and different recycled plastic contents

Parameter	Unmodified	RP-P			RP-E		
		3%	4.5%	6%	3%	4.5%	6%
Viscosity at 60°C	0.131	0.151	0.175	0.280	0.157	0.236	0.346
Softening point	47	60	77	88	49	51	52
Torsional recovery 25°C	1	7	10	10	13	15	22

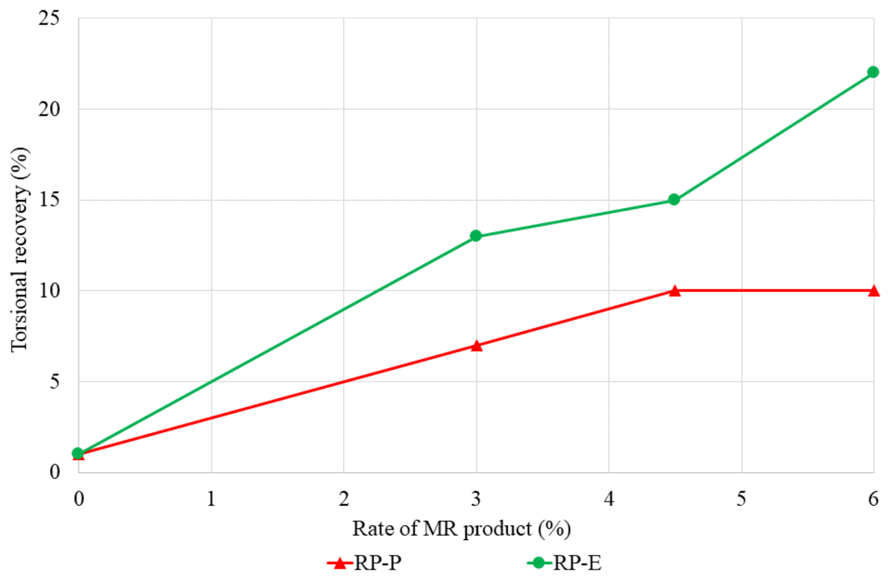

Figure 5: Effect of recycled plastic content on Australian binder torsional recovery

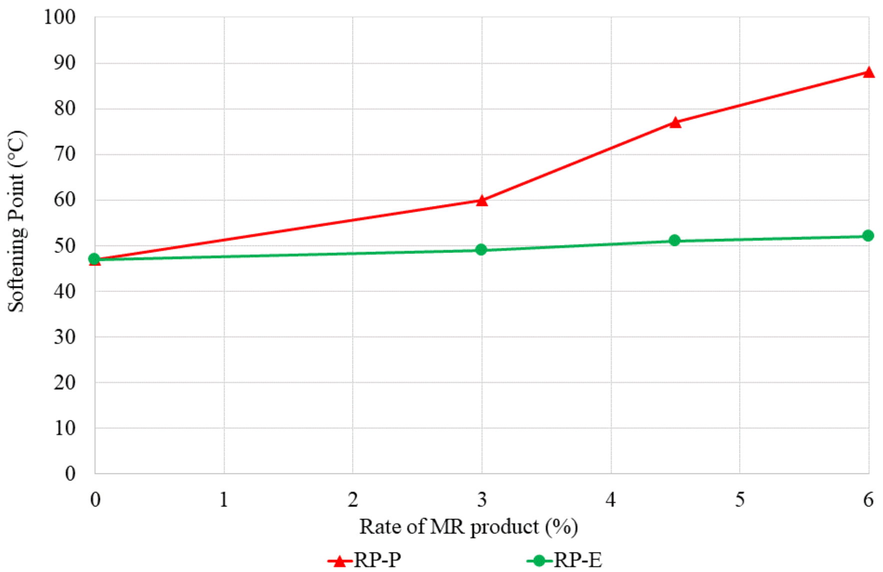

Figure 6: Effect of recycled plastic content on Australian binder softening point

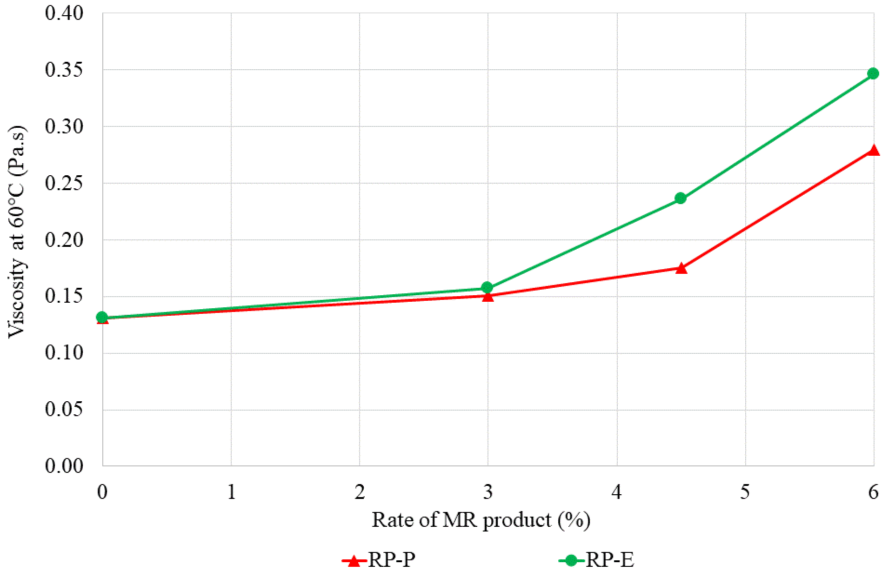

Figure 7: Effect of recycled plastic content on Australian binder viscosity

The binders modified with 6% recycled plastic were also compared to properties reported separately for common Australian asphalt binders. The recycled plastic modified C170 bitumen exhibited a viscosity (Figure 8) and softening point (Figure 9) comparable to C320 (higher viscosity unmodified bitumen), A35P (EVA modified binder) and A10E (highly SBS modified binder). However, the indicator of relative fracture resistance, in this case torsional recovery, was again the result with the greatest difference. All modifiers increased the torsional recovery to a level significantly greater than for the unmodified C320. The torsional recovery associated with the RP-P was less than that associated with plastomeric A35P, while the RP-E modified binder had a higher torsional recovery than A35P. This reflects the intention that RP-P be a plastomeric modifier while RP-E is intended to be an elastomeric modifier. However, neither of the recycled plastic modified binders were as elastomeric as the highly SBS modified A10E which is commonly used in Australia in asphalt mixture for highways and airports.

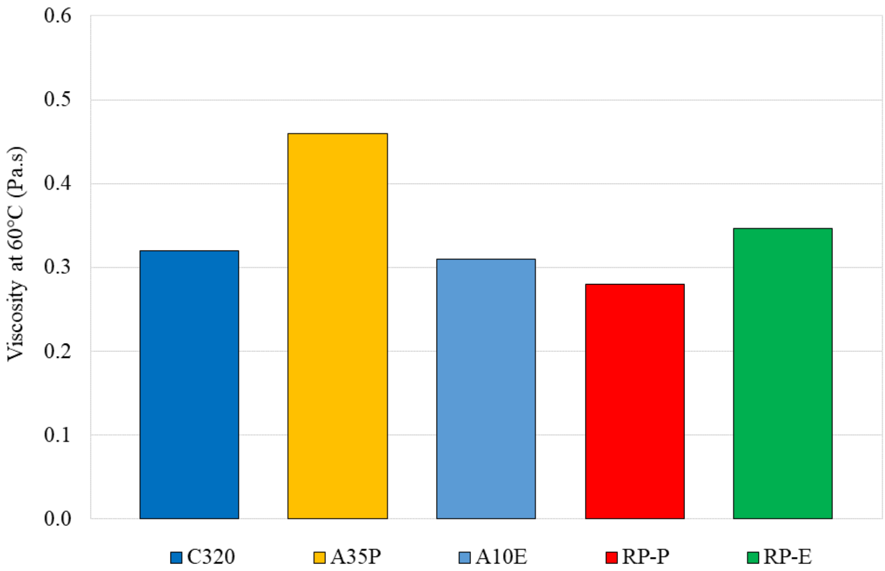

Figure 8: Comparison of recycled plastic and Australian binder viscosity

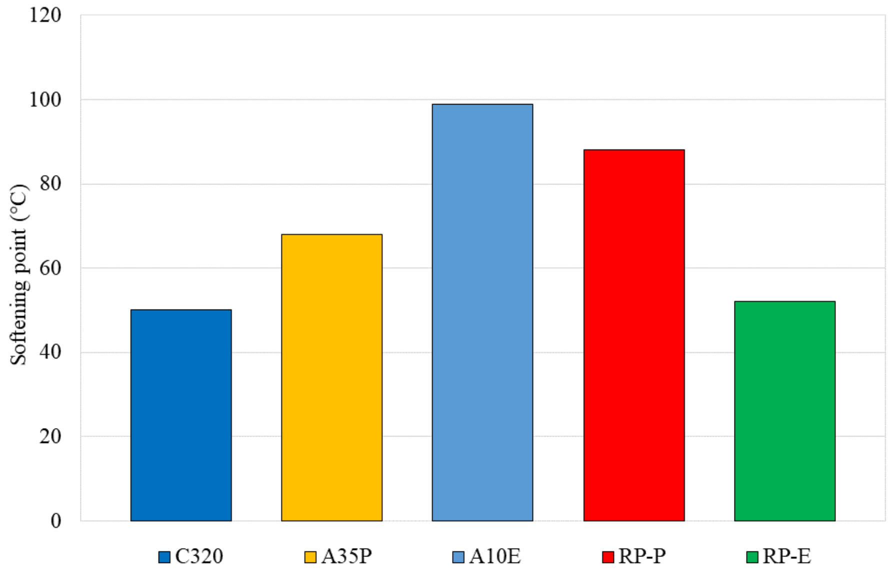

Figure 9: Comparison of recycled plastic and Australian binder softening point

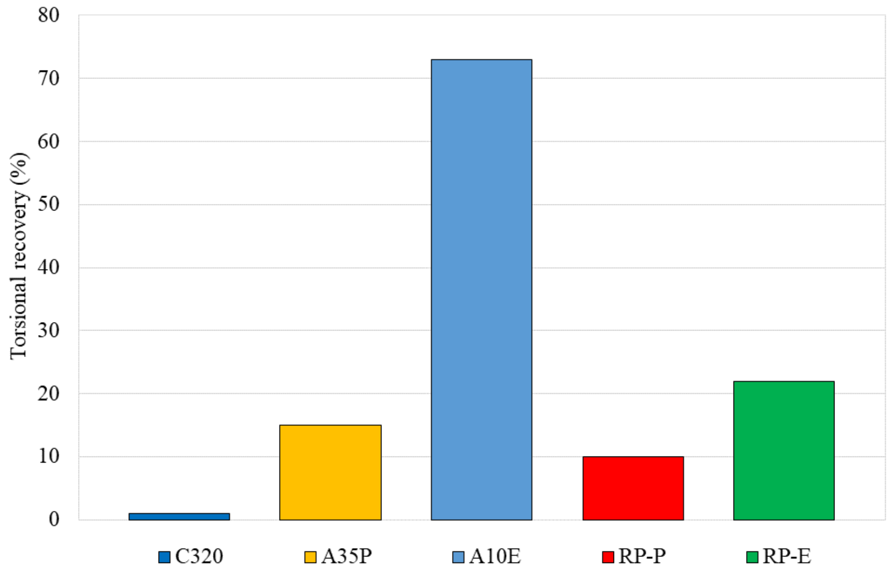

Figure 10: Comparison of recycled plastic and Australian binder torsional recovery

6. UNITED STATES GRADING

Unmodified PG 58-XX bitumen (100-150 penetration grade) and PG 64-XX (50-70 penetration grade) bitumen were both modified with 4%, 6% and 8% (by mass of bitumen) of the two recycled plastic modifiers. Only the high temperature grading ($|G^*|/\sin\delta$ and Jnr at the 3.2 kPa stress level) was measured. For the MSCR results, the Standard traffic and Extreme traffic PG ratings were considered. Regardless of whether the binder PG rating is based on the $|G^*|/\sin\delta$, MSCR for extreme traffic, MSCR (E), or MSCR for standard traffic, MSCR (S), the effects of recycled plastic were significant for both the PG 58 bitumen (Figure 11) and the PG 64 base bitumen (Figure 12), with the high temperature rating increasing by one to five PG grades, which represents up to a 30°C higher service temperature. The PG rating improvement increased with recycled plastic content (Figure 13) with the majority of the measured improvement achieved by 6% recycled plastic content, indicating that the manufacturer's recommended dosage is likely to be optimal. Furthermore, the stiffer (PG 64) base bitumen generally resulted in a higher recycled plastic modified PG rating (Figure 14a) and the PG rating associated with the plastomeric RP-P was generally higher than for the elastomeric RP-E (Figure 14b).

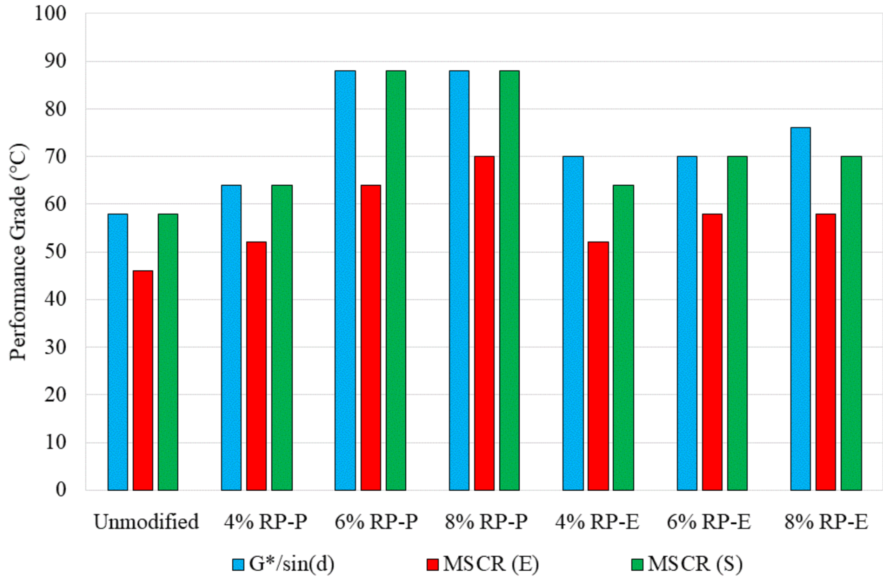

Figure 11: Effect of recycled plastic on PG 58 bitumen US Performance Grading

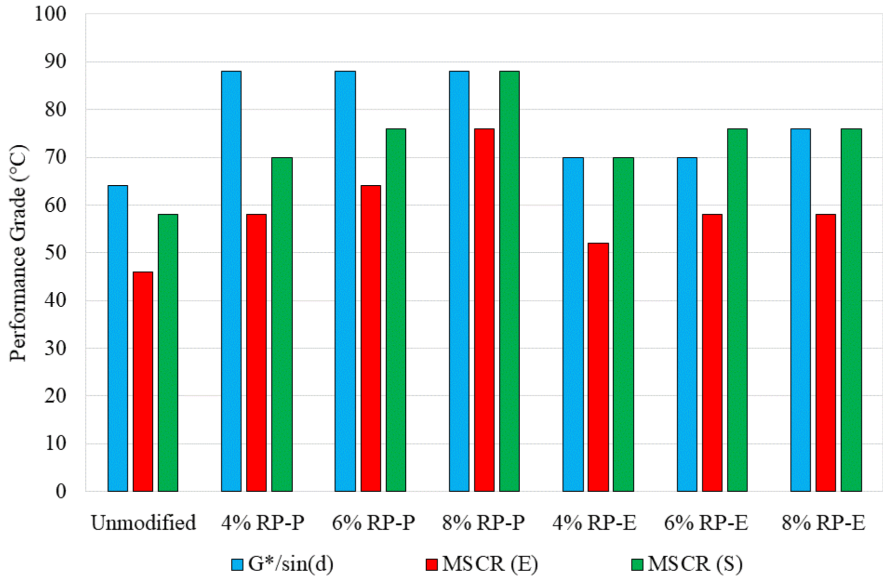

Figure 12: Effect of recycled plastic on PG 64 bitumen US Performance Grading

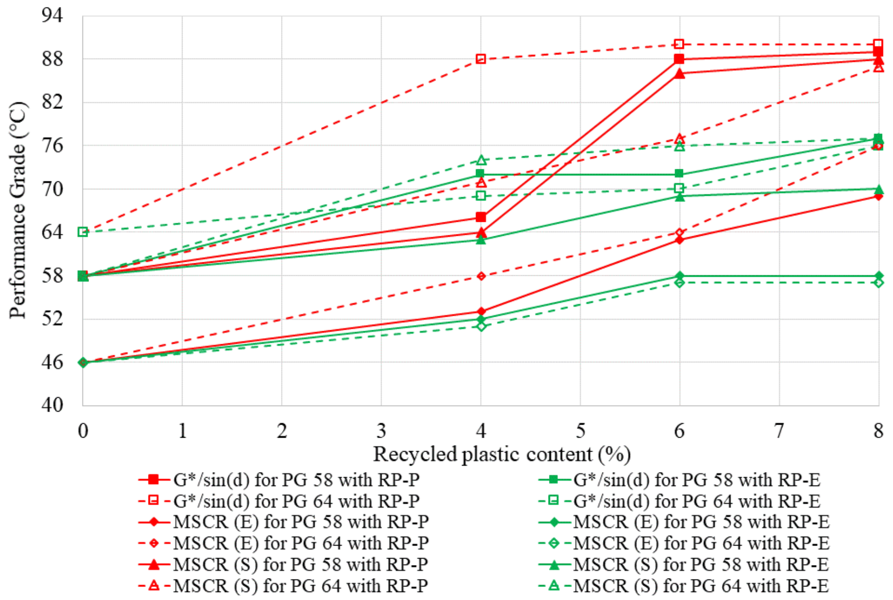

Figure 13: Effect of recycled plastic content on US Performance Grading

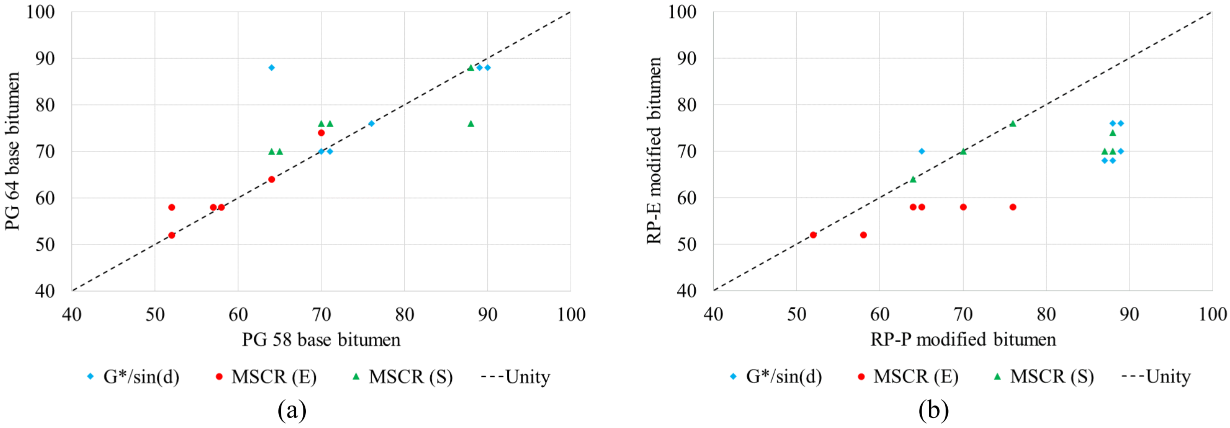

Figure 14: Effect of (a) base bitumen and (b) recycled plastic product on US PG rating

The addition of recycled plastic also increased the MSCR elastic recovery of the binders which was negligible for both the PG 58 bitumen (Figure 15) and the PG 64 (Figure 16) unmodified bitumens. Bitumen modified with RP-P had significantly greater elastic recovery than bitumen modified with RP-P and 6% recycled plastic was required to provide any significant elastic recovery. With increasing temperature, the increased unrecovered creep resulted in some insignificant elastic recovery results and even some impractical negative elastic recoveries. Consistent with the UK and Australian test results, the indicator of elasticity was the parameter most effected by recycled plastic modification. However, in the US, elastic recovery is measured at higher temperature, so it is not necessarily a direct indicator of the fracture resistance potential of asphalt mixtures.

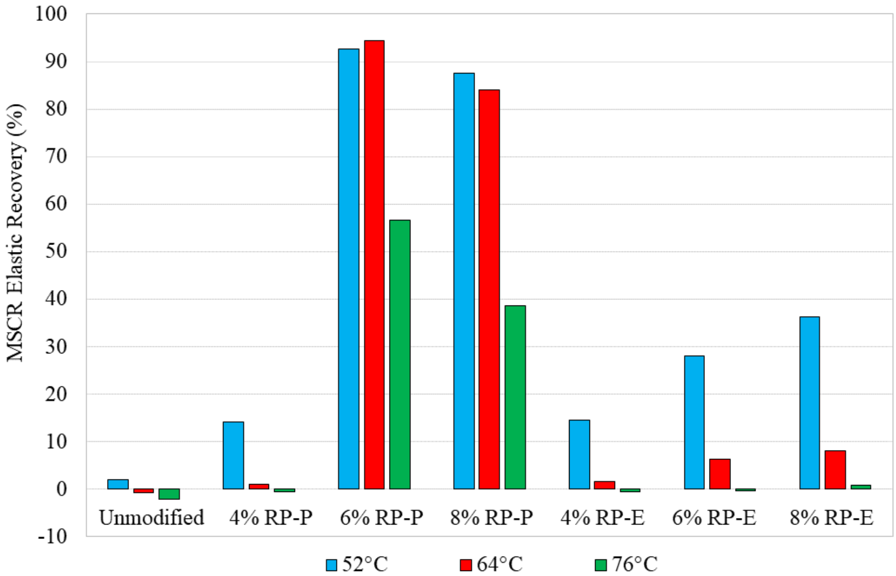

Figure 15: Effect of recycled plastic on PG 58 bitumen MSCR elastic recovery

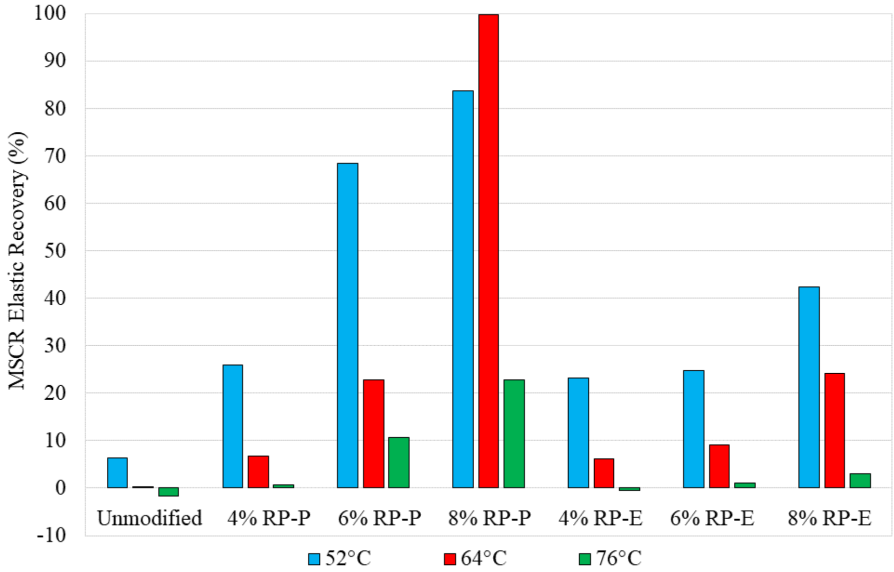

Figure 16: Effect of recycled plastic on PG 64 bitumen MSCR elastic recovery

CONCLUSION

Both the elastomeric (RP-E) and plastomeric (RP-P) recycled plastic extenders/modifiers of bitumen for asphalt production generally resulted in significant improvement of the UK, Australian and US binder grading properties and parameters (Table 6). However, these improvements in binder properties can not be directly related to a predicted improvement in asphalt mixture properties, which requires performance-indicating asphalt mixture testing to determine. However, the recycled plastic products considered in this research had no adverse impact on the measured binder properties, compared to the unmodified bitumen samples, and the effects of the recycled plastic modification were similar to those associated with some conventional polymer modifiers for asphalt production, such as SBS and EVA. In the future, it is recommended that the effects of recycled plastic modification be directly compared to the effect of common polymer modifiers, based on both binder and asphalt properties. Further work is also required to understand the practicalities of recycled plastic modification of binder and asphalt, including digestion during mixing, storage stability and long-term ageing.

Table 6. Summary of effects of recycled plastic on bituminous binder properties

Indicator of	UK testing		Australian testing		US testing	
	RP-P	RP-E	RP-P	RP-E	RP-P	RP-E
Deformation resistance	31%	30%	214%	264%	39%	26%
Temperature resistance	24%	15%	87%	110%	38%	9-31%
Fracture resistance	2200%	7800%	1000%	2200%	970-9200%	385-3700%

Notes:
- UK and Australian deformation resistance is based on penetration and viscosity, respectively.
- UK and Australian temperature resistance based on softening point results.
- UK and Australian fracture resistance is based on force ductility and torsional recovery, respectively.
- US deformation resistance is based on MSCR grading for Extreme traffic.
- US temperature resistance is based on $|G^*|/\sin\delta$.
- US fracture resistance is based on MSCR elastic recovery at 52°C test temperature.
- Ranges of results indicate a difference in effects for different base (unmodified) bitumens grades.

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