RECYCLED WASTE PLASTIC FOR EXTENDING AND MODIFYING ASPHALT BINDERS

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ABSTRACT

Plastic drink bottles, single-use plastic bags and other waste plastics have a significant impact on the environment. Consequently, there is global interest in recycling and reuse of waste plastics. Significant progress has been made towards the incorporation of waste plastics into building and construction materials, although this has focussed mainly on cement and concrete applications. This paper assesses the use of three commercially available recycled plastic products for bituminous binder extension and modification in asphalt mixtures. Using a dry-mixing process, shredded and pelletised recycled waste plastics replace 6% of the binder volume. Comparative laboratory testing of two typical UK asphalt mixtures indicated that asphalt containing the recycled waste plastic products showed improved deformation resistance and fracture resistance compared to conventional 40/60 penetration grade binder. The viability of imported recycled plastic waste use in Australian asphalt mixtures was also evaluated. One of the three recycled plastic products is expected to be a cost effective alternate to M1000 or A35P and another is expected to be a viable alternate to A20E, at a significant cost saving. Partial replacement, without performance enhancement, of C320 bitumen is not viable due to the high cost of recycled waste plastic importation. However, partial C320 replacement may become viable with the introduction of local recycled plastic processing in the future. The findings of this research require validation by objective comparison to Australian asphalt mixtures produced with common Australian asphalt binders, as well as confirmation of likely importation costs. Verification of consistent product digestion and distribution through drum-based asphalt production plants is also required.

INTRODUCTION

Governments, infrastructure management agencies and private infrastructure owners are all striving to achieve more with less. 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 reduced demand on natural resources.

Waste plastic is a significant and growing environmental challenge and includes industrial plastics, plastic bags and plastic bottles. For example, it has been reported that the world generates a million plastic bottles every minute (Laville & Matthews 2017) with less than half of those collected for recycling and less than 7% incorporated back into plastic bottle production. The remainder end up in landfill or find their way into the environment with a plastic island forming in the Atlantic Ocean, plastic washing up on Antarctic beaches (Carrington 2016), contaminating UK beaches (Taylor 2017), being ingested by fish (Van Cauwenberghe & Janssen 2016) and it is predicted that the oceans will contain more plastic (by mass) than fish by the year 2050 (EMF 2016).

As a result, there has been an increased interest in the incorporation of processed and recycled waste plastic into construction materials. At this time, the main 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). Most work has investigated the replacement of the fine aggregate in concrete mixtures. 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).

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This paper evaluates a source of recycled waste plastic from the United Kingdom (UK) as a partial bitumen replacement. Unlike previous work, the recycled plastic is added directly to the asphalt production plant (dry-mixed) rather than being melted into the hot bituminous binder (wet-mixed). Recycled plastic processing and production is summarised before the results of comparative laboratory asphalt mixture evaluation is presented. Finally, further work to allow local validation by objective comparison to Australian binders and asphalt mixtures is outlined.

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 higher 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 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. It is therefore important that recycled materials provide at least comparable performance, at no greater cost, than 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 garbage bags.

Plastic bottles are manufactured from Polyethylene Terephthalate (PET) commonly known as PET, PETE, PETP or PET-P, and are significant contributors to plastic waste. In fact, plastic bottles account for around 30% of the global PET demand (Ji 2013). The resulting plastic is waterproof and stable with physical properties favourable for food packaging production. Depending on its intended use, PET is produced with different intrinsic viscosity, with bottle grade PET 0.70-0.78 dL/g for water bottles and 0.78-0.85 dL/g for carbonated (soft drink) bottles (Gupta and Bashir 2002).

Plastic bags are also a significant contributor to overall waste plastic with over 30 million plastic bags entering the environment each year in Australia (Ting 2012). In Europe, 3,400,000 tonnes of plastic bags were produced in 2008 and in 2010 only 6% were recycled (EC 2011). However, this is still only a small portion of global production which has been estimated to be between 500 million and 1 billion plastic bags annually. The impact of plastic bags on the environment is well established, with bags found from the Arctic circle in the north to the Falkland Islands in the south, and significant research has demonstrated the impact on turtles, seabirds (Hardesty & Wilcox 2015) and fish species (Savoca 2017).

Plastic shopping bags are made of non-renewal petroleum-based products and may be high-density polyethylene, low-density polyethylene or linear low-density polyethylene. The thin, single-use plastic bags commonly associated with supermarkets since the 1980s are usually made from linear low-density polyethylene (Dilli 2007) and are essentially non-biodegradable (Ting 2012), remaining in the environment for many years. Significant effort has been made around the world to reduce the consumption of single-use plastic shopping bags (Rayne 2008; Ayalon et al. 2009; Muthu et al. 2011; Poortinga et al. 2016; Mortimer 2017). However, plastic bags remain a significant environmental issue and researchers have questioned the relationship between bans/charges on single-use plastic bags and actual environmental impact (Mortimer 2017). Therefore, additional opportunities to reuse or recycle plastic bags, as well as plastic bottles and other waste plastics, are required in the future.

Waste plastic recycling requires collection, sorting and processing for sale, followed by additional processing for the particular recycling application. Collection is often performed at the point of disposal, either industrial or domestic, with many parts of the world now providing separate waste disposal bins for recyclable products, including paper, aluminium and plastics. Sorting includes separation, firstly of the plastics from the other recycled products and then separation of the various plastic products. Processing for sale usually includes removal of packaging and paper-based labels, as well as crushing and pressing into bales for transfer to the recycler. It may also include washing and drying. Further (application-specific) processing usually then requires melting to form pellets. Melting allows removal of contaminants by filtration and in combination with shredding processes, is designed to achieve the required properties for incorporation into the new product manufacture.

Bituminous binders

Pavement surfaces around the world have a long history of using bitumen as a binder in asphalt mixtures (Shell 2015). Bitumen itself is a by-product of crude oil refining for the production of petroleum gas, petroleum fuels, diesel fuel and lubricating oils. The residue from the second distillation of crude oil includes bitumen, that is then separated and processed for sale in the road, airport and port pavement construction industry, as well as the production of roof shingles and other products.

Traditionally, asphalt production used unmodified bitumen, usually graded according to either its viscosity or resistance to load penetration at certain temperatures. However, as the required engineering properties of asphalt mixtures increased over time, polymers, acids and other additives were incorporated to increase the resistance of asphalt mixtures to high temperature deformation, low temperature cracking and moisture damage (Shell 2015).

Like many countries, both Australia and the UK primarily use unmodified bitumen or polymer modified bitumen as the binder in asphalt mixtures. The UK retains a penetration grading system for unmodified bitumen while Australia uses a viscosity-based grading. However, viscosity and penetration are generally inversely related and typically equivalent grades are summarised in Table 1, although there is significant overlap between the grades (Figure 1) with the relationship varying between sources. Polymer modified bitumen (PMB) grading is more complex and many countries are transitioning to the Performance Grading (GP) system developed in the USA (FHA 2011). However, Australia retains a system of PMB grades based on production properties indicative of the type and percentage of polymer (White 2017). For high-performance applications, A10E and A35P are common elastomeric and plastomeric PMBs for asphalt production in Australia. Although the bitumen content in asphalt is typically only 5-6%, the binder reflects approximately 60% of the cost of the raw ingredients in asphalt and partial bitumen replacement with by-products and wastes presents a significant cost benefit (Dalhat & Al-Adbul Wahhab 2017) where mixture performance is not adversely affected.

Table 1: Generally equivalent common graded of unmodified bitumen

Viscosity Grade (Pa.s at 60°C)	Generally equivalent Penetration Grade (/0.1 mm at 25°C)
C170 (140-180)	70/100
C320 (260-360)	40/60
C600 (500-700)	30/45

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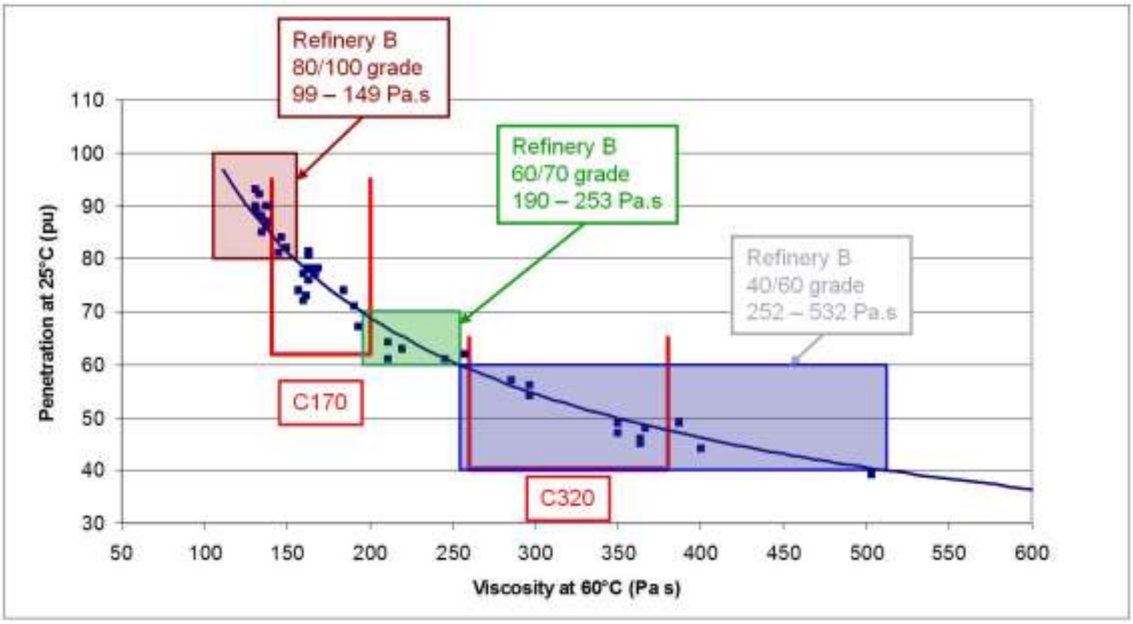

Figure 1: Example Viscosity and Penetration grading of bitumen (Dack 2012).

RECYCLED PLASTIC WASTE

Only limited effort has been made to incorporate recycled plastic waste into asphalt mixtures. 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).

Commercially available products

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 MR6 was developed. MR6 comes in pellet form so it can be incorporated directly into the asphalt production plant and is produced from 100% recycled waste. Other products, known as MR8 and MR10, soon followed with different target applications (Table 2). Each of the three products comes in a different colour and form, with MR8 a shredded plastic, while MR6 and MR10 are produced as pellets (Figure 2).

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, usually in 1 tonnes bulker bags or 3 kg melt-bags. 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 waste plastic.

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Table 2: Recycled plastic products and uses

Product	Binder replacement	Intended use	Likely to be comparable to
MR6	6-10%, with 6% recommended as optimal	Performance enhancement with a focus on deformation resistance	A35P or M1000
MR8	6-10%, with 6% recommended as optimal	Cost reduction with similar or better performance	C320 or C600
MR10	6-10%, with 6% recommended as optimal	Performance enhancement with a focus on fracture resistance	A20E

(a) (b) (c)

Figure 2: (a) MR6 pellets, (b) MR 8 shreddings and (c) MR10 pellets.

Use in the United Kingdom

There is no replacement for demonstrated previous use of a new and innovate product. The recycled plastic waste products have been successfully incorporated into stone mastic and dense graded asphalt mixtures for surfacing and resurfacing works for truck parking depots, roads and service stations in the UK. The runway and taxiways at Carlisle Airport (England) were recently resurfaced (Figure 3) and waste plastic modified asphalt was paved and performed consistently with the conventional, unmodified asphalt with 40/60 bitumen.

(a) (b)

Figure 3: (a) Paving and (b) the surface of MR6 modified asphalt at Carlisle Airport.

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LABORATORY TESTING

Two asphalt mixtures were produced with and without recycled plastic as a partial binder replacement. The mixtures were designed to be typical base course (dense graded 20 mm mix) and Stone Mastic Asphalt (SMA) surface course (10 mm SMA) in the UK (Table 3). The 20 mm base course (AC 20) was produced with unmodified 40/60 binder (similar to C320) and with 6% of the binder replaced by MR6. The 10 mm surface course (SMA 10) was produced with the three recycled plastic waste products (MR6, MR8 and MR10) replacing 6% of the 40/60 bitumen.

Table 3: Asphalt mixture properties

Property	AC20 Mixture	SMA10 Mixture
Binder content (by mass)	4.8%	6.3%
Maximum density	2,524 kg/m^3	2,440 kg/m^3
Bulk density	2,411 kg/m^3	2,350 kg/m^3
Combined aggregate grading (percentage passing the sieve (mm)		
31.5	100	-
20	99	-
14	77	100
10	66	97
8	60	76
6.3	46	45
4	36	38
2	26	24
1	18	17
0.500	14	14
0.250	12	13
0.125	11	11
0.063	9	9.8

Each mixture was evaluated under the applicable British specifications for road asphalt mixtures:

- BS EN 13108-5:2016. For Stone Mastic Asphalt.
- BS EN 13108-1:2016. For Asphalt Concrete.

Importantly, the British specification requires asphalt mixtures to meet a number of performance-indicative properties (Table 4). The AC20 mixture produced with replacement of 6% of 40/60 bitumen by MR6 exhibited slightly reduced post-compaction densification (air voids at refusal density and wheel track rutting), significantly higher stiffness (stiffness modulus) and improved moisture damage resistance (Table 5). The AC20 mix was not tested for fracture toughness. All test results indicate that when other mixture properties remain constant, replacement of 6% 40/60 bitumen (similar to C320) improves the moisture damage (stripping) resistance and densification and shearing (rutting) of AC20 base course asphalt.

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Table 4: British asphalt specification performance tests

Performance property	Test method	Indicative of	Australian equivalent
Air Voids at Refusal Density (not applicable to SMA)	PD 6691 B.3.2.3	Post construction densification	AS/NZS 2891.2.2
Stiffness Modulus	EN 12697-26	Structural contribution	Available from AG:PT/T232
Moisture Damage	BS EN 12697-12	Moisture Damage resistance	AG:PT/T232
Wheel Track Rut Depth	PD 6691-2	Rutting under traffic	Available from AG:PT/T231
Wheel Track Rate	PD 6691-3	Rutting under traffic	AG:PT/T231
Fracture Toughness by notched semi-circular bending	BS EN 12697-44	Fracture resistance	Intent similar to flexural beam fatigue

Table 5: Comparison of AC20 asphalt mixture results

Property	Straight 40/60	6% MR6	Limits	Units
Air Voids at Refusal Density	1.1	1.2	> 0.5	%
Stiffness Modulus	7,827	11,600	> 1,800	MPa
Moisture Damage	95.6	>100.0	Report Only	%
Wheel Track Rut Depth	1.8	1.5	Report Only	mm
Wheel Track Rate	0.046	0.039	< 1.00	mm/10^3 cycles

The SMA10 results are more informative because they compare the mixtures containing the range of recycled plastic waste products, each at 6% replacement of 40/60 bitumen. All mixtures containing recycled plastic as a bitumen replacement exceeded the rut rate performance required by the specification and with the exception of moisture damage, the results were better than the straight 40/60 mixture (Table 6). It is expected that the relative performance of similarly extended and modified Australian asphalt mixtures would be similarly better performing than mixtures containing C320. Furthermore, despite minor differences in the test methods and aggregate sources, the modified products are expected to compare favourably to certain Australian grades of modified binder. For example, an asphalt modulus of 6,400 MPa and wheel tracking rut of 2-3 mm in a typical SMA10 is comparable to M1000, A35P and A20E mixtures in Australia.

Table 6: Comparison of SMA10 asphalt mixture results

Property	Straight 40/60	6% MR6	6% MR8	6% MR10	Limits	Units
Stiffness Modulus	1,823	5,438	4,032	6,451	Report only	MPa
Moisture Damage	94.8	> 100.0	85.0	86.0	Report only	%
Rut Depth	3.1	1.3	2.6	2.0	Report only	mm
Rut Rate	0.11	0.03	0.07	0.05	< 1.00	mm/10^3 cycles
Fracture toughness	23.8	29.1	25.8	27.6	Report only	N/$mm^{3/2}$

COST-BENEFIT

Any waste or by-product recycling technology is only viable if either the performance is improved for similar cost, or comparable performance is achieved at reduced cost. This situation is unlikely to change until environmental impact and sustainability are directly accounted for in infrastructure procurement (DSEWPC 2013). Consequently, the cost of processing and incorporating recycled materials must compete with the saving associated with the reduction in new material demand in comparably performing technologies.

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The cost of the three recycled plastic modifiers, supplied in the UK, and the expected retail cost in Australia are detailed Table 7, including estimated shipping, importation and local supply chain costs. The ten-year average exchange rate of £0.60 to A$1 was used. The estimated cost when 6% of recycled product is used to replace 6% C170 or C320 is also in Table 7. For comparison the indicative cost of common Australian binder grades (as at September 2017) in Brisbane are approximately:

- C170 and C320. $750 per tonne.
- M1000. $1,000 per tonne.
- A35P. $1,300 per tonne.
- A20E. $1,250 per tonne.
- A10E. $1,450 per tonne.

Table 7: Estimated cost of recycled plastic products (in AUD)

Cost	MR6	MR8	MR10
Supply in the UK	£1,350	£350	£1,350
Supply in the UK	$2,215	$574	$2,215
Retail in Australia	$2,800	$1,000	$2,850
6% with 94% C170 or C320	$830	$760	$840

The saving associated with 6% replacement of C170 or C320 with 6% of MR6, MR8 and MR10 are summarised in Table 8. This does not take into account land transportation costs away from the normal import facilities, which are generally located in the State capital cities and major regional centres. However, carting waste plastic is expected to be significantly cheaper than carting hot binder, so the cost savings associated with using waste plastic as an asphalt binder replacement would increase in remote locations, as long as the recycled product is dry-mixed, directly to the asphalt production plant, which is how these products are intended to be used.

Table 8: Estimated saving per tonne of asphalt binder using waste plastic at 6%

Australian Asphalt Binder replaced	Saving for replacement of Australian binder with:		
	MR6	MR8	MR10
C170 or C320	-$80	-$10	-$90
M1000	$130	$200	$120
A35P	$470	$540	$460
A20E	$420	$490	$410
A10E	$620	$690	$610

Table 8 indicates that the use of MR8 as a partial replacement for C170 or C320 solely as a bitumen extender is unlikely to be cost-effective. This largely reflects the cost of shipping from the UK to Australia and local importation and resale costs. However, the cost premium is marginal, even allowing generous costs for the importer, so this may be viable if the margin is reduced on large importation volumes in the future. The return of bitumen prices to the highs of 2011-2014 would also increase the viability of MR8.

The use of MR6 and MR10 at 6% C320 replacement as an alternate to Australian grades of modified binder is more viable, with potential cost savings estimated from $120 to $620 per tonne of binder. The comparative asphalt test results (Table 6) indicate that MR6 is likely to perform similarly to A20E, with the highest fracture toughness, moderate increase in modulus and high moisture damage resistance. Furthermore, Table 6 results indicate that MR10 is likely to perform similarly to M1000 or A35P, with the highest modulus and lowest wheel track rutting.

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Assuming 6% of MR6 is a viable alternate to A20E and MR10 is a viable replacement for M1000 or A35P, the binder, asphalt raw material, asphalt production and finished surface percentage cost savings are estimated in Table 9, based on typical Australian asphalt mixtures, production and construction costs.

Table 9: Estimated saving for waste plastic modified bitumen for PMB

Saving for 6% replacement	MR6 for A35P	MR6 for M1000	MR10 for A20E
Binder supply (per tonne)	$470	$130	$410
Binder supply	35%	12%	30%
Asphalt raw materials	12%	4%	10%
Produced asphalt ex-bin	9%	3%	8%
Paved and finished asphalt	5%	2%	4%

FURTHER WORK

The use of commercially available recycled waste plastic as a binder replacement/modifier in Australian asphalt mixtures appears to be advantageous. The data presented from the UK suggests that similarly performing mixtures are likely to be available at significantly reduced cost. It follows that better performing mixtures are also likely to be available at comparable cost. However, additional work is required to validate the expected benefits.

Comparison to Australian binders

Testing to date has compared the various waste plastic products to 40/60 penetration grade unmodified bitumen in typical British asphalt mixtures. Although the asphalt mixtures are likely to be similar to Australian asphalt mixtures, Australia does not use penetration grade binders. Indicative relationships between penetration and viscosity graded bitumen (Table 1) are interesting, but comparison to Australian modified binder grades (ie. M1000, A35P and A10E) is required. This comparison is best performed in the laboratory using typical Australian asphalt mixtures and Australian test methods.

Verified local performance

Regardless of comparative laboratory testing results, there is no substitute for field performance validation under real vehicular traffic. Following laboratory comparison to Australian binders, it is recommended that full scale production and construction be undertaken in a controlled location to confirm performance, including the practical metering and control of waste plastic incorporation into the asphalt production plant.

Equivalent binder testing

The MR6, MR8 and MR10 recycled plastic waste products are unusual in that they replace bituminous binder but are dry-mixed into the asphalt rather than being wet-mixed by blending into hot bitumen. This is intended to increase the availability of the products by allowing any asphalt production plant to incorporate them regardless of the binder supply. However, it creates a challenge for comparative testing of recycled waste plastic extended bitumen with more conventional asphalt binders. It is clear that binder testing for relative asphalt performance is cost and time effective and a protocol for the laboratory preparation of waste plastic extended and modified bitumen would allow binder tests such as the MSCR protocol to be considered. However, it is unlikely that simply stirring MR6, MR8 or MR10 into C320 bitumen would produce similar results to binder extracted from mixtures incorporating dry-mixed recycled plastic extenders. It is recommended that comparative testing of wet and dry-mixed asphalt and binder samples be undertaken to form the basis of protocols for the preparation of waste plastic extended and modified binders in the laboratory. This would include asphalt manufactured with wet-mixed binder, as well as extracted binder testing of dry-mixed product.

Digestion and distribution consistency

Dry-mixed bitumen modifiers have a chequered history in Australia. For example, there has been variable success associated with Polybilt 101 pellets added directly to asphalt production plants as an alternate to A35P. As long as the additive rate is controlled and metered, the greatest risk to dry-mixed materials is achieving a consistent and uniform distribution through the asphalt mixture. The recycled plastic waste products assessed in this research were developed to melt and be uniformly digested into the asphalt mixture binder within a timeframe allowed by typical asphalt production plants. However, the products were developed in the UK, where batch plants are common for asphalt production, whereas in Australia, double barrel drum plants are more common. Therefore, a production consistency trial is required to demonstrate the digestion and distribution through the asphalt mixture is appropriately consistent.

CONCLUSIONS

Recycled plastic waste has been demonstrated to improve, compared to conventional 40/60, the fracture and deformation resistance of typical asphalt mixtures in the UK. It is expected that the recycled waste products would produce similar performance to M1000 or A35P (MR10) and A20E (MR6) in Australian asphalt mixtures. If verified, this comparable performance presents a potential cost saving of $120-460 per tonne of bituminous binder, equivalent to 2-5% of the cost of produced, constructed and finished asphalt. It is recommended that further laboratory research validate the expected performance of the recycle plastic products compared to typical Australian asphalt binders and that a field trial validates the digestion and distribution efficiency of drum-based asphalt production plants. Research is also required to develop a protocol for preparing representative samples of extended/modified binder without the need to extract binder from produced asphalt samples.

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