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Laboratory Comparison of Wet-mixing and Dry-mixing of Recycled Waste Plastic for Binder and Asphalt Modification

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ABSTRACT
The use of recycled plastic as an extender and modifier of bituminous binder in asphalt mixtures has attracted significant attention in recent times, including the development of commercially available products intended to be either elastomeric and plastomeric in nature. Although the improvement in mechanical properties associated with these products has been demonstrated, a range of practical and logistical issues require further attention, including whether the products should be wet-mixed into the bitumen or dry-mixed by direct addition to the asphalt production plant. Comparison of wet-mixed and dry-mixed binder and mixture results confirmed a significant improvement in most properties, except for fatigue life, which was not significantly affected by recycled plastic modification. Furthermore, the binder and mixture results were generally not statistically different for the wet-mixing and dry-mixing processes. However, the wet-mixing process was associated with higher test result variability, although the sample sizes are too small for this to be considered conclusive. It was concluded that the decision to wet-mix or dry-mix the evaluated recycled plastic products into asphalt mixtures should be based on factors other than the resulting binder or mixture properties, because the results were generally not significantly affected by the mixing process.

INTRODUCTION
Waste plastic is a significant and growing environmental challenge and includes industrial plastics, plastic bags and plastic bottles (*1*). As a result, there has been an increased interest in the recycling of 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 (*1,3,9-11*). 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 (*12*). Some of these products are specifically intended to melt into, extend and modify the bituminous binder for improved asphalt performance (*11,13-14*). These recycled plastic products, often referred to as 'soft plastics', are the most valuable plastics for inclusion in asphalt surfaces because they not only consume plastic that may otherwise be sent to landfill, but they also improve the performance of the resulting asphalt mixture in a similar manner to conventional polymer modified binders (*15*). As detailed below, despite these products having been demonstrated to improve the physical properties of bitumen and asphalt, there remains questions regarding various logistical and safety/environmental issues, including whether they are better to be wet-mixed into the bitumen or dry-mixed directly into the asphalt production plant.

This paper compares otherwise nominally identical asphalt mixtures produced with wet-mixed and dry-mixed recycled plastic. Two recycled plastic products, commercially known as MR6 (intended to be plastomeric) and MR10 (intended to be elastomeric) (*12*) were used to extend and modify the bituminous binder. A control sample was also produced with unmodified 50-70 penetration grade bitumen. Comparisons included asphalt Marshall properties, asphalt properties indicative of deformation, fatigue and moisture damage resistance, as well as extracted binder properties. Although the laboratory test results can not be used to directly predict field performance, they are considered to be robust indicators of relative performance, particularly in light of the consistent aggregate source used and the nominally identical volumetric composition of the mixtures.

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 (*16*). Typically, 10-20% RAP is incorporated, with higher RAP percentages also considered when RAP is available in greater quantities (*17*).

In more recent times, other recycled materials have been incorporated into asphalt mixtures. Waste printer toner (*18*), crushed (cullet) glass (*19*), incinerator waste, municipal waste refuse and coal mine overburden (*20*) 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 impacted (*21*).

Plastics are synthetic materials derived primarily from refined crude oil petroleum products (*2*). 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 (*9*) 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.

One of the main sources of waste plastic in the environment are plastic drink bottles (*1*). However, plastic bottles are manufactured from polyethylene terephthalate (PET) and PET has a melting point of around 260°C. This is much higher than typical bituminous binder and asphalt production and storage temperatures. Consequently, PET can not be readily used as a binder extender and modifier in asphalt production. This highlights the important difference between low melt-temperature plastic as a binder extender (and potential modifier) and using higher melt-temperature waste plastic as an asphalt mixture or aggregate extender. This paper focuses on binder extension and modification using lower melt-temperature recycled plastics products, MR6 and MR10, which are known to be 'soft plastics', melting at around 130-150°C.

Recycled plastic in asphalt mixtures

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 (*15*). For example, Vancouver (Canada) incorporated plastic crate waste as a warm mixed asphalt wax additive in 2012 (*22*) and Rotterdam (The Netherlands) announced a plan to produce recycled plastic segments in a factory for road construction in 2015 (*23*). Also, Janshedpur (India) reported reducing bitumen usage by 7% by dry-mixing shredded recycled plastic into asphalt production (*24*). More recently, a New Zealand asphalt contractor added shredded 4 L engine oil containers to asphalt at Christchurch Airport (*25*) and an independent asphalt producer includes recycled plastic as a bitumen extended in every tonne of asphalt produced. In Australia a comparative trial of three recycled plastic extenders and modifiers was constructed in May 2018 (*11*), which was shortly followed by trials in Melbourne (*26*), Sydney (*27*) and Adelaide (*28*). Meanwhile in the United Kingdom, Cumbria Council was recently awarded a £1.6 M grant by the Department of Transport (UK) to extend its already significant use of recycled plastics in asphalt for road construction (*29*). The University of California (San Diego) recently constructed the first road including recycled plastic in the USA (*30*) and South Africa's Eastern Cape followed suite (*31*).

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 (*10,32*). Although this approach allows high melt-point plastics, such as PET, to be recycled, the cost of depolymerisation is expected to be high and the economic practicality is questioned. In contrast, Ziari et al. (*33*) investigated the effect of unprocessed PET on asphalt rutting performance. The PET was cleaned, dried and cut into 2.5 mm wide battens prior to dry-mixing into the aggregate and heating to 180°C for five hours prior to asphalt production. Rutting decreased with increasing waste plastic content and the efficiency of the waste plastic in reducing rutting increased with smaller (10 mm) batten length, compared to the longer (30 mm) battens. Similarly, 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. Binder penetration reduced, softening point increased and ductility improved. In parallel, asphalt mixture Marshall stability increased and Marshall Flow decreased (*3*). Furthermore, Naghawi et al. (*34*) cleaned and shredded PET prior to adding to asphalt mixtures. Although the mixing method was not reported, Marshall Stability and Marshall Flow both increased, along with indirect tensile strength, with the optimum plastic content found to be 7.5% of the binder mass (*34*). These efforts have produced interesting results, but their adoption by industry is unlikely to be economically practical. Other researchers have more practically concentrated on soft plastics with melting points below normal modified binder blending and asphalt production temperatures.

Dalhat & Wahhub (*8*) 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 Performance Grading (*35*) 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 were both predicted to reduce significantly (*8*). 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 (*36*). 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 (*36*). 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. In related work, White (*15*) reported comparable moisture damage resistance and improved fatigue life of asphalt mixtures produced with the same products.

The potential for recycled plastics to improve the performance properties of asphalt mixtures has clearly been demonstrated in the UK and other counties. However, various practical issues remain unanswered. One such question is whether recycled plastics should be wet-mixed into the bituminous binder or dry-mixed into the asphalt.

Wet and dry mixing

Most conventional polymers use a wet-mixing process, where the polymer is mixed through the bitumen in a high-shear mill. This ensures thorough distribution. However, some plastomeric polymers are also able to be effectively dry-mixed by controlled or manual feeding directly into the asphalt production plant. Wet-mixing requires specialized mixing and storage facilities (*11*) but is generally recognized as providing more complete and reliable mixing than dry-mixing processes. In contrast, dry-mixing is logistically simpler for asphalt production in small quantities and in remote locations, where bitumen blending facilities are not usually available (*37*).

Many plastics suitable for recycling in asphalt production have different densities, viscosities and chemical compatibility to bitumen, meaning they tend to separate during hot storage (*14*). This risk is avoided by dry-mixing processes but some researchers have questioned the adequacy of the mixing time in typical batch and drum production plants, with undigested plastic particles identified in some asphalt samples (*11*). These issues are likely to be specific to the type of plastic used and research continues to achieve better wet-mixed recycled plastic modified binder storage stability using crosslinkers are other chemical additives (*14*).

Wet-mixing versus dry-mixing crumbed rubber into asphalt binder and mixtures has similarly been debated for many years (*38*). Most projects and research have focused on binder properties, and therefore used wet-mixing processes (*39*). Furthermore, because it is less popular within the industry, there are less standards or guidance documents relating to the dry-mixing process for crumbed rubber (*39*). However, one comparative study found that dry-mixing of crumbed rubber resulted in an increase in mixture resilient modulus, reduced Cantabro losses and lower permeability than nominally identical asphalt produced with dry-mixed crumbed rubber (*38*). This indicates that the less common method is not necessarily flawed or less viable, it is just less well understood and researched.

METHODS

Asphalt and binder samples were prepared with two (MR6 and MR10) recycled plastic products, both wet-mixed and dry-mixed, as well as control samples that did not include recycled plastic. All asphalt mixtures were a nominally identical 10 mm maximum sized dense graded asphalt meeting the requirements of British BS EN 130108 and PD 6691 for a mixture containing basaltic coarse aggregate (**Table 1**). For the recycled plastic modified mixtures, the plastic products were added at 6% (by mass) of the 50-70 penetration bitumen (meeting EN 12591), as recommended by the supplier. The control mixture included the same 50-70 penetration bitumen only.

For the wet-mixed samples, the recycled plastic was sheared into the bituminous binder for 15 minutes in a Silverson laboratory mixer. The binder was then rested at 175°C overnight before being mixed into the pre-graded and pre-heated aggregates at 175°C for 5 minutes. For the dry-mixed samples, the recycled plastic was simply added to the heated aggregate immediately prior to adding the unmodified binder. Test specimens were subsequently prepared and tested according to the various BS EN 12697 methods (**Table 2**). Following asphalt mixture testing, the binder was extracted, according to BS EN 12697-3, from specimens for binder testing, according to the various BS EN 14023 methods (**Table 3**).

TABLE 1 Asphalt mixture properties

Property	Test method	Specification limit	Target value
Binder content (by mass) (%)	BS EN 12697-1	4.5-5.5	5.2
Voids in the aggregate (%)	BS EN 12697-8	18.0-22.0	20.0
Percentage passing (%) standard sieve size (mm)			
Sieve size (mm)	**Test method**	**Specification limit (%)**	**Target value**
10	BS EN 12697-2	90-100	99
6.3		62-68	68
2		25-33	32
1		17-26	22
.063		4-8	7

At the completion of mixture testing and binder extraction, the samples were visually inspected for evidence of undigested (in the binder) or insoluable (in the extraction agent) plastic residue. No asphalt mixture samples exhibited any unmelted plastic particles, indicating that both the wet-mixing and dry-mixing processes achieved complete digestion of the plastic into the binder. Furthermore, no undisolved plastic was identified in the aggregate of any aggregate sample following binder extraction, indictaing the plastic was fully extracted along with the binder.

Except for the volumetric composition and fatigue, all testing was performed on triplicate specimens. Only one bulk sample of each mixture was tested for volumetric composition, while as many fatigue tests as was necessary were performed to achieve a relationship between initial strain and cycles to failure, with a R^2 value greater than 0.90, for each mixture.

TABLE 2 Asphalt test methods

Property	Method	Description
Reference density	BS EN 12697-9	Dry density of a sample compacted using 50 blows to each side by a standard Marshall hammer
Aggregate gradation	BS EN 12697-2	Unwashed sieve analysis after soluble binder extraction
Binder content	BS EN 12697-1	Percentage of binder extracted from a bulk asphalt sample after extraction
Void characteristics	BS EN 12697-8	Voids in the aggregate and air voids in samples compacted by a standard method
Marshall Stability/Flow	BS EN 12697-34	Stability and Flow of samples prepared by 50 blows to each side by a standard Marshall hammer and tested at 60°C
Deformation resistance	BS EN 12697-22	Average deformation following 10,000 passes of a Cooper's wheel tracking wheel at 45°C of samples compacted using a laboratory slab compactor
Indirect tensile strength	BS EN 12697-23	Maximum tensile strength of samples tested at 10°C after compaction to 8% air voids content in a gyratory compactor
Moisture sensitivity	BS EN 12697-12	Ratio of indirect tensile strength of conditioned and unconditioned samples, where conditioning includes vacuum saturation followed by 72 hours in a 40°C water bath
Resistance to fatigue	BS EN 12697-24	Indirect tensile fatigue life of samples prepared to 8% air voids content in a gyratory compactor, over a range of initial tensile strain magnitudes to allow a relationship between initial strain and cycles to failure to be determined with a R^2 value greater than 90%

TABLE 3. Binder test methods

Property	Method	Description
Penetration	EN 1426	Penetration by a standard needle, over 5 seconds, into a sample of binder at 25°C.
Softening point	EN 1427	Softening temperature of a binder sample according to the Ring and Ball method.
Elastic recovery	EN 13398	Percentage of elongation until separation of a binder sample at 25°C.

In additional to graphical comparisons, the results were analysed by T-tests for the difference of means (*40*). P-values were calculated with a p-value of 0.05 or less indicating a significant difference between the populations. Because the fatigue life testing resulted in a log-log relationship between initial strain and cycles to failure, the p-values for judging statistical significance were based on the differences of the linear (in the log-log space) regression equations.

RESULTS

The various mixture gradings were generally consistent with the specification and the target grading (**Figure 1**). The other mixture volumetric properties are in **Table 4**, while the Marshall properties are in **Table 5**. The performance properties are in **Table 6**, except the fatigue results, which are shown in **Figure 2**, along with the resulting regression equations. Finally, the pre-mixed wet-mixed, wet-mixed extracted binder and dry-mixed extracted binder property results are in **Table 7**.

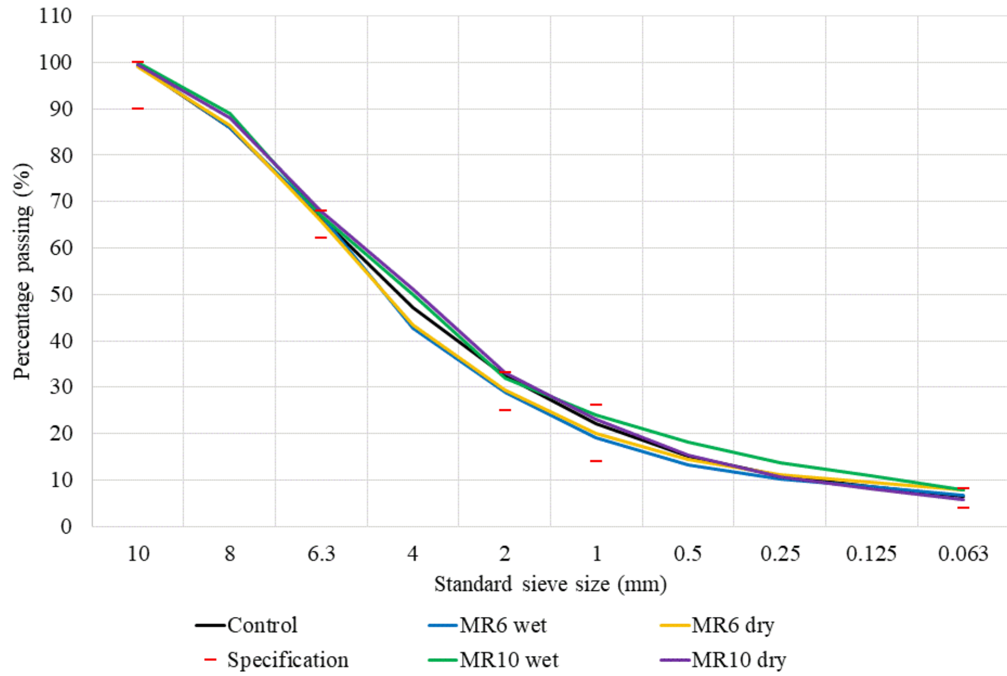

Figure 1 Specification limits and bulk sample gradings

TABLE 4 Asphalt mixture volumetric property results

Mixture	Binder content (%)	Voids in the Aggregate (%)	Voids filled with Binder (%)
Control mix	5.2	19.5	61.9
MR6 wet	5.1	20.2	59.5
MR6 dry	5.1	20.9	57.4
MR10 wet	5.3	20.1	59.2
MR10 dry	5.1	20.9	55.4

TABLE 5 Asphalt mixture Marshall results

Mixture	Marshall air voids (%)	Marshall Stability (kN)	Marshall Flow (mm)
Control mix	7.5	4.1	3.1
	7.2	3.8	3.7
	7.6	4.3	3.7
MR6 wet	7.7	7.3	3.2
	9.1	7.6	3.1
	8.5	7.6	2.9
MR6 dry	9.1	7.3	4.5
	8.8	7.8	2.7
	8.8	7.0	3.3
MR10 wet	7.5	9.6	3.4
	7.5	8.6	3.7
	10.1	7.6	4.0
MR10 dry	8.8	10.3	2.9
	8.8	10.9	3.2
	8.9	11.0	5.2

TABLE 6 Asphalt mixture performance results

Mixture	Wheel track rutting (mm)	Indirect tensile strength (kPa)	Tensile strength ratio (%)
Control mix	8.8	1260	0.90
	12.4	1790	0.74
	10.8	1690	1.00
MR6 wet	3.4	1920	0.69
	3.0	2360	0.91
	3.4	2040	1.06
MR6 dry	4.7	1710	0.85
	3.6	1830	0.71
	3.2	1630	0.90
MR10 wet	5.8	2230	1.10
	5.3	2410	0.68
	6.0	1920	0.83
MR10 dry	7.0	2250	0.83
	6.7	2140	0.95
	5.1	2070	0.86

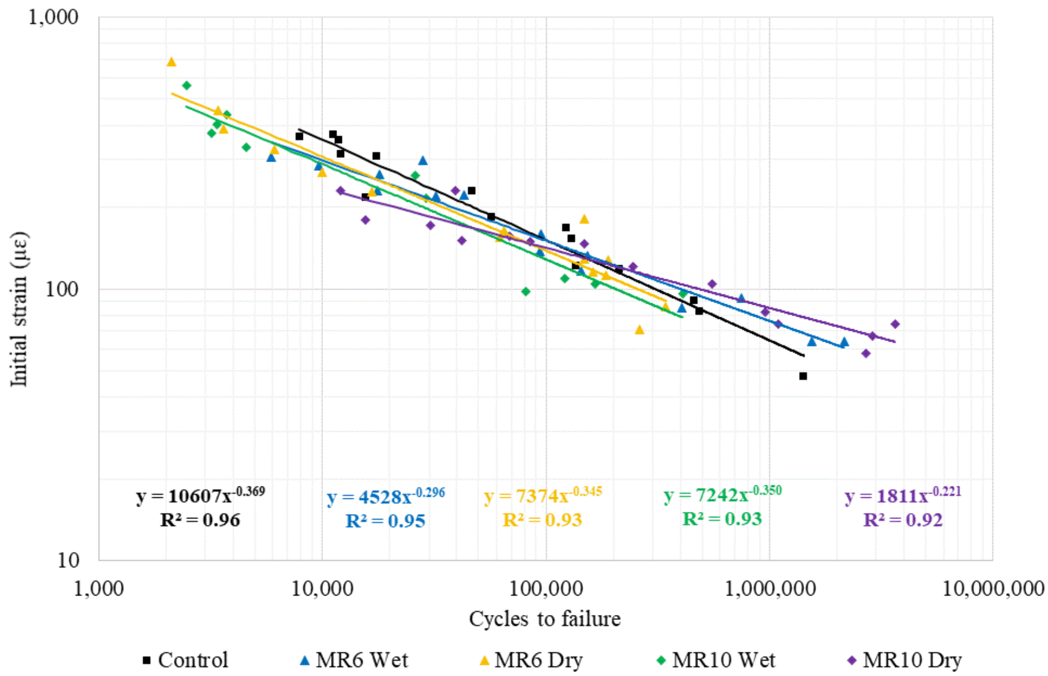

Figure 2 Mixture fatigue results and associated relationships

TABLE 7 Binder property test results

Mixture/Binder	Penetration ($10mm^{-1}$)		Softening point (°C)		Elastic recovery (%)	
	Pre-mixing	Extracted	Pre-mixing	Extracted	Pre-mixing	Extracted
Control mix	62	51	48	50	1.9	5.5
	66	54	48	50	1.0	5.3
	64	57	48	51	2.5	5.5
MR6 wet	42	46	57	52	3.0	5.3
	46	37	57	56	3.2	9.8
	46	31	56	56	3.2	9.3
MR6 dry	-	35	-	55	-	10.0
	-	42	-	52	-	5.3
	-	37	-	55	-	10.5
MR10 wet	47	51	53	58	48	58
	44	46	56	59	43	61
	45	34	54	57	33	48
MR10 dry	-	38	-	54	-	47
	-	39	-	55	-	46
	-	36	-	55	-	45

Note: pre-mixing results are not possible for samples that were dry-mixed.

DISCUSSION

Isolation of the effects of interest

To understand the degree to which the asphalt property improvement was isolated to the addition of recycled plastic, it was first important to consider the consistence in volumetric composition of asphalt mixtures. Similarly, to understand how the wet-mixing and dry-mixing processes affected the binder properties, it was first important to understand whether the asphalt production and binder extraction processes had affected the binder properties.

Figure 1 shows that all bulk asphalt mixtures were produced within the applicable specification limits and were generally consistent with each other, within the limits of typical production variability. Furthermore, **Table 3** shows generally consistent binder content and ait void contents across the five bulk mixtures. Consequently, it was concluded that the various mixtures were produced to be volumetrically consistent enough to isolate the effects of the binder properties on mixture performance and other properties.

The wet-mixed binder properties were compared to those for binder that was incorporated into the various mixtures and then extracted after asphalt sample testing (**Figure 3**). It is noted that this included mixing into heated aggregates, asphalt compaction, sample conditioning and testing, binder extraction, binder conditioning and finally binder testing. In general, the mixing and extraction processes were associated with a penetration reduction, softening point increase and elastic recovery increase (**Table 8**). Despite the changes being relatively minor in many cases, the low variability of the triplicate test results means that some differences were still statistically significant. For example, all three binder properties were significantly different for the control (50-70) bitumen, although the differences were generally not significant for the modified binders, primarily reflecting the higher variability in plastic modified binder properties, particularly those associated with the extracted binder samples. It was concluded that the mixing and extraction processes may affect binder properties, meaning that only general comparison of wet-mixed and dry-mixed extracted binder results are possible. However, when comparing dry-mixed and wet-mixed extracted binder, all samples are subject to asphalt mixing, sample compaction and binder extraction. Consequently, the results are expected to be more reliably compared than the results of pre-mixed and extracted binder samples.

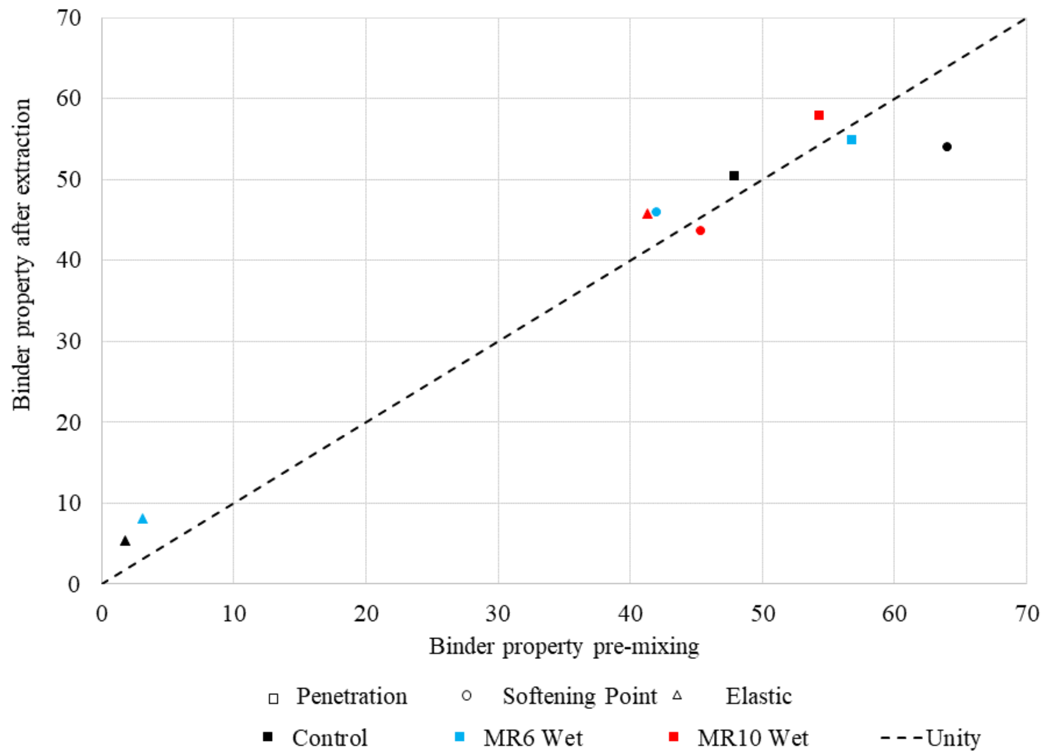

Figure 3 Comparison of pre-mixed and extracted binder properties

TABLE 8 Summary statistics for pre-mixed and extracted binder properties

Mixture/Binder	Statistic	Penetration (10mm^{-1})		Softening point (°C)		Elastic recovery (%)	
		Pre-mixed	Extracted	Pre-mixed	Extracted	Pre-mixed	Extracted
50-70 control	Average	64.0	54.0	47.9	50.3	1.8	5.4
	Std. Dev.	2.0	3.0	0.3	0.3	0.8	0.1
	P-value	0.01		<0.01		<0.01	
MR6	Average	44.7	38.0	56.8	54.9	3.1	8.1
	Std. Dev.	2.3	7.5	0.6	2.3	0.1	2.5
	P-value	0.22		0.23		0.02	
MR10	Average	45.3	43.7	54.3	57.9	41.3	55.3
	Std. Dev.	1.5	8.7	1.6	1.0	7.5	6.9
	P-value	0.76		0.03		0.07	

Std. Dev. is the standard deviation of triplicate results. P-value is for a Student T test for the difference of means for pre-mixed and extracted binder.

Effect on asphalt Marshall properties

The average and variability of the Marshall Stability and Marshall Flow are shown in **Figure 4** and **Figure 5**. It is clear that the addition of recycled plastic, whether by wet or by dry mixing, resulted in a significant increase in the Marshall Stability (p-values all <0.01) but had no significant effect on the average Marshall Flow (p-values 0.10 to 0.99). This is consistent with other research (*1,11,15*) that has shown that MR6 and MR10 recycled plastic products significantly stiffen asphalt mixtures without adversely affecting mixture ductility. **Figure 5** also shows that the variability of the Marshall Flow results was much greater for the dry-mixed samples than for the wet-mixed samples, which is discussed later.

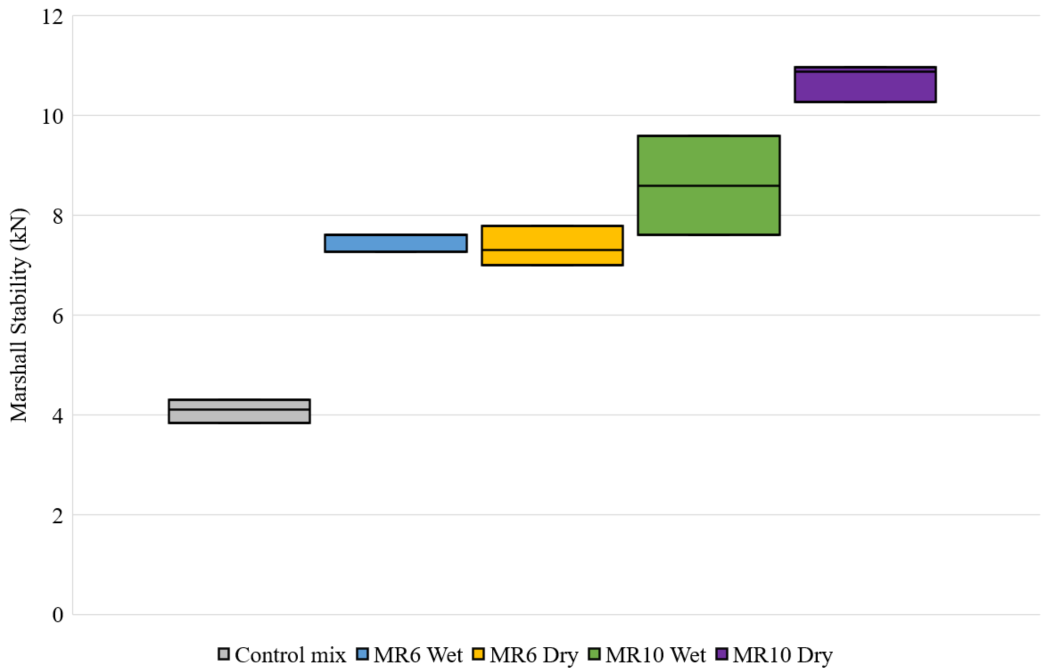

Figure 4 Asphalt mixture Marshall Stability comparison

Note: the top and bottom of the box represents the maximum and minimum of the triplicate results while the average of the triplicate results is indicated by the horizontal bar.

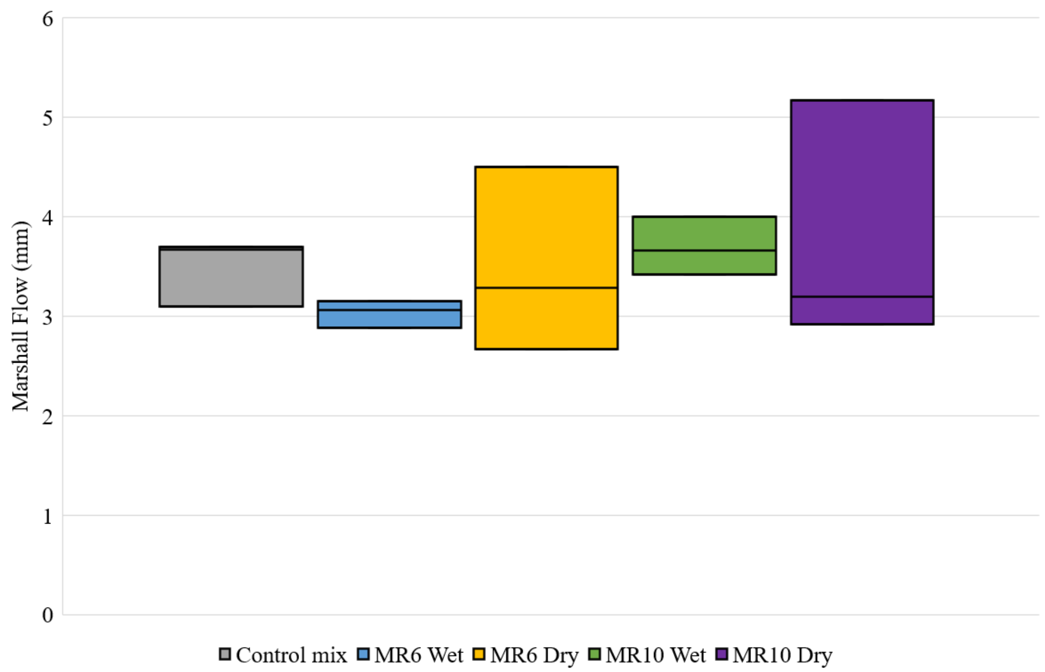

Figure 5 Asphalt mixture Marshall Flow comparison

Effect on binder properties

The pre-mixed binder properties were all significantly different to the control 50-70 properties (**Table 9**). The addition of recycled plastic significantly reduced the penetration, increased the softening point and introduced significant elastic recovery capacity. These changes are indicative of a stiffening of the bitumen associated with recycled plastic modification. Again, these results are similar to other research (*1,11,13*) that has shown that MR6 and MR10 increase the Performance Grade of bitumen, similar to conventional polymers. The wet mixed MR6 and MR10 modified binder penetration and softening point were comparable, but MR10 introduced substantially more elastic recovery than MR6 did. This reflects the intended plastomeric nature of MR6, compared to the intended elastomeric nature of MR10.

TABLE 9 Effect of waste plastic on wet-mixed binder properties

Binder property	Statistic	Control	MR6	MR10
Penetration	Average	64.0	44.7	45.3
	Std. Dev.	2.0	2.3	1.5
	T-test p-value	-	<0.01	<0.01
Softening point	Average	47.9	56.8	54.3
	Std. Dev.	0.3	0.6	1.6
	T-test p-value	-	<0.01	<0.01
Elastic recovery	Average	1.8	3.1	41.3
	Std. Dev.	0.8	0.1	7.5
	T-test p-value	-	0.04	<0.01

Std. Dev. is the standard deviation of triplicate results. T-test p-values are all compared to the control 50-70 binder.

Effect on asphalt performance properties

Fatigue life (**Figure 2**) and TSR (**Figure 6**) were not significantly affected by the addition of recycled plastic, supported by the T-test p-values (**Table 10**). This reflects the intent of the MR6 and MR10 products to not adversely affect the fracture resistance or moisture damage resistance of asphalt mixtures. However, this also indicates that MR10, which is intended to be an elastomeric modifier, does not induce the same level of fatigue cracking resistance as conventional elastomeric polymers, such as SBS. In contrast, the wheel tracking (**Figure 7**) was significantly improved by recycled plastic modification, based on the T-test p-values (**Table 10**). Finally, the additional of recycled plastic increased the average indirect tensile strength of the mixtures (**Figure 8**) but these increases were only significant for MR10 (**Table 10**). Again this is consistent with other research regarding these products, which shows that the modulus increases significantly, particularly for MR10 modified mixtures (*1,15*).

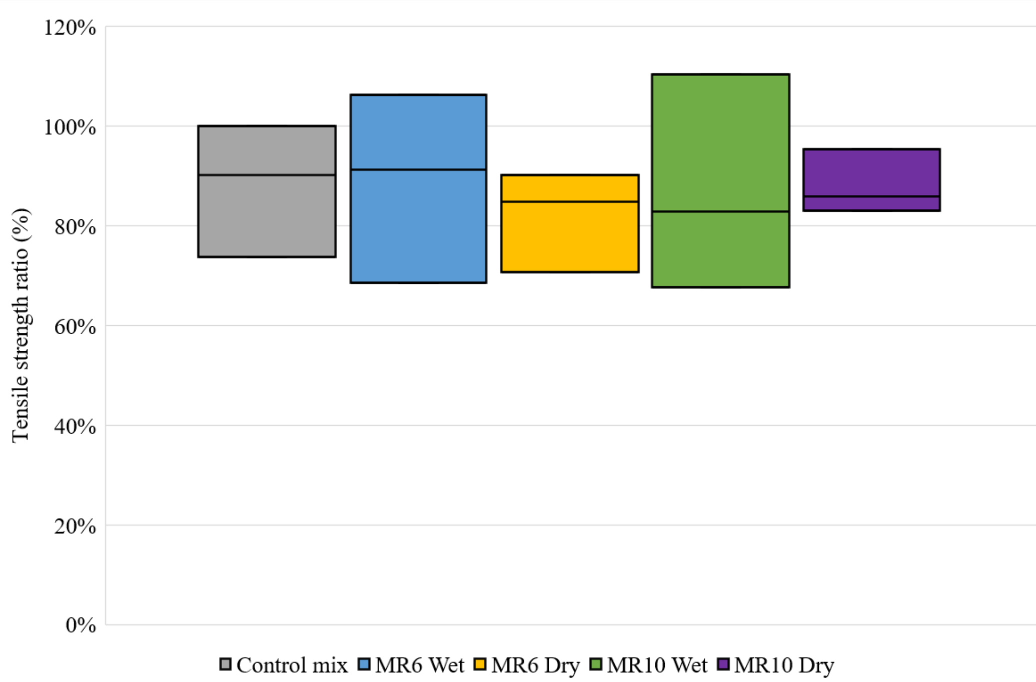

Figure 6 Asphalt mixture moisture resistance comparison

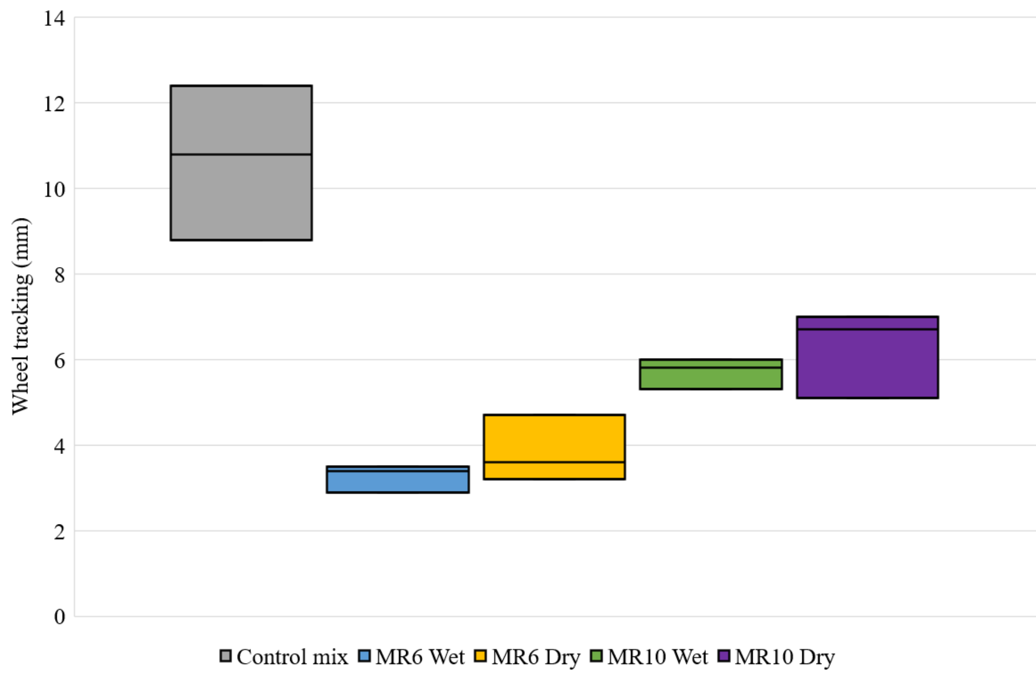

Figure 7 Asphalt mixture deformation resistance comparison

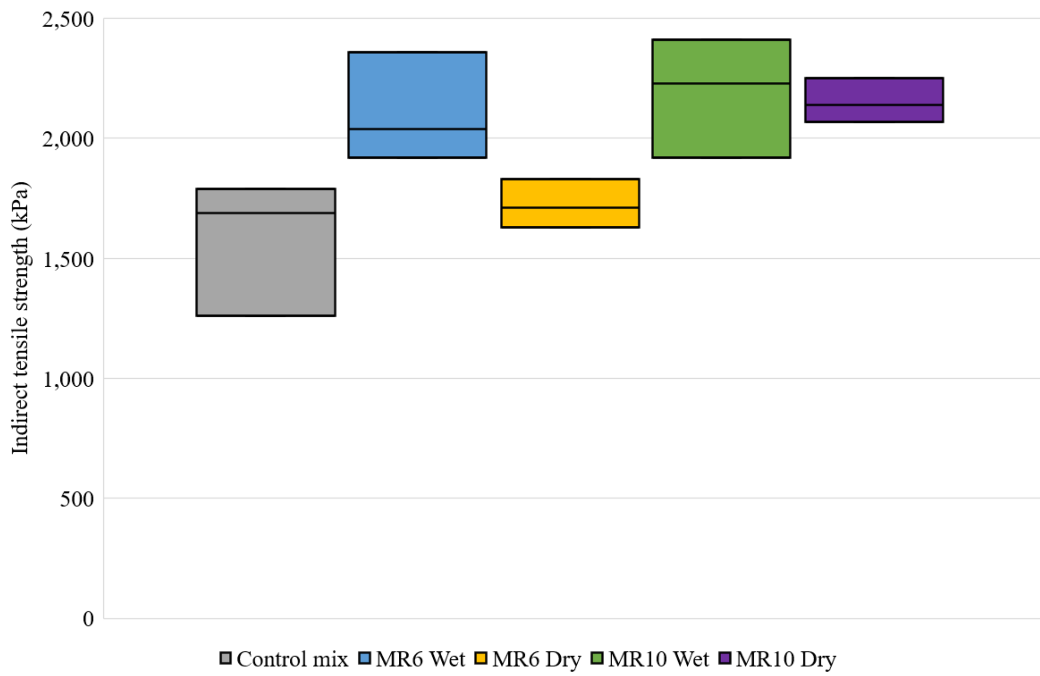

Figure 8 Asphalt mixture tensile strength comparison

TABLE 10 Effect of waste plastic on asphalt mixture performance properties

Binder property	Statistic	Control	MR6 Wet	MR6 Dry	MR10 Wet	MR10 Dry
Fatigue resistance	Regression p-value	-	0.43	0.23	0.18	0.57
Deformation resistance	Average	10.7	3.3	3.8	5.7	6.3
	Std. Dev.	1.8	0.3	0.8	0.4	0.1
	T-test p-value	-	<0.01	<0.01	0.01	0.02
Moisture resistance	Average	0.88	0.89	0.82	0.87	0.88
	Std. Dev.	0.13	0.19	0.10	0.22	0.06
	T-test p-value	-	0.96	0.56	0.95	0.99
Tensile strength	Average	1580	2107	1723	2187	2153
	Std. Dev.	282	227	101	248	91
	T-test p-value	-	.07	0.45	0.04	0.03

Std. Dev. is the standard deviation of triplicate results. Fatigue resistance p-value was based on the regressions equations in **Figure 2** compared to the mixture containing the control 50-70 binder. Other T-test p-values are all compared to mixture containing the control 50-70 binder.

Wet-mixing versus dry-mixing effects on binder properties

The different effects of wet-mixing and dry-mixing on the binder properties were evaluated by comparing the recovered binder properties from the asphalt samples that were produced with wet-mixed modified binder and dry-mixed asphalt mixture modification. The results are shown in **Figure 9** (penetration), **Figure 10** (softening point) and **Figure 11** (elastic recovery). Despite some differences in the results, the average values were generally not significantly different (**Table 11**) with only the MR10 softening point difference being statistically significant. This significant difference is expected to be an anomaly, resulting from the unusually low variability of the softening point triplicate test results, particularly for wet-mixing, which was just 0.3, or just 0.6% of the average value. Overall, there was little difference in the extracted binder properties associated with wet-mixing or dry-mixing of the recycled plastic products, particularly in light of the significant differences in the pre-mixed and extracted binder properties for the wet-mixed products shown in **Figure 3**.

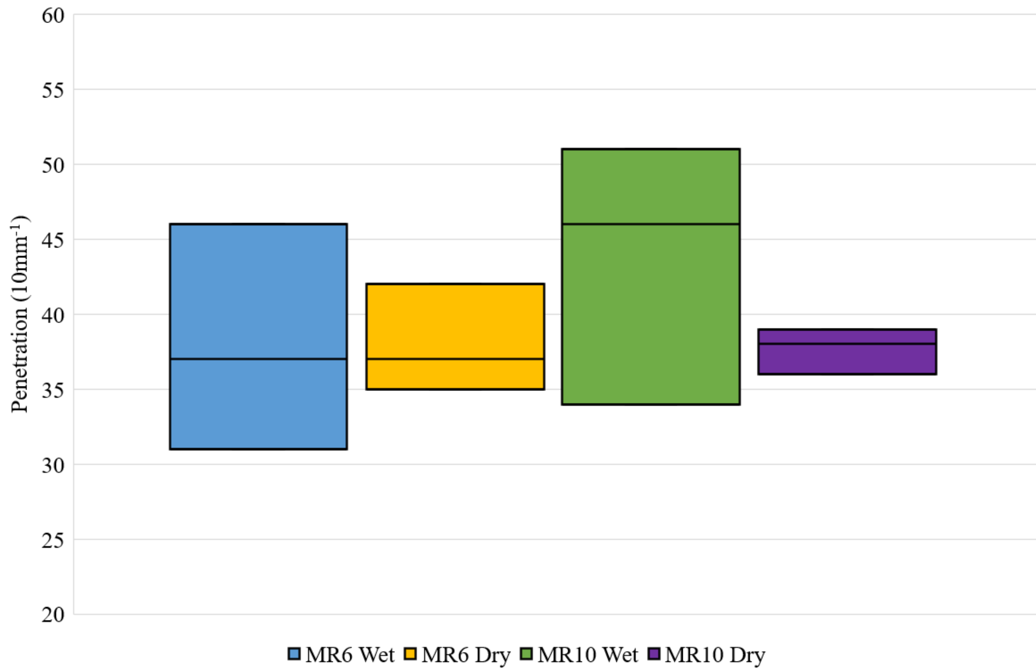

Figure 9 Mixing effect on extracted binder penetration

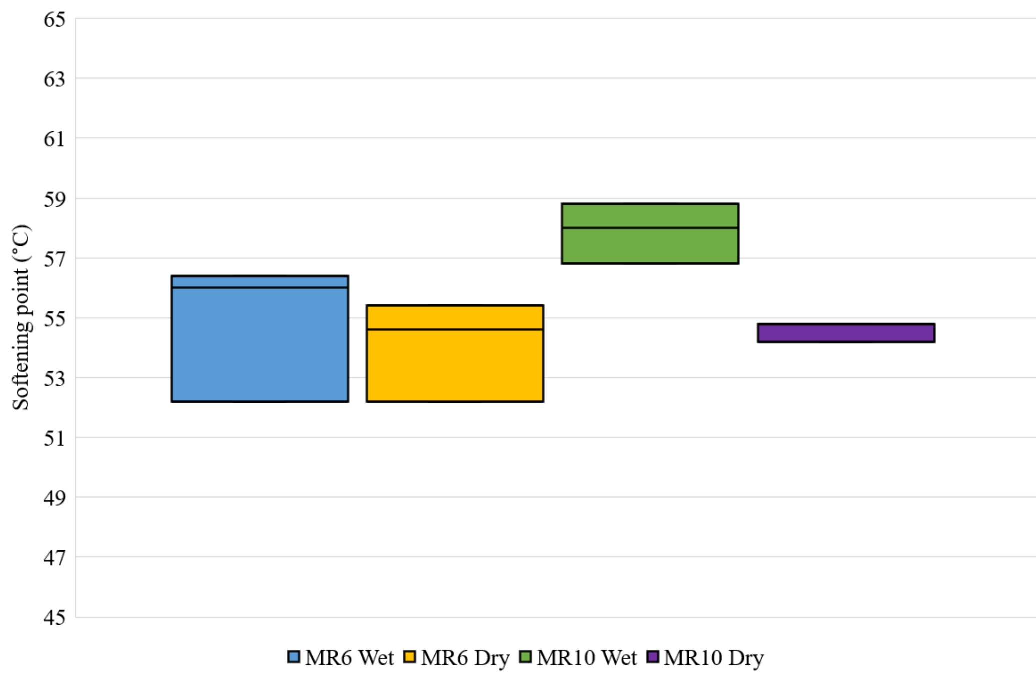

Figure 10 Mixing effect on extracted binder softening point

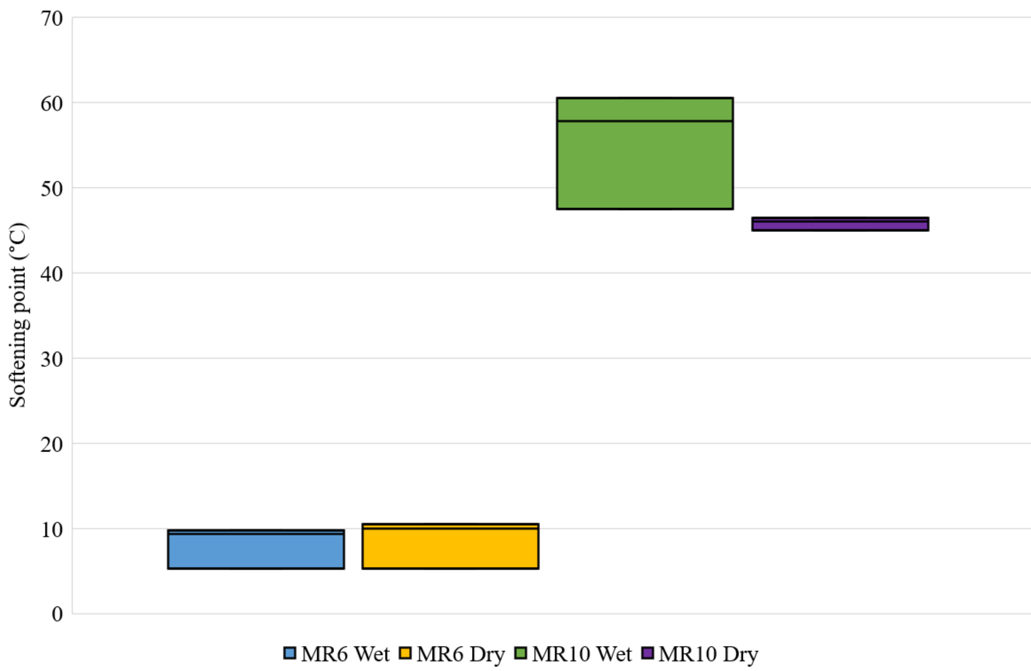

Figure 11 Mixing effect on extracted binder elastic recovery

TABLE 11 Effect of production method on extracted binder properties

Binder property	Statistic	MR6 Dry	MR6 Wet	MR10 Dry	MR10 Wet
Penetration	Average	38.0	38.0	43.7	37.7
	Std. Dev.	7.5	3.6	8.7	1.5
	T-test p-value	>0.99		0.31	
Softening point	Average	54.9	54.1	57.9	54.6
	Std. Dev.	2.3	1.7	1.0	0.3
	T-test p-value	0.65		0.01	
Elastic recovery	Average	8.1	8.6	55.3	45.8
	Std. Dev.	2.5	2.9	6.9	0.8
	T-test p-value	0.84		0.08	

Std. Dev. is the standard deviation of triplicate results. T-test p-values compare dry-mixed and wet-mixed results after binder extraction.

Wet-mixing versus dry-mixing effects on asphalt properties

Similar to the binder property comparison, the difference in the effect of wet-mixing and dry-mixing was evaluated by comparing the asphalt mixture results for the samples produced by each method. The averages, standard deviations and associated T-test p-values are summarised in **Table 12**. The Marshall Stability (**Figure 4**) was significantly different for MR10, but the MR6 Marshall Stability, as well as both the MR6 and MR10 Marshall Flow (**Figure 5**) values were not significantly different for wet-mixed and dry-mixed recycled plastic modification.

Despite some apparent differences in the wheel tracking (**Figure 7**) and tensile strength (**Figure 8**) results, none of the asphalt mixture performance properties were significantly affected by whether the recycled plastic products were wet-mixed or dry-mixed (**Table 12**). Similarly, the fatigue life results (**Figure 2**) were all comparable for the recycled plastic modified samples and the minor differences were not significant for wet-mixing and dry-mixing (p-values 0.89 and 0.77). This is consistent with the binder property results (**Table 10**) again indicating that the process of incorporating recycled plastic into asphalt mixtures does not significantly affect the resulting mixture properties. However, it is clear that the wet-mixing process was generally associated with greater variability of TSR (**Figure 6**) and indirect tensile strength (**Figure 8**) results. This was generally consistent with the extracted binder testing, which also showed greater variability associated with the wet-mixing, as shown in **Figure 9** (penetration), **Figure 10** (softening point) and **Figure 11** (elastic recovery). In contrast, the variability associated with the Marshall Flow (**Figure 5**) was higher for the dry-mixing process than for wet-mixing. It is likely that the Flow result is anomalous and reflects the small sample sizes used in this study, with only triplicate results for each property/mixture.

TABLE 12 Effect of production method on asphalt mixture properties

Binder property	Statistic	MR6 Dry	MR6 Wet	MR10 Dry	MR10 Wet
Marshall Stability	Average	7.5	7.4	8.6	10.7
	Std. Dev.	0.2	0.4	1.0	0.4
	T-test p-value	0.64		0.03	
Marshall Flow	Average	3.0	3.5	3.7	3.8
	Std. Dev.	0.1	0.9	0.3	1.2
	T-test p-value	0.46		0.93	
Deformation resistance	Average	3.3	3.8	5.7	6.3
	Std. Dev.	0.3	0.8	0.4	0.1
	T-test p-value	0.31		0.42	
Moisture resistance	Average	0.89	0.82	0.87	0.88
	Std. Dev.	0.19	0.10	0.22	0.06
	T-test p-value	0.61		0.94	
Tensile strength	Average	2107	1723	2187	2153
	Std. Dev.	227	101	248	91
	T-test p-value	0.06		0.84	
Fatigue resistance	Regression p-value	0.89		0.77	

Std. Dev. is the standard deviation of triplicate results. Fatigue resistance p-value was based on the wet and dry mixed regressions equations in **Figure 2**. Other T-test p-values are for wet and dry mixed asphalt samples modified with the same waste plastic product.

CONCLUSIONS

Based on statistical analysis of bituminous binder and asphalt mixture properties associated with wet-mixing and dry-mixing of two commercially available recycled plastics, it was found that the recycled plastic significantly improved most binder and asphalt properties. The only exception was the fatigue life relationships for the asphalt mixtures, which were not significantly different to that of the control mixture produced with unmodified bitumen. However, it was concluded that the mixing process was not generally associated with significant differences in the otherwise nominally identical extracted binder and asphalt mixture properties. That is, the decision to incorporate recycled plastic products by wet-mixing or dry-mixing processes should not be based on the resulting binder properties, asphalt Marshall properties or asphalt mixture performance properties, such as deformation resistance, tensile strength or moisture damage resistance. Instead, such decisions should be based on practical issues, such as the potential for wet-mixed recycled plastic to segregate during hot storage and transportation, as well as the logistics of the particular application, both of which are outside the scope of this research. Despite the similarity in the average values of the various properties measured, the asphalt mixture and extracted binder properties associated with wet-mixing were generally more variable than the dry-mixing results.

This suggests that dry-mixing processes are expected to produce a more consistent asphalt mixture, but the sample sizes were too small for this observation to be considered conclusive.

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