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OBJECTIVE EVALUATION OF THE PRACTICAL BENEFITS OF ASPHALT BINDERS MODIFIED WITH RECYCLED PLASTIC

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Abstract

Commercially available recycled plastic for asphalt production was incorporated into typical British surface and base course mixtures. The asphalt fatigue life and modulus both improved compared to otherwise identical mixtures without recycled plastic modification. The relative improvement in asphalt mixture properties were used to characterise asphalt properties for layered elastic pavement thickness design. Pavements representative of local roads containing recycled plastic modified asphalt were, on average, 11 mm thinner than identical pavements without recycled plastic. Similarly, representative highway pavement structures were, on average, 59 mm thinner, or would support nine times as much traffic, compared to pavements without recycled plastic. It is recommended that British asset owners consider recycled plastic as an alternate to conventional polymer modification of binders. However, it should not be inferred from this research that asphalt surface life will also increase with recycled plastic modification.

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, but 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, 4-7]. When considering the use of recycled plastic in asphalt production, the differences between aggregate extension, bitumen extension and binder modification are important, with the melting temperature of the particular plastic polymer a primary determinant. Although aggregate and bitumen extension offer a means of reusing plastics otherwise destined for landfill, as well as 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.

Two of the main sources of waste plastic in the environment are plastic drink bottles and single-use plastic bags [1]. However, plastic bags are made from low or high density polyethylene (LDPE or HDPE) and plastic bottles are manufactured from polyethylene terephthalate (PET). PET has a melting point of around 260°C and polyethylene has a melting point of 115°C up to 270°C, compared to typical asphalt production temperatures of 160-180°C. Consequently, PET and many LDPE/HDPE products 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 a commercially available low melt-temperature recycled plastic, also referred to as a 'soft plastic'.

The aim of this research was to objectively determine the practical effects on pavement structures constructed with asphalt mixtures modified with recycled plastic. Typical UK asphalt mixtures, with an without recycled plastic as a bituminous binder extender and modifier, were characterised for modulus and fatigue life. Once the effect of the recycled plastic modification of asphalt mixtures was established, mechanistic-empirical pavement analysis and design methods were used to objectively evaluate the effect on practical pavement thickness and/or structural design life.

Background

Recycled plastic use

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 [7]. For example, Vancouver (Canada) incorporated plastic crate waste as a warm mixed asphalt wax additive in 2012 [8] and Rotterdam (The Netherlands) announced a plan to produce recycled plastic segments in a factory for road construction in 2015 [9]. Also, Janshedpur (India) reported reducing bitumen usage by 7% by dry-mixing shredded recycled plastic into asphalt production [10]. More recently, a New Zealand asphalt contractor added shredded 4 L engine oil containers to asphalt at Christchurch Airport [11] 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, which was shortly followed by trials in Melbourne [12], Sydney [13] and Adelaide [14]. 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 [15].

Laboratory evaluations

Some of the above mentioned 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 [6, 16]. 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. [17] 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. Other researchers have more practically concentrated on soft plastics, with melting points below normal modified binder blending and asphalt production temperatures.

Dalhat & Wahhub [5] 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 [18] high temperature rating. Asphalt modulus increased and when a typical asphalt pavement was modelled in a pavement management system, the predicted rut depth and top-down longitudinal cracking were both predicted to reduce significantly [5]. 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 [19]. 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 [19]. 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 [7] 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, no objective investigation of the practical benefits for pavement design has been reported. Consequently, there is a need to understand the practical benefits associated with recycled plastic modified asphalt for the construction of typical pavement structures.

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In 2015, a commercial recycled plastic venture was initiated in Scotland aiming to [20]:

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

The recycled plastic extender/modifier, now known as MR 6 was developed. MR 6 comes in pellet form and was intended to be incorporated directly into the asphalt production plant. It is produced from 100% recycled plastic. The recycled plastics used have melt-temperature below the typical asphalt and binder production temperatures and readily melt into the bitumen to extend and modify it [1].

Other products, known as MR 8 and MR 10, soon followed with different target applications. MR 8 was developed as an economical bitumen extender without performance enhancement, while MR 10 was developed to provide a more crack resistant binder. The original MR 6 was developed to improve deformation resistance via an increase in asphalt stiffness. The three products come in a different forms, with MR 6 and MR 8 a shredded plastic and MR 10 is produced as melted, extruded and cut pellets (**Figure 1**). MR 6 was originally produced as a pellet and MR 8 was originally produced as a flake, but the product form was modified to improve digestibility into bitumen. The chemical position was unaltered by the MR 6 and MR 8 form changes.

(a) (b) (c)

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

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

Pavement analysis and design

Unlike many other countries, the UK does not use layered-elastic mechanistic-empirical software for routine pavement thickness design. Rather, a chart-based or nomograph-based thickness determination method is published, based on layered-elastic analysis of common pavement structures and materials [21]. Although it is possible to have a departure from standards approved, this is not common. It is important to understand that the absence of routine mechanistic-empirical design does not affect the appropriateness of routinely prepared designs. However, it does limit research and other specialised evaluation of non-standard structures and materials. For example, a chart-based method usually only includes one asphalt modulus per asphalt mixture type. This prevents modified or otherwise improved asphalt mixtures, with different modulus values, from being directly evaluated by the chart-based methods. Consequently, a non-standard layered-elastic or finite element software is required to evaluate non-standard materials and structures.

Circly is a layered-elastic mechanistic-empirical software for routine road pavement thickness design in Australia [22]. Circly was first developed in the 1970s [23] and has been improved over time to become widely recognised as an advanced layered-elastic mechanistic-empirical pavement design software. It is both transparent to the user and offers greater flexibility to the pavement designer than is permitted by some other design tools [24]. Circly is calibrated to meet the requirements of Australian road pavement owners [25] but the material characteristics, such as the layer modulus values and the failure criteria, also known as performance models or transform functions, can also be set by the user [22]. Circly was used in this research to objectively evaluate the effect on pavement life and pavement thickness of the modified asphalt mixture characteristics.

Flexible pavement evaluation

Layered-elastic evaluation of flexible pavements relies primarily on elastic material characteristics and the associated failure criteria [26]. Failure criteria primarily relate to permanent vertical subgrade deformation (rutting) and bound material cracking (fatigue). Each bound layer is assigned a fatigue life failure criterion and the subgrade is assigned a rutting failure criterion [27]. Other materials, such as unbound base and sub-base layers are not usually assigned failure criteria. In addition, each layer in the layered-elastic model representing the pavement structure is assigned an elastic modulus and a Poisson's ratio. These are used to calculate the indicator(s) of pavement damage, usually stress and/or strain, during one load repetition. Critical damage indicators are used to calculate the number of load repetitions to failure via the failure criteria [26]. In practice, the modulus has a significant influence on the critical stresses and strains in the pavement, while the Poisson ratio has little effect and presumptive values of Poisson ratio are usually adopted.

When the effect of a non-standard material on the life, or the required thickness, of a pavement structure is evaluated, the failure criteria and/or the layer modulus are the primarily elements modified. A stiffer material is represented by a high modulus and a more fracture resistant bound material is represented by an adjusted fatigue life failure criterion. However, the subgrade rutting failure criterion is rarely changed unless the subgrade is somehow modified or improved. Circly and other fully transparent and flexible software are well suited to the manipulations required to objectively evaluate the effects of improved materials on pavement strength and/or life.

Methods and Results

Two pavement structures were designed, one representing a deep lift asphalt highway and one representing a granular pavement with thin asphalt surfaced local road, using the layered-elastic mechanistic-empirical software Circly. Each of the two structures was designed with standard asphalt material characteristics, as well as with recycled plastic modified asphalt characteristics. The pavement thickness was reduced until the same pavement life was projected, to indicate the potential reduction in pavement thickness associated with recycled plastic modification. The pavement structure was then held at a constant thickness and the effect of recycled plastic modification on projected pavement life was determined. All analyses were based on asphalt material characteristics, relative to the characteristics of the otherwise identical unmodified mixtures, as determined from laboratory testing.

Pavement structures and Loads

Two pavement structures were considered, one intended to be typical of a local road and one intended to be typical of a major highway (**Table 1**). The asphalt surface layers were 10 mm sized stone mastic asphalt (SMA 10) and for the deep lift asphalt pavement, the base course was a 20 mm sized dense graded mixture (DGM 20). In both cases a soaked CBR 6 subgrade was selected to represent a low plasticity and high stiffness clay or silt and then a sensitivity analysis was conducted for CBR 3 and CBR 10 subgrade conditions.

Table 1: Representative pavement structures

Layer	**Structure typical of:**	
	Local (thin asphalt on granular)	**Highway (deep lift asphalt)**
Surface course	50 mm of SMA 10	50 mm of SMA 10
Base course	200 mm of crushed rock base	As required thickness of DGM 20
Sub-base course	As required thickness of gravel	150 mm of gravel
Subgrade	CBR varies	CBR varies

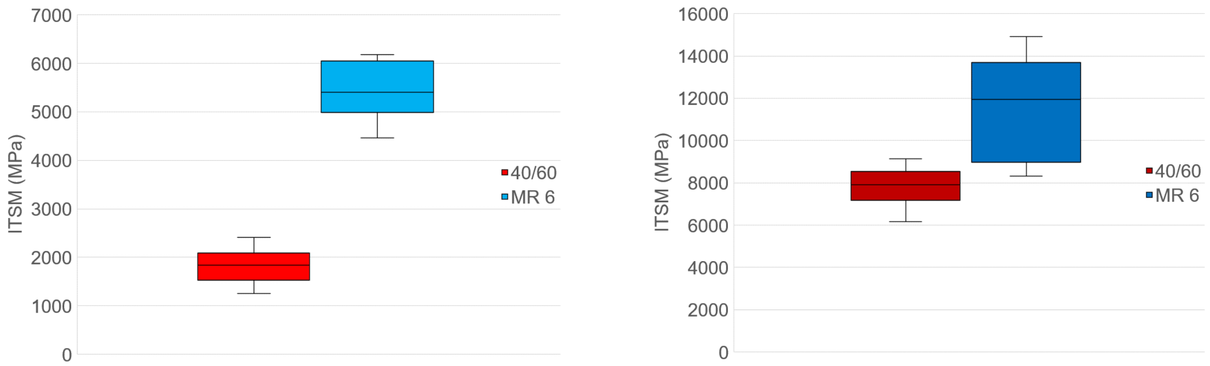
For both pavement structures, the adopted traffic loading was 5,000,000 equivalent standard axle repetitions. An equivalent standard axle repetition is defined as a 8.2 tonnes on a single dual tyred axle with a dual tyre spacing of 330 mm and a tyre contact pressure of 750 kPa. This is typical of standardised or equivalent road pavement design load vehicles in many countries. The subsequent sensitivity analysis included 1,000,000 and 10,000,000 equivalent standard axle load repetitions.

Material characteristics

Each layer of the pavement was characterised to allow pavement thickness determination. The effects of recycled plastic modification were introduced via different elastic modulus values and fatigue life models, based on laboratory testing. In all cases, the Poisson ratio was held constant at a value typically used for layered elastic pavement analysis and design.

The SMA 10 and the DGM 20 were typical of road asphalt mixtures specified in the UK (BS EN 13108-X:2016). The only difference between the standard and modified mixtures was the replacement of 6% (by mass) of the bituminous binder with MR 6 recycled plastic. The unmodified mixtures used a 40-60 penetration grade of unmodified bitumen. All asphalt was produced in a full-size batching plant and bulk asphalt samples were transferred to the laboratory where they were reheated to produce test specimens.

The laboratory modulus characterisation was based on indirect tensile stiffness modulus (BS:EN 12697-26). The range of general distribution of results from the six replicate test specimens in shown in **Figure 2** and the average values are summarised in **Table 2**. For the SMA, the average modulus increased by 196% and for the DGM 20 base mixture, the average modulus increased by 48%. This difference reflects the higher bituminous binder content in SMA mixtures compared to base course mixtures, so the modification of the binder had a much greater effect on the mixture stiffness.



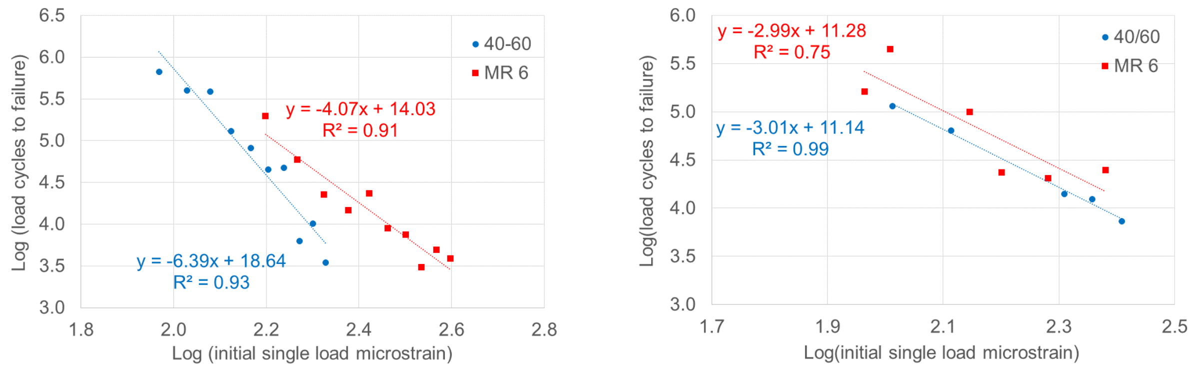
(a) (b)

Figure 2. Laboratory (a) SMA 10 and (b) DGM 20 modulus results

Table 2: Summary of average asphalt modulus values

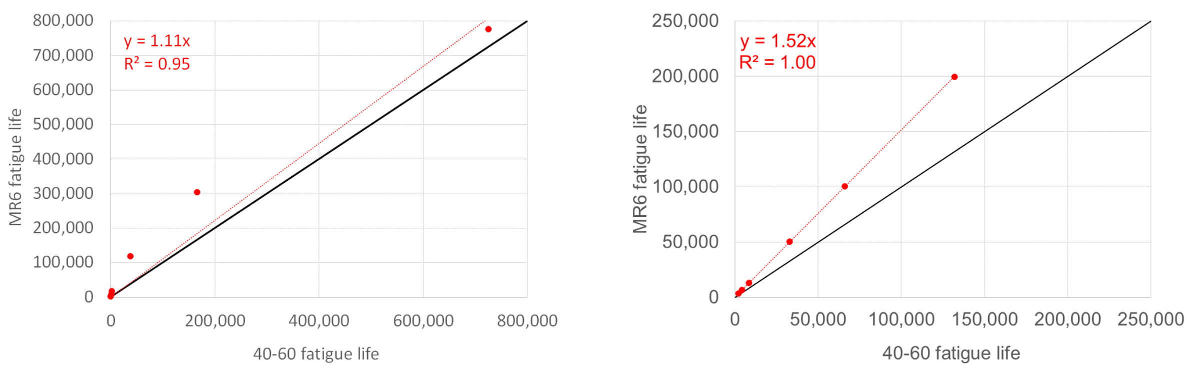
Asphalt type	Without recycled plastic modification	With recycled plastic modification
SMA 10 (surface)	1,820 MPa	5,400 MPa
DGM 20 (base)	7,830 MPa	11,600 MPa

The asphalt fatigue characterisation was based on a stress controlled repeated indirect tension test at different stress levels (BS EN 12697-24:2012) to generate a laboratory relationship between induced initial strain and fatigue life (in the log-log scale) for each mixture (**Figure 3**). A relationship was then derived between the unmodified and recycled plastic modified asphalt fatigue lives, at various practical strain levels, and the relative fatigue performance was determined (**Figure 4**). For simplicity, a linear relationship (in the natural scale) was selected, with the vertical axis intercept set to zero. On average, for the SMA 10 mixture the recycled plastic modified mixture fatigue life was 11% greater than for the unmodified mixture. Similarly, for the DGM 20 base mixture, the improved fatigue life associated with recycled plastic modification was 52%.



(a) (b)

Figure 3. Laboratory (a) SMA 10 and (b) DGM 20 fatigue life results



(a) (b)

Figure 4. Laboratory (a) SMA 10 and (b) DGM 20 relative fatigue life

It is important to understand that the actual asphalt material characteristics for pavement design are not necessarily the values measured in the lab. Due to sample geometries, test temperatures and load frequencies, factors are commonly applied to convert between laboratory measured values and values used for layered elastic design. Consequently, the relative performance was considered in the pavement analysis below. That is, typical values of each characteristic were selected for the asphalt mixtures containing unmodified bitumen and then the relative laboratory performance was used to determine the equivalent characteristic value for the recycled plastic modified material. For example, a modulus of 1,400 MPa was used for SMA 10 containing 40-60 unmodified bitumen and a modulus of 4,144 MPa (196% higher) was used for the SMA 10 with modified binder, as summarised in **Table 3**.

The fatigue life model in Circly is a simplified form of the Shell fatigue model [27] as in *Equation 1*, where the constant (k) is fixed based on the typical volume of binder in the mixture and the nominated mixture elastic modulus. To reflect the improved fatigue life associated with recycled plastic modification, the constant was adjusted. For example, for SMA 10, the constant was increased by a factor of 1.021 so that when raised to the fifth power, the calculated fatigue life increased by 11%, as determined above. The resulting fatigue life characterisation is summarised in **Table 4.** Importantly, the relative fatigue performance was measured at a fixed level of strain, which means that the force required to induce a particular level of strain was higher for the higher modulus (recycled plastic modified) mixtures. Because the laboratory test was performed with controlled strain, rather than controlled stress, any impact of the stiffer mixture on fatigue life was already accounted for in the adjusted fatigue constant. This would not be the case if the test was stress controlled, in which case a second adjustment of the fatigue constant would also be required.

Table 3: Summary of average asphalt modulus values

Material	**Characteristic**	**40-60**	**MR 6**
SMA 10	Modulus	1,400 MPa	4,144 MPa
	Poisson ratio	0.40	0.40
DGM 20	Modulus	3,000 MPa	4,400 MPa
	Poisson ratio	0.40	0.40

$$N = (k/\varepsilon)^b \quad \text{......} \quad \textit{Equation 1}$$

Where N = calculated fatigue life, ε = the load induced microstrain, k = the material constant and b = the fatigue exponent.

Table 4: Summary of asphalt fatigue model characteristics

Material	**Characteristic**	**40-60**	**MR 6**
SMA 10	k	0.005889	0.006013
	b	5	5
DGM 20	k	0.004067	0.004422
	b	5	5

For the granular pavement materials, in all cases:

- The subgrade was characterised by a modulus value equal to ten times the CBR, in this case 60 MPa for CBR 6, and a Poisson ratio of 0.45.
- The crushed rock base course was sub-layered automatically by Circly, with a maximum modulus of 800 MPa, representing a typical granular base course with CBR 80.
- The gravel sub-base was sub-layered automatically by Circly, with a maximum modulus of 300 MPa, representing a typical granular base course with CBR 30.

Pavement analysis

The benefits associated with recycled plastic modification of asphalt mixtures was quantified in two ways. Initially, the reduction in pavement thickness to achieve the same theoretical structural design life was determined. Subsequently, the extension to the theoretical structural design life was calculated for a pavement structure that was retained at the originally required thickness.

The results of the pavement thickness determination are in **Table 5**. In all cases the fatigue life of the asphalt layer governed the pavement thickness rather than the rutting of the subgrade. For the local road, that was fatigue of the SMA 10 surface, while for the highway pavement, the DGM 20 base layer fatigue governed.

Table 5: Summary of pavement thicknesses and allowable repetitions

Scenario and parameter	Without recycled plastic	With recycled plastic
Local road pavement thickness for 5,000,000 load repetitions	436 mm	427 mm
Highway pavement thickness for 5,000,000 load repetitions	359 mm	300 mm
Local road allowable load repetitions for 436 mm thick pavement	5,000,000	6,068,000
Local road allowable load repetitions for 359 mm thick pavement	5,000,000	44,642,000

To allow the sensitivity of the reduced pavement thickness and/or potential structural life extension to the design scenario, alternate subgrade CBR conditions and traffic repetitions were considered. A higher (CBR 10) and lower (CBR 3) subgrade were considered, as well as lower (1,000,000) and higher (10,000,000) equivalent standard axle load repetitions. The results are summarised in **Table 6**. In all cases, fatigue of the lower asphalt layer governed the design thickness. For high subgrade support (CBR 10) and low load repetitions (1,000,000 standard axles) the designed layer thickness was less than the minimum 50 mm allowed by Circly, and these cases were omitted from further analysis.

Table 5: Summary of pavement thicknesses and allowable repetitions

Design scenario	Parameter	Highway pavement		Local road pavement	
		No plastic	With plastic	No plastic	With plastic
CBR 3 subgrade and 1,000,000 loads	Thickness	141 mm	87 mm	506	474
	Life	1.0 M	11.1 M	1.0 M	1.9 M
CBR 3 subgrade and 5,000,000 loads	Thickness	186 mm	121 mm	554	551
	Life	5.0 M	50.0 M	5.0 M	1.1 M
CBR 3 subgrade and 10,000,000 loads	Thickness	208 mm	141 mm	570	580
	Life	10 M	90.9 M	10 M	0.8 M
CBR 6 subgrade and 1,000,000 loads	Thickness	316	267 mm	386 mm	347 mm
	Life	1.0 M	10.0 M	1.0 M	2.1 M
CBR 6 subgrade and 10,000,000 loads	Thickness	380 mm	316 mm	455 mm	458 mm
	Life	10 M	83.3 M	10 M	10 M
CBR 10 subgrade and 1,000,000 loads	Thickness	N/A	N/A	N/A	N/A
	Life	N/A	N/A	N/A	N/A
CBR 10 subgrade and 5,000,000 loads	Thickness	334	281	349 mm	334 mm
	Life	5.0 M	41.7 M	5.0 M	6.9 M
CBR 10 subgrade and 10,000,000 loads	Thickness	355	296	368 mm	365 mm
	Life	10 M	76.9 M	10 M	10.6 M

N/A indicates design scenarios where the designed layer thickness was less than 50 mm.

Discussion

Recycled plastic modification of bituminous binder in asphalt mixtures increased the mixture stiffness by 49% and 196%, for DGM 20 and SMA 10, respectively. This increase in stiffness was consistent with the 35-58% reduction in wheel track rutting (10,000 passes at 60°C) depth reported elsewhere [7] and reproduced in **Figure 5**. Similarly, the 11% (SMA 10) and 52% (DGM 20) increase in fatigue life was consistent with the 7-18% improvement in asphalt fracture toughness, also reported elsewhere [7] and reproduced in **Figure 6**.

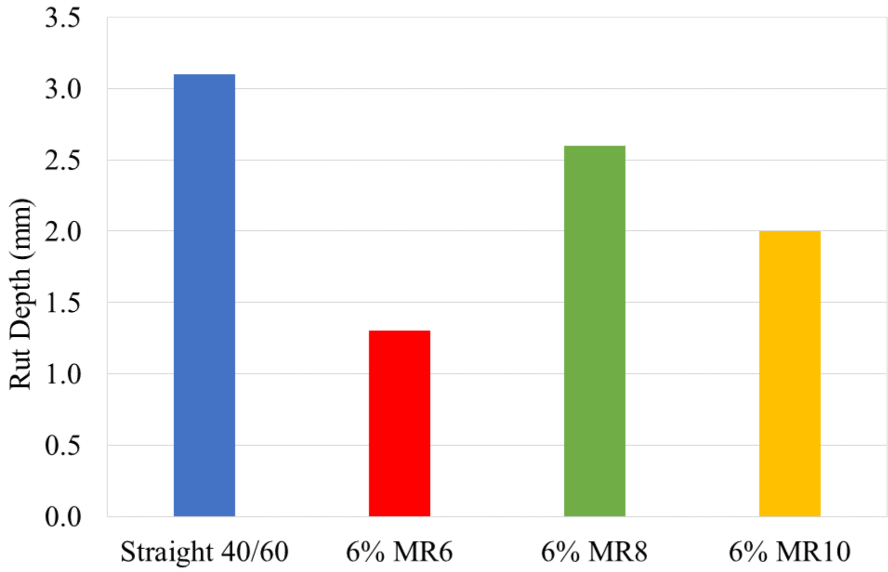


Figure 5. Effect of recycled plastic on asphalt wheel tracking rut depth.

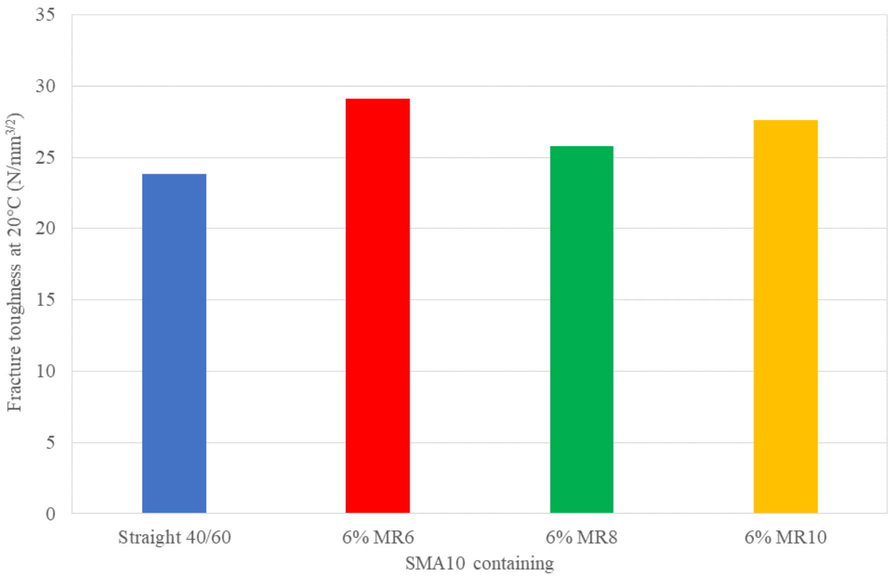
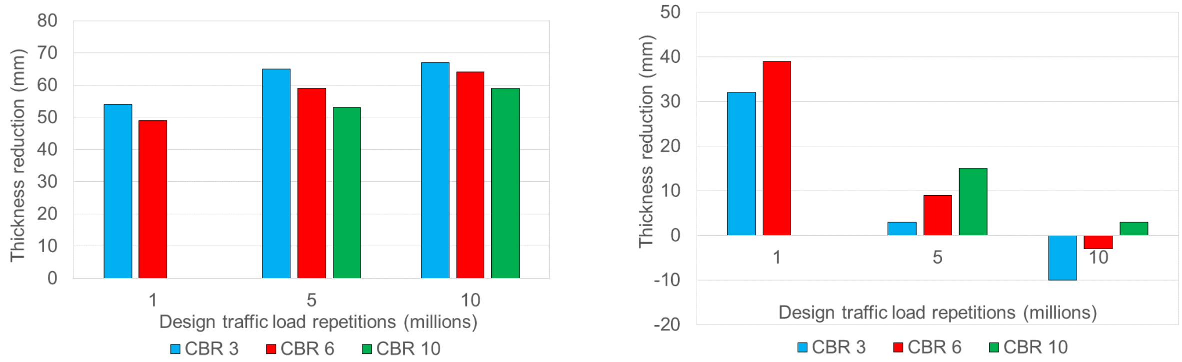


Figure 6. Effect of recycled plastic on asphalt fracture toughness.

For pavements designed for 5,000,000 equivalent standard axle repetitions on a typical CBR 6 subgrade, the local road with recycled plastic was a modest 9 mm thinner. When the local road pavement with recycled plastic was retained at the original (without recycled plastic) design thickness, the pavement with recycled plastic was determined to be suitable for 6.1 M load repetitions. That is, a pavement life increase factor of 1.2, or a 20% increase in pavement life. The effect of recycled plastic on pavement thickness and/or life was more significant for the highway pavement, reflecting the greater thickness of asphalt, which magnified the effect of the improved asphalt performance properties associated with recycled plastic modification. For the highway pavement, a total thickness reduction of 59 mm was determined and when the recycled plastic modified highway pavement was retained at the original thickness, the pavement was determined to capable of enduring 9.1 times more load repetitions than the pavement without recycled plastic.

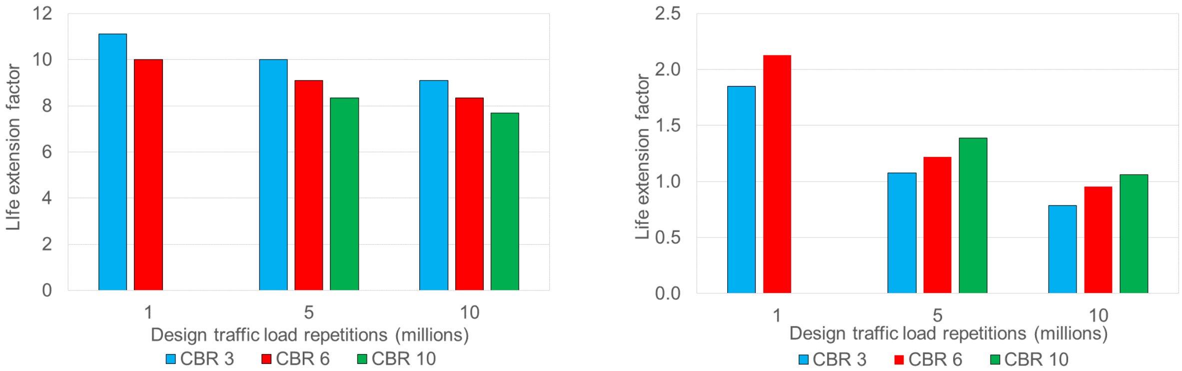
Varying the subgrade condition and the design load repetitions also had a significant affect on the relationship between strength and/or structural life of pavements with and without recycled plastic. For the highway pavement, the reduction in total pavement thickness associated with recycled plastic modified asphalt was 59 mm (**Figure 7a**) which is approximately 16% of the average total pavement thickness. However, for the local roads, the average reduction in pavement thickness was just 11 mm or approximately 3% (**Figure 7b**). Furthermore, for high load repetitions (10,000,000) on weaker (CBR 3 and CBR 6) subgrades, the pavements with recycled plastic modified asphalt were actually thicker than the equivalent unmodified asphalt pavements. This reflects anomalies in the granular base and sub-base sub-layering protocols embedded within Circly. Slight differences in pavements can result in different numbers of sub-layers and sub-layer modulus values in the granular materials, resulting in slightly thicker pavements for materials which are actually stiffer and better performing than the alternates. This is one limitation of layered elastic analysis, compared to finite element analysis, where a continuous stress-dependent modulus value is usually assigned to granular layers. However, the practical importance of this anomaly is limited as a local road is unlikely to be designed to accommodate 10,000,000 equivalent standard axles, which are intended to represent truck loadings, regardless of the subgrade condition.



(a) (b)

Figure 7. Pavement thickness reduction for (a) highway and (b) local road

When the pavement with recycled plastic modified asphalt was retained at the thickness associated with the unmodified asphalt, for the same subgrade CBR and load repetitions, the extension to structural pavement was determined (**Figure 7**). For the highway pavement, the extra pavement thickness resulted in a 7 to 11 fold increase in predicted structural pavement life (**Figure 8a**) with an average life extension of nine times the design load repetitions. The lower pavement thickness reductions associated with recycled plastic modified asphalt for local roads meant the equivalent pavement life extension was only 1.1 to 2.1 fold, for 1,000,000 and 5,000,000 equivalent standard axle repetitions (**Figure 8b**). For the high load repetitions and lower CBR design cases, the life extension factor was 0.8 to 1.0, which is a life reduction, consistent with the increase in thickness required for the pavements with recycled plastic modified asphalt. Again, this is of little practical importance given the unlikeliness of a local road structure being used for such high load repetitions of heavy vehicles.



(a) (b)

Figure 8. Pavement life extension for (a) highway and (b) local road

The overall effect of recycled waste plastic modification on flexible pavement thickness and/or life is illustrated in **Figure 9**. The effect on pavement thickness was linear and highly correlated (R^2 = 0.95) across all subgrade conditions, all traffic loadings and both the highway and local road pavements. In contrast, the correlation was much lower (R^2 = 0.27) for pavement life because of the difference between the thin asphalt surfacing of the local road and near full-depth asphalt thickness associated with the highway pavement. However, when the life extension for the local roads and highway pavements were considered separately, the correlations were high (R^2 = 0.97 for highways and 0.91 for local roads).

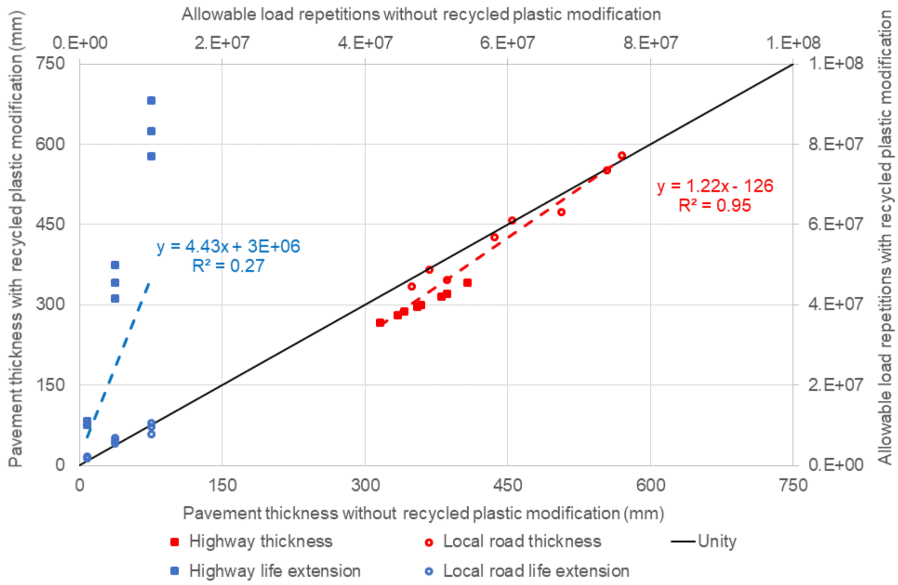


Figure 9. Overall effect of recycled plastic modification on pavement thickness and life

Conclusions

Recycled plastic modification of bituminous binder for asphalt production resulted in a significant improvement in the fatigue life of the asphalt mixtures, as well as an increase in the stiffness of modulus, measured by common UK laboratory test methods. When the improved asphalt properties were used in layered elastic pavement design, the required pavement thickness reduced for the same traffic loadings, and the expected structural life of the pavement increased, when the unmodified pavement thickness was retained. It is recommended that UK and other pavement owners consider recycled plastic modification of asphalt for improved asphalt performance and more efficient pavement structures. However, the life extending benefits of recycled plastic modification quantified by this research were restricted to the structural or design life of the pavement structures. The conclusions do not imply that the expected life of the asphalt surface will also increase, because other factors impact asphalt surface life and resurfacing is often triggered by non-structural defects.

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