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# Laboratory Evaluation of Asphalt Containing Recycled Plastic as a Bitumen Extender and Modifier

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**Abstract:** Recent interest in recycling and reuse of waste plastic has resulted in a dramatic increase in the evaluation of waste plastic as an extender and/or modifier of bituminous binder for asphalt production. Although significant field trials of waste plastic modified asphalt have been reported in Australia since 2017, no laboratory evaluation of the effects of these products on the engineering properties of binder and asphalt has been published. In this research, two commercially available recycled waste plastic products were evaluated in the laboratory. One product is intended to be plastomeric while the other is intended to be elastomeric in nature. Compared to unmodified viscosity grade bitumen and acid modified multigrade, the recycled plastic products increased the viscosity and softening temperature of the binder and introduced significant elastic recovery. Following dry-mixing into asphalt, the recycled plastic products were associated with improved mixture deformation resistance and increased mixture stiffness. However, the mixtures containing recycled plastic were also associated with an increase in moisture susceptibility and their fatigue lives were not significantly different to those of the control mixtures. Further research is recommended to better understand the modest reduction in moisture damage resistance associated with recycled plastic, as well as the digestion of recycled plastic via the dry-mixing process.

**Key words:** Asphalt, plastic, extender, modifier.

## 1. Introduction

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

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

This paper evaluates asphalt containing commercially available recycled plastic products as bituminous binder modifiers. Binder and asphalt properties intended to be indicators of relative asphalt field performance are compared for asphalt containing

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recycled plastic and otherwise nominally identical control mixtures. Samples containing two different recycled plastic products, one intended to be elastomeric and one intended to be plastomeric, are compared to samples produced with a conventional (unmodified) and acid modified binder commonly used in Brisbane, Australia. The change in binder and asphalt properties was considered, as well as how the change in binder properties was reflected in the otherwise nominally identical asphalt samples. Although the materials and test methods are necessarily Australian, the products evaluated are available globally and the findings are generally applicable to all jurisdictions.

## 2. Background

### *2.1 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 [14]. Typically, 10-20% RAP is incorporated, with higher RAP percentages also considered when RAP is available in greater quantities [15].

In more recent times, other recycled materials have been incorporated into asphalt mixtures. Waste printer toner [16], crushed (gullet) glass [17], incinerator waste, municipal waste refuse and coal mine overburden [18] have all been reported. In general, there is a desire to increase recycled material use in asphalt mixtures, as long as performance is not adversely impacted [19].

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 provide many benefits, but also mean that waste plastic remains in the environment for hundreds of years [8] creating an increasing environmental challenge. Furthermore, the toxic chemicals within many plastics are bio-cumulative, presenting a health and safety risk throughout the food chain, including humans.

Two of the main sources of waste plastic in the environment are plastic drink bottles and single-use plastic bags [1]. However, plastic bags are made from high density polyethylene (HDPE) and plastic bottles are manufactured from polyethylene terephthalate (PET). PET has a melting point of around 260 °C and HDPE has a melting point of up to 270 °C, which are both higher than typical bituminous binder and asphalt production and storage temperatures. Consequently, PET and some HDPE cannot 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 low melt-temperature recycled plastics, which are also known as “soft plastics”.

### *2.2 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 [11]. For example, Vancouver (Canada) incorporated plastic crate waste as a warm mixed asphalt wax additive in 2012 [20] and Rotterdam (The Netherlands) announced a plan to produce recycled plastic segments in a factory for road construction in 2015 [21]. Also, Janshedpur (India) reported reducing bitumen usage by 7% by dry-mixing shredded recycled plastic into asphalt production [22]. More recently, a New Zealand asphalt contractor added shredded 4 L engine oil containers to asphalt at Christchurch Airport [23] and an independent asphalt producer includes recycled plastic as 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 [24], Sydney [25] and Adelaide [26]. Meanwhile in the United Kingdom, Cumbria

Council was recently awarded a £1.6 M grant by Department of Transport (UK) to extend its already significant use of recycled plastics in asphalt for road construction [27].

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 (e.g. plastic drink bottles) depolymerised the PET with acids and glycols and the residual was chemically recycled [10, 28]. 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. [29] 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. [30] 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 [30]. 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 [9] shredded and ground low and high density polyethylene, as well as polypropylene, and wet mixed the recycled plastic products into bitumen prior to asphalt manufacture in the laboratory. The viscosity of the binder increased, as did the Performance Grading (PG) [31] of 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 [9]. Acrylonitrile butadiene styrene (ABS) also melts at lower temperatures and was wet and dry mixed at 4-12% of the binder content, into otherwise similar asphalt mixtures [32]. 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 [32]. 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 [11] 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 has been reported in Australia, despite field trials in Brisbane, Sydney, Melbourne and Adelaide. Consequently, there is a need for an objective comparison of the practically implementable recycled plastic modifiers for asphalt production, using Australian materials and Australian test methods, with common Australian asphalt mixtures used as the control for relative performance evaluation.

## 3. Methods

Binder and asphalt samples were tested in the laboratory and the results were compared for samples with recycled plastic to those without. The results were analysed using simple statistical methods, including mean, standard deviation and variability. For properties with more than three replicate results, box and whisker plots and two-tailed student *t*-tests for differences of means were used. *P*-values are reported for *t*-tests, with a *p*-value of 0.05 or less indicating a significant difference between the results for samples with and without recycled plastic.

### *3.1 Asphalt Mixtures*

Typical 14 mm maximum sized dense graded asphalt for road pavement surfacing (Table 1) was produced with four different binders. The mixture is specified by Brisbane City Council and is locally known as BCC Type 3 [33]. The four binders were:

- C320. A conventional (unmodified) bitumen graded and primarily controlled by viscosity at 60 °C and similar to 50/70 penetration grade bitumen [34]. C320 is a common bitumen for asphalt production for local road surfacing in Australia.
- M1000. A multi-grade binder commonly produced in Australia by the addition of poly phosphoric acid forming chemicals [35]. M1000 is commonly used by Brisbane City Council for its high temperature performance and from 2006 to 2014 was the primary binder for airport asphalt surfacing of Australian airport pavements [36].
- MR 6. Conventional (unmodified) C320 bitumen, similar to 50/70 penetration bitumen [34] with 6% (by mass) of the recycled plastic product known as MR 6 [12]. MR 6 is intended to be plastomeric in nature, producing asphalt with a high stiffness and resistance to deformation [1].
- MR 10. Conventional (unmodified) C320 bitumen, similar to 50/70 penetration bitumen, with 6% (by mass) of the recycled plastic product known as MR 10 [12]. MR 10 is intended to be elastomeric in nature, producing asphalt with a high fracture resistance [1], although it has been found to produce asphalt that is more plastomeric in nature [11].

The asphalt was produced in Brisbane City Council's batch plant located at Riverview in western Brisbane. The recycled plastic products were incorporated by pre-weighed quantities added to the mixing bowl at the same time as the aggregate and bitumen. The asphalt was manufactured at 170-180 °C, as is normal practice for Brisbane City Council. 150 kg of each asphalt mixture was sampled, cooled and returned to the laboratory where it was reheated and specimens were produced for testing.

**Table 1 Asphalt mixture properties.**

| Property | Target value |
|---|---|
| Binder content (by mass) | 4.9% |
| Maximum density | 2,502 kg/m$^3$ |
| Combined aggregate grading (percentage passing the sieve (mm)) | |
| 19 | 100 |
| 13.2 | 98 |
| 9.5 | 81 |
| 6.7 | 65 |
| 4.75 | 53 |
| 2.36 | 39 |
| 1.18 | 30 |
| 0.6 | 23 |
| 0.3 | 16 |
| 0.15 | 8.2 |
| 0.075 | 6.1 |

Each asphalt sample was tested in the laboratory for index and performance-indicative properties, using local methods equivalent to national test methods (Table 2). Different numbers of replicate samples were prepared and tested for the different properties:

- Eight replicates of basic volumetrics, Marshall properties and resilient modulus.
- Four replicates of fatigue life.
- Two replicates of wheel track rutting.
- Three unconditioned and three conditioned replicates for indirect tensile strength.

In addition, flexural (complex) dynamic modulus testing was performed at different temperatures and different sinusoidal loading frequency (Table 3) from which flexural modulus master curves were generated.

*3.2 Bituminous Binders*

A sample of unmodified C170, comparable to 80-100 penetration bitumen [34] and commonly used for modified binder production, was sub-sampled and sub-samples were modified by the additional of 6% (by mass) of the two recycled plastic products. The samples were prepared by heating the C170 to 170 °C, adding the required mass of recycled plastic and mixing in a Silverson laboratory high-sheer mixer for 30 seconds, followed by immediate testing. An unmodified (control) sample of C170 was also retained. Each binder sample was tested for standard Australian asphalt binder production properties including [37]:

- Viscosity at 60 °C. AS 2341.2. An indication of resistance to viscous flow and deformation at upper in-service temperatures.
- Softening point. AG:PT/T131. An indication of relative temperature susceptibility.
- Torsional recovery at 25 °C. AG:PT/T122. An indication of the elasticity of the binder and fracture resistance in the intermediate temperature range.

## 4. Results

The bituminous binder test results are in Table A1. The Marshall test results for the asphalt mixtures are in Table A2 while the performance-indicating asphalt mixture test results are in Table A3. Finally, Table A4 contains the complex modulus test results for the asphalt mixtures.

**Table 2 Asphalt test methods.**

| Property | Method | Description |
|---|---|---|
| Marshall air voids | AS/NZS 2891.5 | Air void content measured on a sample compacted by 50 blows of a standard Marshall hammer |
| Marshall stability | AS/NZS 2891.5 | Stability measured on a sample compacted by 50 blows of a standard Marshall hammer |
| Marshall flow | AS/NZS 2891.5 | Flow measured on a sample compacted by 50 blows of a standard Marshall hammer |
| Wheel tracking | AG:PT/T231 | Copper's wheel tracker to 10,000 passes at 50 °C, an indicator of relative deformation resistance at high in-service temperatures |
| Fatigue life | AG:PT/T274 | Four-point bending at 20 °C and 200 με sinusoidal, an indicator of relative fracture resistance at intermediate in-service temperatures |
| Tensile strength ratio | AG:PT/T232 | Modified Lottman test, an indicator of moisture damage (stripping) resistance |
| Resilient modulus | AS 2891.13.1 | Indirect tensile modulus at 25 °C, an indicator of relative material stiffness |
| Complex modulus | AG:PT/T274 | Flexural modulus from four-point beam bending, an indicator of relative materials stiffness over a range of temperatures and load frequencies, and for characterisation of mixtures for thickness design via modulus master curves |

**Table 3 Flexural modulus test parameters.**

| Parameter | Levels | Units |
|---|---|---|
| Load frequency | 0.1, 0.5, 1, 3, 5, 10, 15, 20 | Hz |
| Test temperature | 5, 15, 25, 30 | °C |

## 5. Discussion

### *5.1 Effect on Bituminous Binder*

As discussed above, Australia uses, amongst other properties, viscosity, softening point and torsional recovery as modified binder production control properties. Although these properties are not intended to be directly indicative of field performance, they do provide an indication of the type and level of modification.

MR 6 and MR 10 increased the viscosity at 60 °C of the binder to a level comparable to that of C320 (Fig. 1) which is one of the commonly used unmodified binders in Australian asphalt production. That is, the addition of 6% recycled plastic increased the viscosity at a typical upper in-service temperature to approximately that of a common binder. M1000 has a much higher viscosity at 60 °C, which is the intention of this multigrade product.

MR 6 significantly increased the softening point of the binder, much higher than either C320 or M1000 (Fig. 2). That is, one recycled plastic product produced binder with much lower temperature susceptibility than that associated with C320 and M1000 binders commonly used. Interestingly, MR 10 did not result in the same level of softening point increase, with a result comparable to C320 and M1000.

Both C320 and M1000 have negligible torsional recovery at 25 °C (Fig. 3) which is an indication of elasticity and crack resistance at lower typical in-service temperatures. The addition of MR 6 introduced modest torsional recovery (10%) while MR 10 introduced higher torsional recovery (22%). The difference between the MR 6 result and MR 10 result reflects the intention that MR 6 is a plastomeric modifier while MR 10 is intended to be an elastomeric modifier. These results are comparable to results associated with conventional plastomeric binders, such as the Australian A35P (EVA based) and some hybrid proprietary binders used for Australian airport asphalt production, but not as elastomeric as the conventional elastomeric polymer modified binders commonly used in Australia, such as A10E (SBS based) [36].

The addition of recycled plastic to conventional bitumen produced binders with comparable or higher viscosity, significantly increased softening point and moderate torsional recovery, to other asphalt binders used locally. This is consistent with the evaluation of

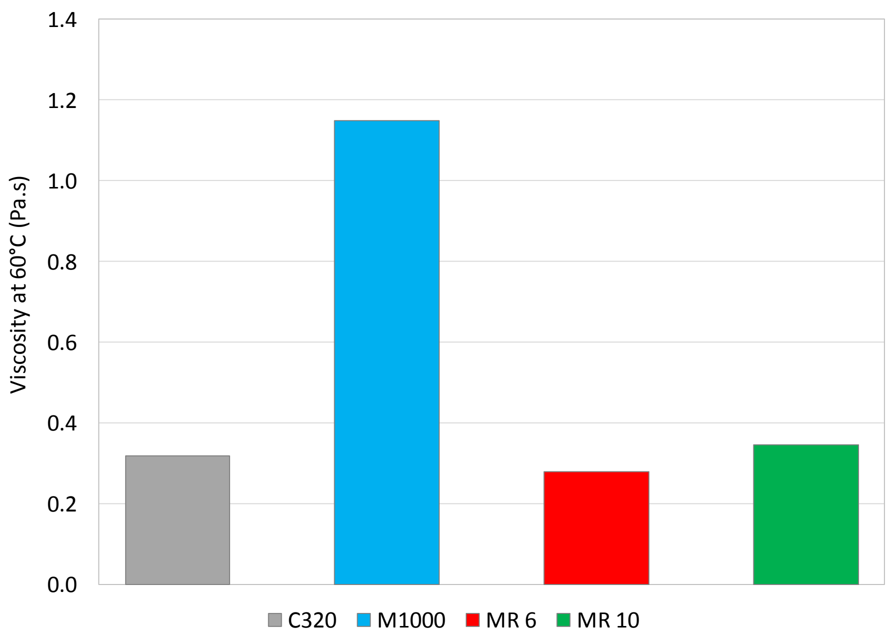


**Fig. 1 Effect of recycled plastic products on binder viscosity.**

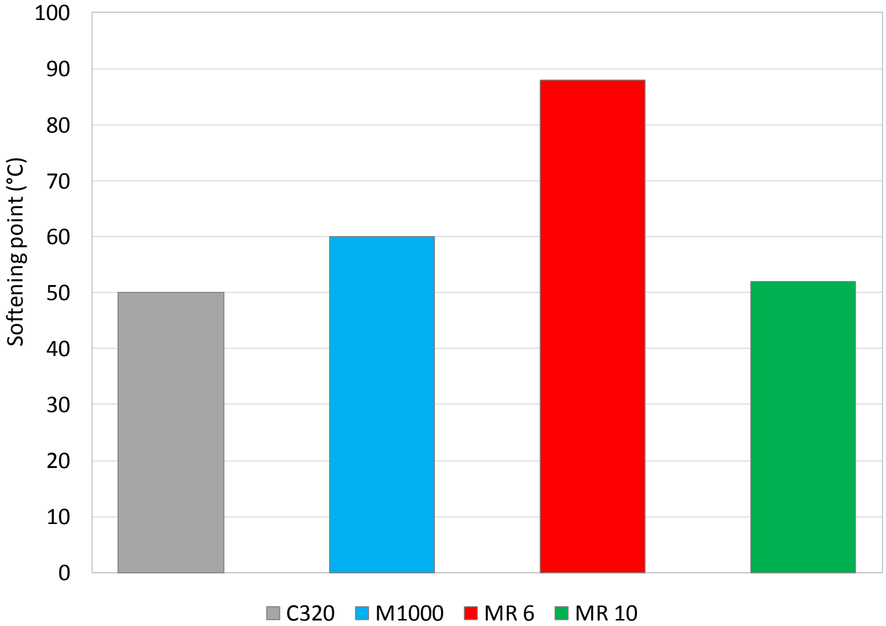


**Fig. 2 Effect of recycled plastic products on binder softening point.**

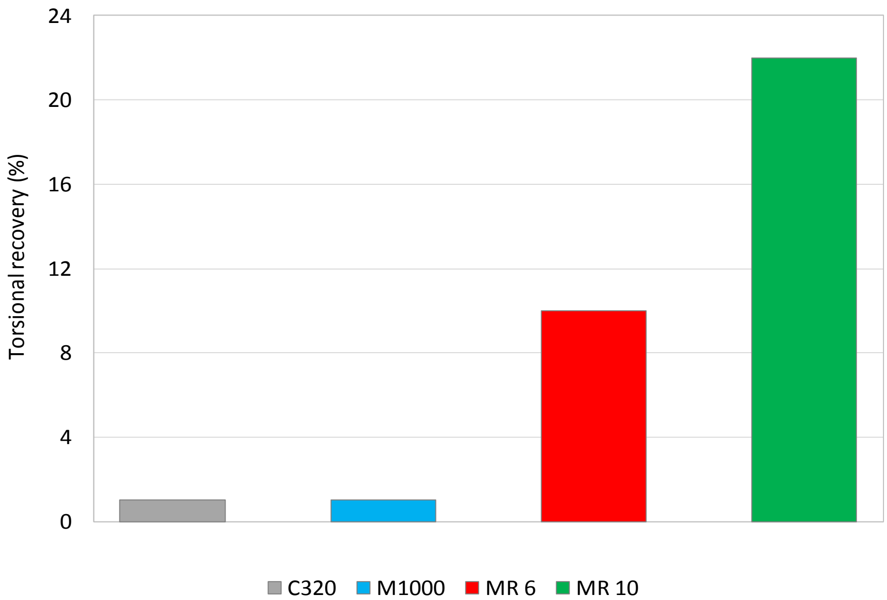


**Fig. 3 Effect of recycled plastic products on binder torsional recovery.**

the same recycled plastic products using Multiple Stress Creep Recovery and G*/sin(δ) PG rating [13]. It is expected that these binder property changes will result in improved asphalt performance properties.

*5.2 Consistence of Mixtures*

Because the asphalt mixtures were produced from the same aggregates and with the same target volumetric composition, the effect of the recycled plastic modified binder was isolated. The production consistence was first evaluated by the variability across the eight replicates of each of the Marshall properties and resilient modulus (Table 4). The coefficients of variation were all comparable, regardless of the binder type, indicating the generally consistent distribution of the recycled plastic products through the produced asphalt mixture.

During fatigue beam preparation, one semi-digested MR 10 pellet was observed in the mixture, along a sawn asphalt beam face (Fig. 4). No un-digested or semi-digested pellets were identified in any other samples and this may have been an anomaly. Certainly, it did not reflect a mixture production inconsistence, which would be identifiable in the CoV values of the recycled plastic mixture results (Table 4). However, digestion and distribution of recycled plastic products through the asphalt mixture is an important issue for their practical acceptance and is worthy of further investigation.

### *5.3 Effect on Mixture Marshall Properties*

Under the standard compactive effort of the Marshall hammer, the recycled plastic modified binders produced slightly lower air voids contents (Fig. 5). The differences were significant (both $p$-values < 0.01) indicating improved workability at asphalt paving and production temperatures.

MR 6 modification resulted in a Marshall stability significantly higher than C320 ($p$-value < 0.01) and comparable to M1000 ($p$-value 0.77) (Fig. 6). The stability results associated with MR 10 modification were also significantly higher than for C320 but not as high as M1000 (both $p$-values < 0.01). The effect of MR 6 was significantly greater than the effect of MR 10, which reflects the plastomeric nature of MR 6, the more elastomeric nature of MR 10, in combination with the relationship between mixture Marshall stability and binder stiffness.

In contrast to the Marshall stability, the Marshall flow values were not significantly affected by recycled plastic binder modification (Fig. 7) with $p$-values for comparison to C320 of 0.21 (for M1000), 0.61 (MR 6) and 0.39 (for MR 10). This likely reflects the influence of the aggregate skeleton on asphalt resistance to deformation, as well as the inherently higher variability associated with the Marshall flow test than the Marshall stability test (Table 4).

**Table 4 Mixture property coefficients of variation (eight replicates).**

| Property | C320 | M1000 | MR 6 | MR 10 |
|---|---|---|---|---|
| Air voids (%) | 5.5% | 7.0% | 7.6% | 8.0% |
| Stability (kN) | 7.9% | 11.1% | 9.4% | 6.2% |
| Flow (mm) | 12.3% | 15.3% | 15.4% | 11.9% |
| Resilient modulus (MPa) | 6.0% | 4.1% | 5.9% | 4.2% |

**Fig. 4 Semi-digested MR 10 pellet in fatigue beam (highlighted by yellow circle).**

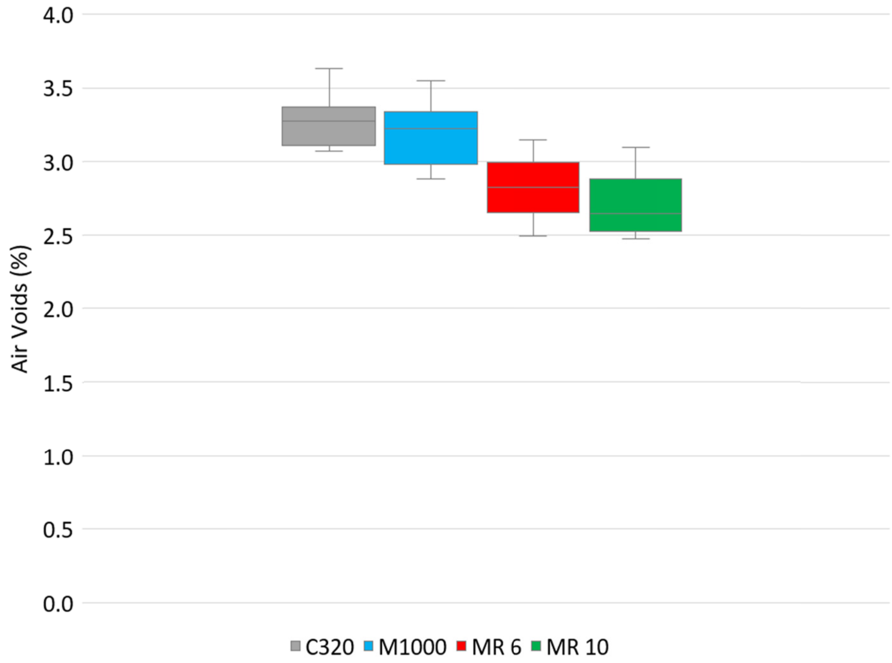


**Fig. 5 Effect of recycled plastic on mixture Marshall air voids.**

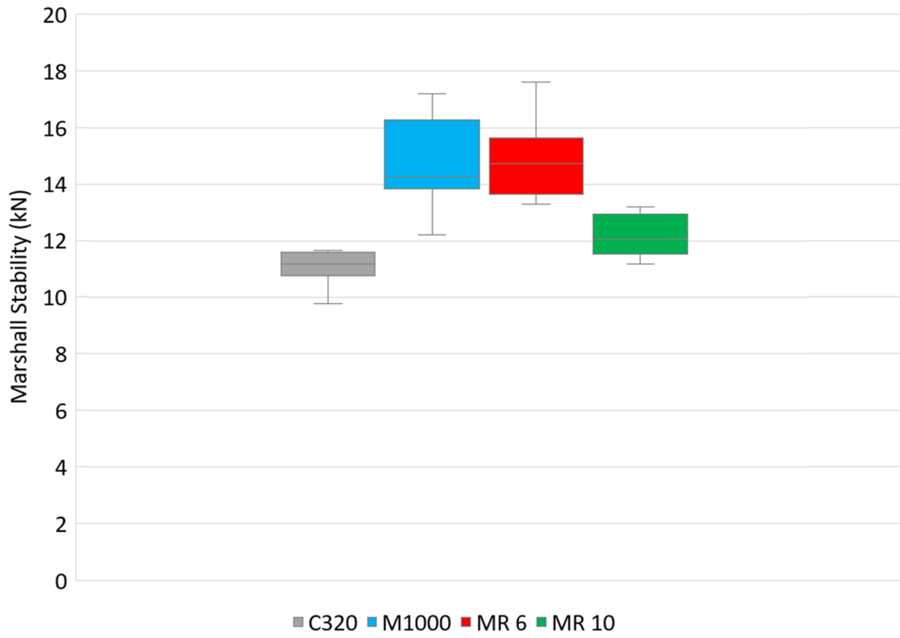


**Fig. 6 Effect of recycled plastic on mixture Marshall stability.**

Overall, the recycled plastic increased the mixture Marshall stability but did not significantly affect the Marshall flow. The Marshall air voids also reduced for samples containing recycled plastic. This is similar to results reported by White [11] on the same products compared to unmodified penetration grade bitumen in the UK, using British test methods. Although mixture Marshall properties are not directly indicative of field performance, higher stability, lower flow and lower air voids are generally associated with better asphalt performance [38]. Consequently, it is expected that the recycled plastic modified mixtures will exhibit improved mixture performance properties.

*5.4 Effect on Mixture Performance Properties*

All modified mixtures had a lower TSR (tensile strength ratio) than the C320 mixture (Fig. 8) indicating an increased susceptibility to moisture damage, also known as stripping. Although the test is recognised as being associated with highly variable results, the TSR values for MR 6 (60%) and MR 10 (68%) are below the 80% generally accepted as representing a low risk of asphalt mixture damage and are worthy of further consideration. It is possible that these results are an anomaly. However, further research is recommended to better understand this.

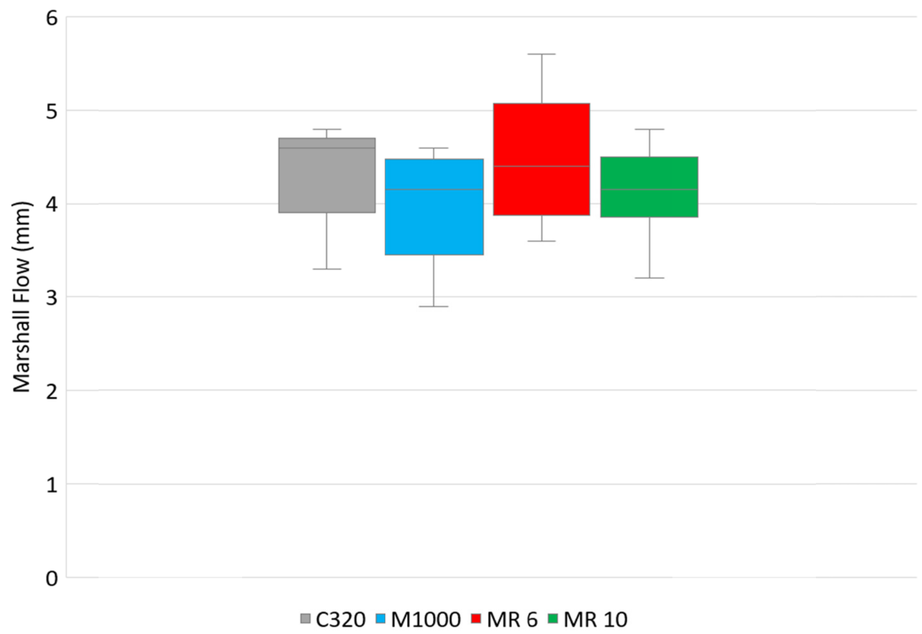


**Fig. 7 Effect of recycled plastic on mixture Marshall flow.**

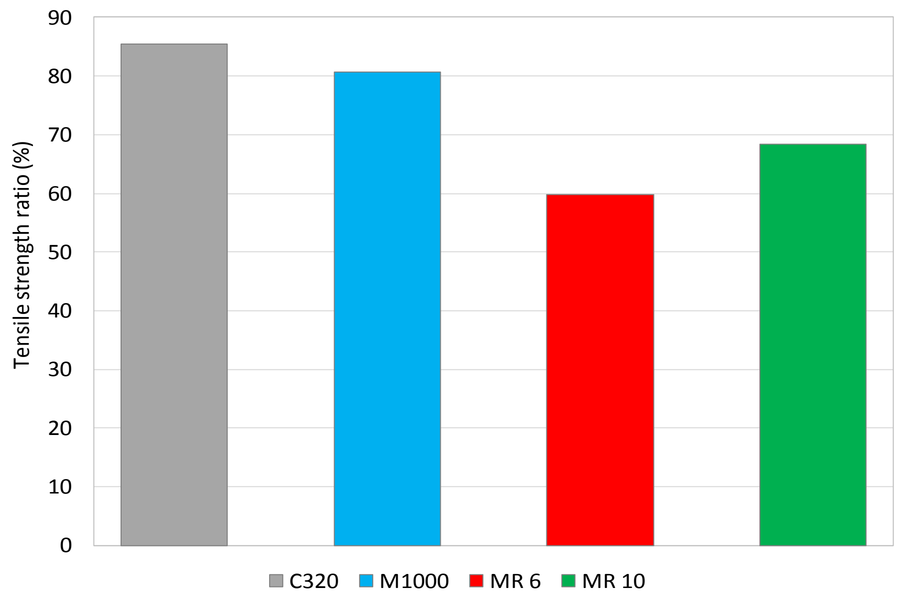


**Fig. 8 Effect of recycled plastic on mixture TSR.**

Recycled plastic modification reduced the wheel track rutting of the mixtures compared to C320 (Fig. 9). The MR 6 average rut depth (1.0 mm) was less than for M1000 (1.2 mm) while the MR 10 rut depth (1.4 mm) was greater than for M1000 but less than for C320 (1.8 mm). These results indicate that recycled plastic improved the mixture deformation resistance, although all mixtures had excellent deformation resistance, which is generally indicated by any result less than 3.5 mm when tested under the standard Australian conditions (60 °C for 10,0000 passes) [39].

On average, the mixtures modified by recycled plastic had a lower fatigue life than the C320 and M1000 samples (Fig. 10). However, fatigue life results are highly variable, with CoV values of 17% for C320, up to 54% for MR 10. Consequently, the differences in fatigue life were not significant, with *p*-values of 0.32 (for MR 6) and 0.67 (for MR 10) compared to C320 and 0.23 (for MR 6) and 0.40 (for MR 10) compared to M1000. This indicates no significant difference to C320 and M1000 fracture resistance associated with recycled plastic modified mixtures.

Overall, waste plastic modification did not significantly affect the fatigue life of the asphalt mixture but did improve the deformation resistance. The moisture resistance results were lower for the mixtures containing recycled plastic and this requires further investigation.

### *5.5 Effect on Mixture Stiffness*

Resilient modulus provides a simple, single temperature, comparison of relative mixture stiffness. The mixtures modified with recycled plastic exhibited much higher modulus values than the C320 and M1000 mixtures (Fig. 11). The differences were significant (all *p*-values < 0.01 compared to both C320 and M1000) indicating a much greater contribution to the structural capacity of pavements. This result is consistent with the findings of White [11] using UK mixtures and British test methods.

Master curves of complex modulus were developed for each mixture from the flexural modulus test results, against reduced frequency (Fig. 12). M1000 and MR 6 showed significantly higher modulus, particularly at

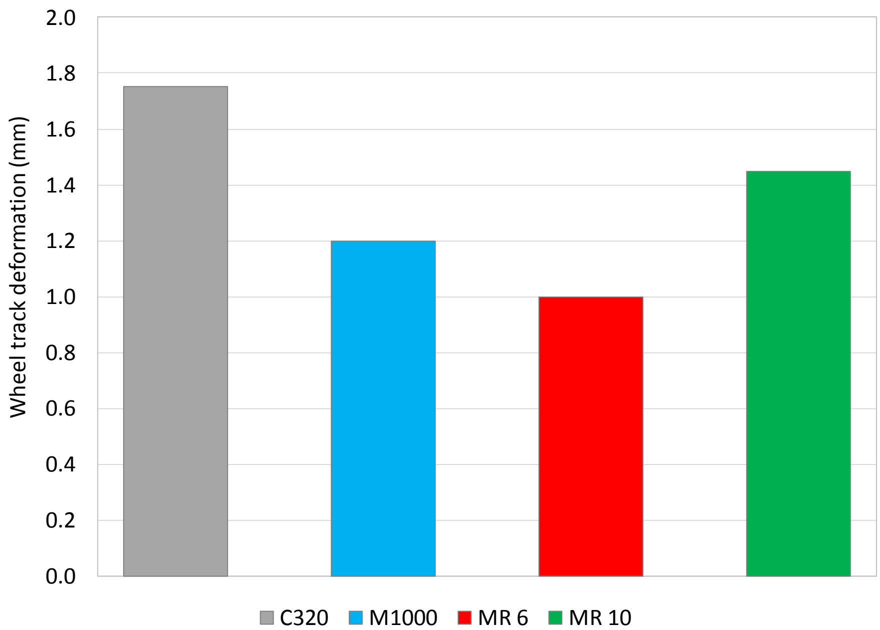


**Fig. 9 Effect of recycled plastic on mixture wheel track rutting.**

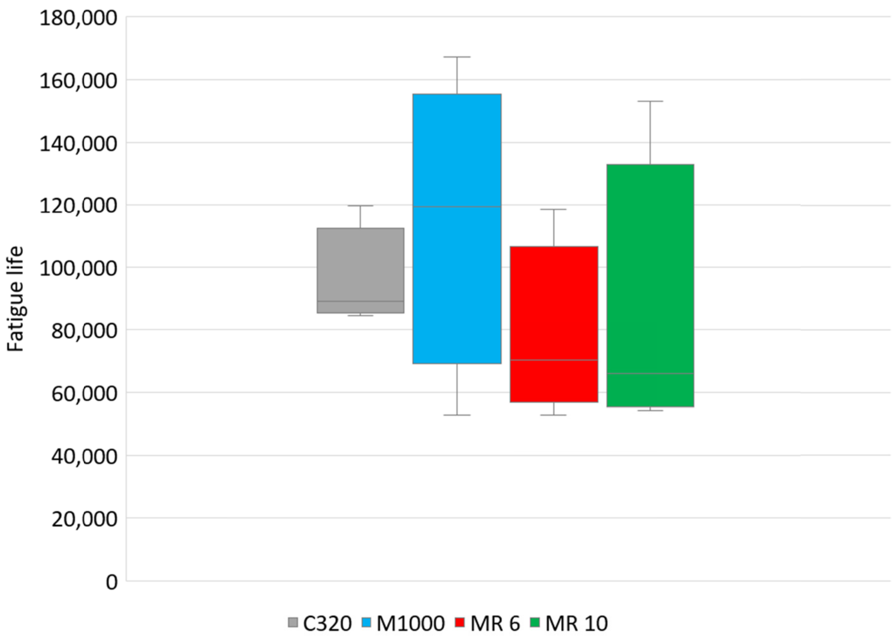


**Fig. 10 Effect of recycled plastic on mixture fatigue life.**

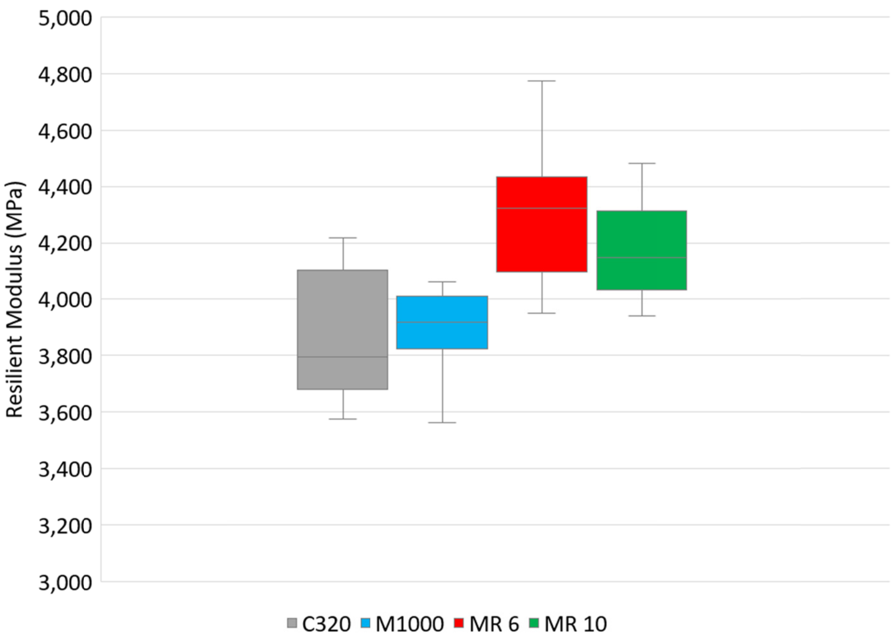


**Fig. 11 Effect of recycled plastic on mixture resilient modulus.**

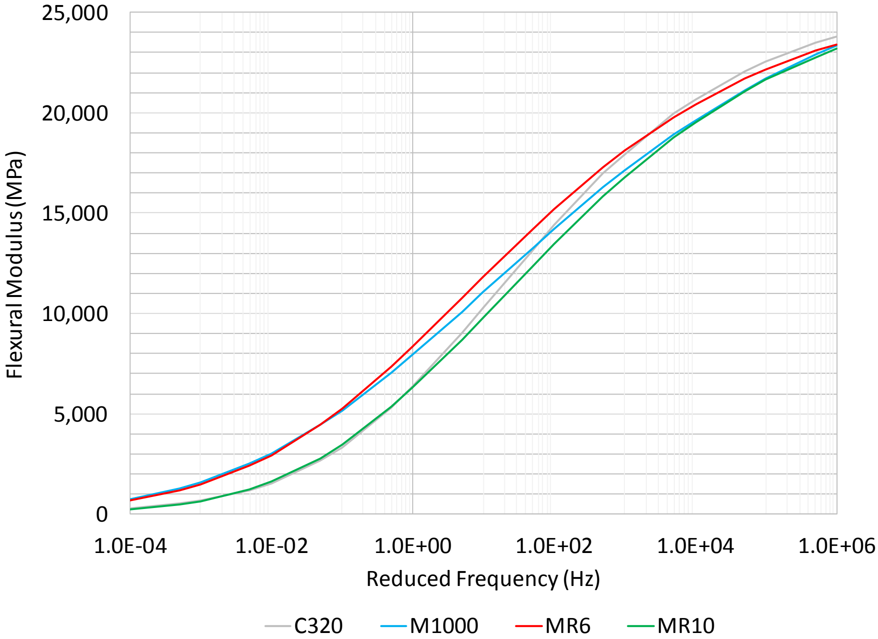


**Fig. 12 Master curves for mixture complex modulus.**

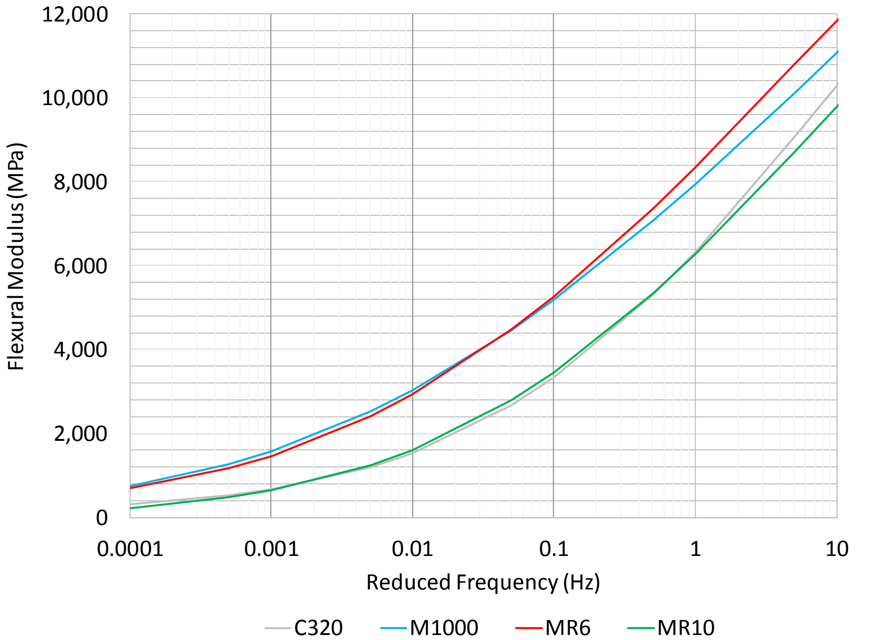


**Fig. 13 Effect of recycled plastic on mixture complex modulus (practical range).**

**Table 5 Summary of recycled plastic effects.**

| Performance property | Basis of effects | MR 6 | MR 10 |
|---|---|---|---|
| Mixture workability | Mixture Marshall air voids | Modest improvement | Modest improvement |
| Deformation resistance | Mixture Marshall flow<br>Mixture wheel tracking<br>Binder viscosity | Significant reduction in wheel track rutting, likely reflecting the increased binder viscosity | Modest reduction in wheel track rutting, likely reflecting the increased binder viscosity |
| Fracture resistance | Mixture fatigue life<br>Binder torsional recovery | No significant change in fatigue life but a modest introduction of torsional recovery | No significant change in fatigue life but a significant introduction of torsional recovery |
| Moisture damage resistance | Mixtures TSR | Reduction to below a TSR result that is considered indicative of good performance | Reduction to below a TSR result that is considered indicative of good performance |
| Structural contribution | Mixture Marshall stability<br>Mixture resilient modulus<br>Mixture complex modulus | Significant increase in stability and resilient modulus and a complex modulus similar to M1000 | Significant increase in stability and resilient modulus and a complex modulus similar to C320 |
| Temperature susceptibility | Mixture softening point | Significant increase in softening point | Modest increase in softening point |

low reduced frequency, which represents high temperature and slow load speeds. In general, MR 6 showed comparable modulus to M1000, while the modulus of MR 10 ranged from comparable to C320 (low reduced frequency) to comparable to greater than all other mixtures (high reduced frequency). Over the practically-important range of modulus (100-10,000 MPa) MR 10 was similar to C320 while MR 6 was comparable to M1000 (Fig. 13).

Modulus testing results indicate that MR 6 increased the mixture modulus in a comparable manner or significantly greater than using M1000, while MR 10 produced a mixture with a complex modulus similar to that of C320, but a resilient modulus significantly greater than both C320 and M1000. Clearly, there were significant differences between the relative effect of recycled plastic on mixture modulus for the resilient and complex modulus test methods. Consequently, further work is required to determine the most appropriate method for characterisation of asphalt modulus for pavement thickness design.

### *5.6 Summary of Effects*

A summary of the effects of recycled plastic on the bituminous binder and asphalt mixture properties is in Table 5. Although there are differences associated with the various performance-indicating properties, MR 6 generally produced asphalt that is comparable with asphalt produced with M1000. MR 10 was associated with binder and mixture properties that are more elastomeric than MR 6 but are significantly less elastomeric than conventional elastomeric binders such as those produced with SBS.

## 6. Conclusion

Recycled plastic had a significant effect on the binder and asphalt properties considered to be indicative of relative asphalt field performance. Binder resistance to viscous flow increased, the temperature susceptibility reduced and elastic recovery was introduced by the introduction of both recycled plastic products. Similarly, asphalt workability, resistance to deformation and structural contribution increased, but the fracture resistance did not change significantly and the moisture damage resistance decreased. The asphalt mixture results indicated no increase in variability associated with recycled plastic modification, indicating a uniform distribution of recycled plastic throughout the asphalt. Overall, MR 6 was considered to produce asphalt with properties similar to M1000 (acid modified multi-grade binder) and with generally better performance than MR 10 modified asphalt binder. Further research is recommended to better understand the observed reduction in moisture damage resistance, as well as the digestion of recycled plastic into the binder via dry mixing processes.

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## Appendix A

**Table A1 Bituminous binder testing results.**

| Property | C320 | M1000 | MR 6 | MR 10 |
|---|---|---|---|---|
| Viscosity at 60 °C (Pa·s) | 0.320 | 1.150 | 0.280 | 0.346 |
| Softening point (°C) | 50 | 60 | 88 | 52 |
| Torsional recovery 25 °C (%) | 1 | 1 | 10 | 22 |

**Table A2 Asphalt mixture Marshall testing results.**

| Property | Replicate results | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| For asphalt with C320 | | | | | | | | |
| Air voids (%) | 3.3 | 3.3 | 3.4 | 3.6 | 3.1 | 3.3 | 3.2 | 3.1 |
| Stability (kN) | 11 | 10.7 | 11.1 | 9.8 | 11.4 | 11.3 | 12.9 | 11.7 |
| Flow (mm) | 3.3 | 4.6 | 4.6 | 4.7 | 4.8 | 3.8 | 4.2 | 4.7 |
| For asphalt with M1000 | | | | | | | | |
| Air voids (%) | 2.9 | 3.3 | 3.0 | 3.0 | 3.4 | 3.2 | 3.2 | 3.5 |
| Stability (kN) | 13.9 | 12.2 | 16.7 | 15.0 | 13.8 | 14.3 | 17.2 | 14.2 |
| Flow (mm) | 4.5 | 2.9 | 4.3 | 3.4 | 4.0 | 4.6 | 4.4 | 3.6 |
| For asphalt with MR 6 | | | | | | | | |
| Air voids (%) | 2.9 | 2.5 | 3.1 | 2.6 | 2.7 | 3.0 | 2.7 | 2.9 |
| Stability (kN) | 14.5 | 13.3 | 13.4 | 14.4 | 14.9 | 15.0 | 17.6 | 15.9 |
| Flow (mm) | 4.6 | 5.1 | 3.8 | 3.6 | 4.1 | 4.2 | 5.0 | 5.6 |
| For asphalt with MR 10 | | | | | | | | |
| Air voids (%) | 3.1 | 2.7 | 2.8 | 2.5 | 2.5 | 2.9 | 2.6 | 2.5 |
| Stability (kN) | 11.2 | 11.9 | 11.6 | 12.2 | 12.8 | 11.5 | 13.0 | 13.2 |
| Flow (mm) | 4.1 | 4.2 | 4.6 | 4.8 | 4.2 | 3.8 | 3.2 | 4.0 |

**Table A3 Asphalt mixture performance testing results.A**

| Property | Replicate results | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| For asphalt with C320 | | | | | | | | |
| Resilient modulus (MPa) | 4,217 | 3,990 | 3,576 | 4,142 | 3,746 | 3,674 | 3,698 | 3,846 |
| Fatigue life (cycles) | 84,780 | 87,690 | 119,690 | 90,670 | | | | |
| Wheel track rut (mm) | 1.8 | 1.7 | | | | | | |
| Indirect tensile strength unconditioned (kN) | 1,441 | 1,460 | 1,440 | | | | | |
| Indirect tensile strength conditioned (kN) | 1,250 | 1,180 | 1,276 | | | | | |
| For asphalt with M1000 | | | | | | | | |
| Resilient modulus (MPa) | 3,880 | 4,011 | 3,563 | 4,061 | 3,819 | 4,006 | 3,835 | 3,958 |
| Fatigue life (cycles) | 118,350 | 120,000 | 52,930 | 167,190 | | | | |
| Wheel track rut (mm) | 1.2 | 1.2 | | | | | | |
| Indirect tensile strength unconditioned (kN) | 1,360 | 1,408 | 1,467 | | | | | |
| Indirect tensile strength conditioned (kN) | 1,116 | 1,098 | 1,202 | | | | | |
| For asphalt with MR 6 | | | | | | | | |
| Resilient modulus (MPa) | 4,775 | 4,310 | 3,950 | 4,280 | 4,038 | 4,333 | 4,343 | 4,465 |
| Fatigue life (cycles) | 118,480 | 52,880 | 69,250 | 71,720 | | | | |
| Wheel track rut (mm) | 1.0 | 1.0 | | | | | | |
| Indirect tensile strength unconditioned (kN) | 1,650 | 1,567 | 1,601 | | | | | |
| Indirect tensile strength conditioned (kN) | 929 | 969 | 979 | | | | | |

(Table A3 continues)

| Property | Replicate results | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| For asphalt with MR 10 | | | | | | | | |
| Resilient modulus (MPa) | 4,170 | 4,481 | 4,082 | 4,278 | 4,017 | 3,940 | 4,323 | 4,123 |
| Fatigue life (cycles) | 54,290 | 152,960 | 72,660 | 59,240 | | | | |
| Wheel track rut (mm) | 1.3 | 1.6 | | | | | | |
| Indirect tensile strength unconditioned (kN) | 1,404 | 1,384 | 1,441 | | | | | |
| Indirect tensile strength conditioned (kN) | 956 | 955 | 981 | | | | | |

**Table A4 Asphalt mixture modulus testing results.**

| Temperature (°C) | Frequency (Hz) | C320 | M1000 | MR 6 | MR 10 |
|---|---|---|---|---|---|
| 5 | 0.1 | 12,110 | 13,400 | 13,452 | 11,589 |
| | 0.5 | 15,021 | 15,502 | 15,906 | 14,004 |
| | 1 | 15,930 | 16,322 | 16,719 | 15,056 |
| | 3 | 17,836 | 17,744 | 18,123 | 16,645 |
| | 5 | 18,623 | 18,360 | 18,754 | 17,391 |
| | 10 | 19,493 | 19,085 | 19,463 | 18,191 |
| | 15 | 19,943 | 19,464 | 19,812 | 18,677 |
| | 20 | 20,480 | 19,936 | 20,091 | 19,171 |
| 15 | 0.1 | 5,609 | 7,485 | 7,737 | 5,591 |
| | 0.5 | 8,322 | 9,629 | 10,184 | 7,990 |
| | 1 | 9,546 | 10,544 | 11,256 | 9,040 |
| | 3 | 11,423 | 12,072 | 12,847 | 10,826 |
| | 5 | 12,420 | 12,816 | 13,685 | 11,727 |
| | 10 | 13,553 | 13,663 | 14,564 | 12,758 |
| | 15 | 14,012 | 13,950 | 15,032 | 13,139 |
| | 20 | 14,539 | 14,420 | 15,559 | 13,527 |
| 25 | 0.1 | 1,921 | 3,484 | 3,368 | 1,986 |
| | 0.5 | 3,199 | 4,978 | 5,074 | 3,274 |
| | 1 | 4,060 | 5,767 | 5,920 | 3,997 |
| | 3 | 5,582 | 7,151 | 7,377 | 5,499 |
| | 5 | 6,315 | 7,854 | 8,235 | 6,165 |
| | 10 | 7,552 | 8,786 | 9,264 | 7,197 |
| | 15 | 7,992 | 9,118 | 9,594 | 7,759 |
| | 20 | 8,331 | 9,436 | 9,882 | 7,974 |
| 30 | 0.1 | 1,166 | 2,288 | 2,121 | 1,308 |
| | 0.5 | 2,051 | 3,386 | 3,291 | 2,073 |
| | 1 | 2,576 | 4,031 | 3,984 | 2,571 |
| | 3 | 3,674 | 5,179 | 5,234 | 3,626 |
| | 5 | 4,325 | 5,827 | 5,912 | 4,141 |
| | 10 | 5,184 | 6,712 | 6,879 | 4,982 |
| | 15 | 5,806 | 7,203 | 7,399 | 5,621 |
| | 20 | 6,085 | 7,383 | 7,570 | 5,785 |