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Impact of Recycled Plastic on Asphalt Binder and Mixture Performance

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16. Abstract

The concept of recycling plastic waste in new plastic products can greatly reduce the dependence of landfill space while conserving resources and protecting the environment. However, recent statistics indicate that only approximately 8% of all plastic waste in the US is actually reused. There is limited recent data on the impact of plastic waste on asphalt binder and mixture performance. A research study was conducted to evaluate the impact of three different plastic waste materials on asphalt binder and mixture performance; Polyolefins, thermoplastics, and co-block plastic polymer. For this study, the wet process of introducing the plastic waste to asphalt was utilized in an effort to minimize the potential for undigested plastic material and micro-plastics. The study indicated that separation of the plastic waste, even after high shear milling, can be problematic at higher dosage rates. While both the polyolefin and co-block plastic waste were found to shift the PG grade properties warmer, the thermoplastic plastic waste showed negligible change in the high temperature grade while slightly improving the low temperature properties. Similar performance trends were found when utilizing rheological and fracture-based asphalt binder testing after different conditioning levels. After showing good asphalt binder performance, the thermoplastic plastic waste was preblended in a PG64-22 asphalt binder and used in mixture performance testing. Compared to a PG64-22 and SBS modified PG76-22, mixture performance testing showed the PW modified mixture had better rutting resistance than the neat PG64-22, while showing equal to better fatigue and low temperature cracking performance. The study indicates that the use of plastic waste in asphalt materials may be viable and actually provide a benefit when compared to unmodified asphalt materials.

17. Key Words

Plastic waste, Wet Process, Asphalt Binder Cracking Device, Performance Grading, Fatigue Cracking, Rutting Resistance

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INTRODUCTION

In 2017, China passed the National Sword Policy which initiated a national movement to better address environmental protection and human health. Once this policy was established, China no longer imported waste plastics from other countries. In fact, up until January 2018 before the National Sword Policy was enacted, China took in approximately 45% of all of the world's waste plastic, estimated at approximately 106 million metric tons annually (Brooks et al, 2018). The 2018 mandate by the Chinese government put the United States and the rest of the world in a tailspin regarding how to manage the ever-growing waste plastic stream. With current estimates showing that only approximately 9% of all of the waste plastic in the United States is actually recycled, with over 80% landfilled, the transportation infrastructure sector was called upon to see if waste plastic could be used in construction materials, in particular, asphalt materials.

After the National Sword Policy was announced, the media reports began generating interest in the possibility of using waste plastic as a means of simultaneously improving the quality of asphalt pavements while helping address the issue of the accumulating plastic waste. The concept of utilizing plastic in asphalt binder and mixtures is not new and has been around for almost fifty (50) years. In an extensive literature review conducted by the National Center for Asphalt Technology (NCAT) under the National Cooperative Highway Research Project (NCHRP) 9-66, *Performance Properties of Laboratory Produced Recycled Plastic Modified (RPM) Asphalt Binders and Mixtures*, it was noted that Europe first began utilizing plastic in asphalt as early as the 1970's (NCAT et al., 2021), where high density polyethylene (HDPE) was used in what was called Gussaphalt for pourable asphaltic mixture applications (Bardesi et al, 1999). In the 1990's, the product Novophalt was developed using a blend of low-density polyethylene (LDPE) and styrene-butadiene-styrene (SBS). The product required a mobile high-shear blending unit on site to ensure separation of the plastic and polymers in the asphalt binder did not occur. Products like Novophalt in the 1990's lost attention to conventional elastomeric polymers, like SBS, due to associated costs and complexities required to implement them at an asphalt plant. There were also concerns regarding their fatigue cracking and durability resistance (NCAT et al., 2021)

With the renewed interest for using waste plastic in asphalt applications, local, state and federal agencies are looking for information regarding the viability of plastic waste materials in asphalt applications and how they can be responsibly used, while not only ensuring that the integrity of the pavement structure is maintained, but also so that plastic issues, such as micro-plastics, are not generated when producing and recycling asphalt pavements with waste plastic.

RESEARCH OBJECTIVES

The objective of the research study was to evaluate the potential for three different waste plastic types to be utilized within asphalt materials using the wet process. The wet process is defined as blending the waste plastic directly into the asphalt binder and digesting the plastic within the liquid in a similar manner to conventional asphalt binder polymer modification. The benefit of utilizing the wet process is that it eliminates the potential for micro-plastics to be generated during the production and construction of the waste plastic modified asphalt mixture. In addition, it reduces the complexities of requiring additional feeding and metering equipment at the asphalt plant to accurately incorporate the waste plastic into the drum plant or pug mill.

The three plastic types evaluated in the study include (Figure 1);

1. Polyolefin (called MR6 in the study);
2. Thermoplastic (called MR8 in the study); and
3. Co-block polymer plastic (called MR10 in the study).

(a) **(b)** **(c)**

Figure 1 – Waste Plastic Materials Evaluated in Study; a) Polyolefin (MR6); b) Thermoplastic (MR8); c) Co-block Polymer Plastic (MR10)

The polyolefin plastic compounds are commonly found in plastic bags, food packaging, electrical cable coating and plastic crates and boxes. The thermoplastic plastic compounds are commonly found in sports equipment, CD/DVD's, car parts and types of drinking bottles. Lastly, the co-block polymer plastic compounds are typically found in PVC tubing and injection molding applications. It should be noted that both the polyolefin (MR6) and thermoplastic (MR8) materials were recently CO_2 Verified under ISO 14064, *International Standard for GHG Emissions Inventories and Verification*. Under ISO 14064, for every one kilogram of MR6 product used, 3.77 kilograms of CO_2 emissions are reduced. The MR8 product showed that for every one kilogram used, 1.55 kilograms of CO_2 emission are reduced. No data was available for the MR10 product. The waste plastic materials were processed and supplied by MacRebur Ltd. out of Lockerbie, United Kingdom.

Each of the different plastic types was evaluated at different dosage rates in an unmodified PG64-22 asphalt binder and evaluated for their respective asphalt binder properties. If deemed appropriate and well performing based on the asphalt binder properties, the waste plastic modified asphalt binder would be incorporated into a standard asphalt mixture and evaluated for its respective stiffness, rutting resistance, cracking resistance and resistance to moisture damage. A conventional unmodified asphalt binder (the same base asphalt binder used in the waste plastic modification) and a conventional SBS polymer modified asphalt binder were used as comparison asphalt mixtures to gauge the level of performance that could be expected from the waste plastic modified asphalt mixtures.

LABORATORY TESTING PROGRAM

A laboratory testing program was established to evaluate the asphalt binder and mixtures properties using plastic waste as an asphalt modifier. Each of the plastic waste types was preblended in a PG64-22 asphalt binder at 3, 6, and 9% by total weight of the asphalt binder. A Silverson high shear mixer with a slotted disintegrating head was utilized for the blending. The asphalt binder was heated and blended in a 1-gallon can mantle heater for 4 hours at 165^{o}C. No crosslinkers or compatibilizers were incorporated. Visual observations after the blending noted that although a majority of the binders appeared to be fully blended, the 9% MR6 did still appear to have some residual plastic waste. Upon cooling, it was also noticed that a thin film developed on the surface of the asphalt binder, almost visually indicating phase separation was taking place.

After the asphalt binders were blended, a number of conventional, rheological and fracture-based testing was conducted. These included;

- Separation Testing: ASTM D7173
- Performance Grading: AASHTO M320 and M332
- Rheological Master Curves: Glover-Rowe and (Loss Tangent)^2 at $G^* = 10$ MPa
- Double Edge Notched Tension Test (DENT): AASHTO TP113
- Asphalt Binder Cracking Device (ABCD): AASHTO T387

The performance of the asphalt binder testing was used to establish an optimized plastic waste dosage rate for use within the asphalt mixture testing program. The optimized plastic waste/dosage rate was then compared to identical asphalt mixtures but with an unmodified PG64-22 and a SBS modified PG76-22, respectively. The asphalt mixture testing conducted on the mixtures were;

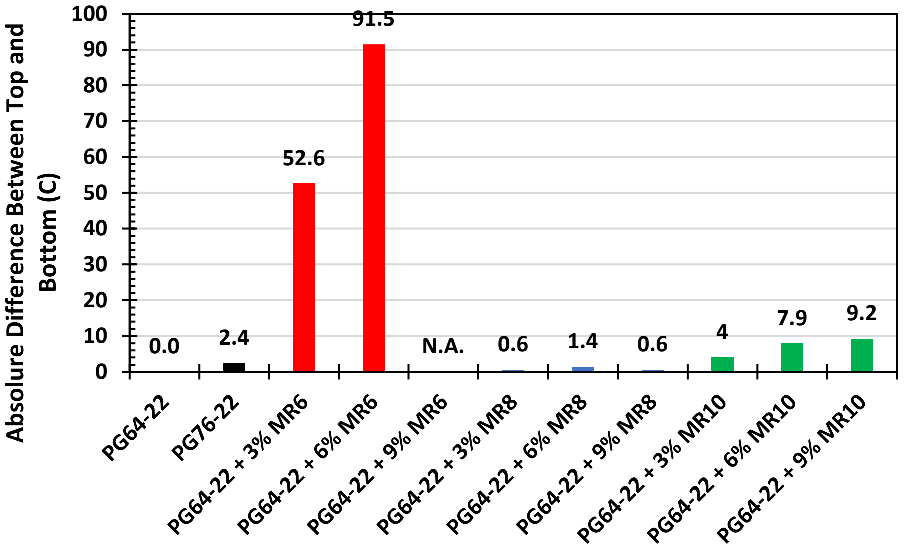
- Stiffness
    - Dynamic Modulus Test: AASHTO T378
- Rutting
    - Hamburg Wheel Tracking Test: AASHTO T324
    - Asphalt Pavement Analyzer: AASHTO T340
    - High Temperature IDT: NCHRP 9-33
    - Repeated Load Permanent Deformation: AASHTO T387
- Fatigue Cracking
    - Flexural Beam Fatigue: AASHTO T321
    - SCB Flexibility Index: AASHTO T393
    - IDEAL-CT Cracking Index: ASTM D8225
    - Overlay Tester: NJDOT B-10
- Low Temperature Cracking
    - Disk Shaped Compact Tension Test (DCT): ASTM D7313
- Moisture Damage
    - Tensile Strength Ratio (TSR): AASHTO T283
    - Hamburg Wheel Tracking Test (Stripping Inflection Point): AASHTO T324

PHASE 1 – ASPHALT BINDER TESTING

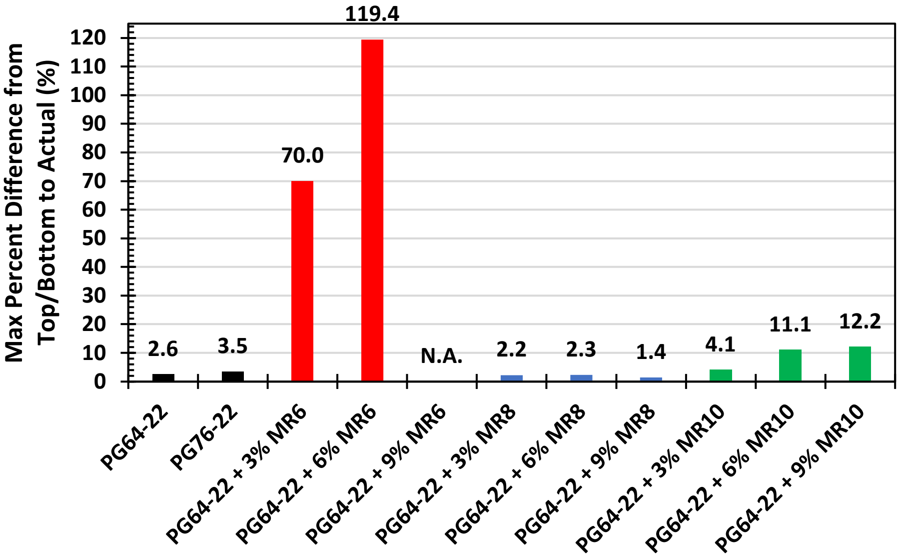
Separation Testing - ASTM D7173

ASTM D7173, *Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt*, was utilized to assess the separation potential of the preblended plastic waste material. The test uses a 140 mm thin-walled aluminum tube that is filled with the blended asphalt binder. After filling, the tube is sealed closed and set in vertical position for 48 hours in 163 +/-5°C oven. After the 48 hours, the binder filled tube is maintained vertically and then placed into a freezer for at least 4 hours. After cooling and hardening, the aluminum tube is taken out of the freezer and the upper and bottom one-third of the tube are removed with the center discarded. The asphalt binder properties of the upper and bottom portion of the tube are tested and values compared. Although Softening Point has been traditionally used to evaluate separation potential, this study utilized the high temperature PG grade in accordance with AASHTO M320, *Standard Specification for Performance-Graded Asphalt Binder* and ASTM D7643, *Standard Practice for Determining the Continuous Grading Temperatures and Continuous Grades for PG Graded Asphalt Binders*.

The results in Figure 2 show that the MR6 plastic waste resulted in the largest separation, and in fact, could not be determined at a 9% dosage rate due to difficulties in handling/pouring. Meanwhile, the MR8 plastic waste showed the lowest potential for separation and resulted in values quite similar to the conventional unmodified PG64-22 and SBS modified PG76-22 asphalt binders.



(a)



(b)

Figure 2 - High Temperature PG Grade Measurements After ASTM D7173 Separation Conditioning; a) Absolute Difference in High Temperature PG Grade Between Top and Bottom; b) Maximum Percent Difference from the Top or Bottom to Actual

Performance Grading Test Results – AASHTO M320/M332

The plastic waste modified asphalt binders were performance graded in accordance with AASHTO M320 and M332, *Standard Specification for Performance-Grade Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*. Table 1 summarizes the performance grading results. Overall, the following trends in the asphalt binder performance grading was observed;

- All three plastic waste resulted in an increase in asphalt binder viscosity as measured using the Rotational Viscometer. In the case of MR6 and MR10, significant changes in viscosity were observed with higher dosage rates, resulting in viscosity values higher than the SBS modified PG76-22. A slight increase in viscosity was observed due to the addition of the MR8 material;
- Both the MR6 and MR10 materials improved the high temperature stiffness properties of the asphalt binder, however, in none of the cases did the % Recovery from the MSCR test meet the minimum elastomer standards. Meanwhile, the MR8 material showed little to no change in the high temperature performance of the asphalt binder, whether this was the high temperature PG grade or the MSCR.
- Low temperature performance grade testing showed that the addition of either MR6 or MR10 resulted in raising the low temperature PG grade warmer than the -22^{o}C base low temperature grade. This would have resulted in re-grading the low temperature grade of the asphalt binder to a -16^{o}C. Meanwhile, the addition of the MR8 product appears to help slightly lowered (improved) the low temperature PG grade.

Table 1 - Performance Grading Test Results of Plastic Waste Modified Asphalt Binders

Base Binder	Plastic Waste Type	Dosage Rate (%)	Rotational Viscosity (Pa-s)		High Temperature PG Grading				Inter. PG Grade (°C)	Low Temperature PG Grading		
			135C	165C	Original (°C)	RTFO (°C)	MSCR @ 64C			Stiffness (°C)	m-value (°C)	ΔTc (°C)
							Jnr (1/kPa)	% Rec				
64-22	**N.A.**	**0%**	**0.428**	**0.117**	**66.6**	**67.1**	**3.28**	**0.0**	**21.7**	**-25.5**	**-24.8**	**-0.7**
64-22	**MR6**	**3%**	**0.812**	**0.282**	**73.7**	**74.7**	**1.10**	**3.2**	**26.1**	**-24.0**	**-21.1**	**-2.9**
		6%	**1.612**	**0.519**	**78.1**	**85.6**	**0.29**	**25.0**	**27.3**	**-23.4**	**-16.7**	**-6.7**
		9%	**N.A**									
	MR8	**3%**	**0.463**	**0.127**	**67.2**	**67.1**	**3.04**	**0.8**	**22.7**	**-26.2**	**-23.9**	**-2.3**
		6%	**0.469**	**0.129**	**66.4**	**67.1**	**3.10**	**1.0**	**22.2**	**-26.8**	**-26.3**	**-0.5**
		9%	**0.523**	**0.142**	**67.1**	**66.3**	**3.01**	**0.2**	**19.3**	**-27.7**	**-26.9**	**-0.8**
	MR10	**3%**	**0.650**	**0.175**	**71.1**	**71.4**	**1.66**	**4.0**	**24.1**	**-24.7**	**-21.5**	**-3.2**
		6%	**0.884**	**0.243**	**74.0**	**74.2**	**1.15**	**9.1**	**24.7**	**-25.0**	**-20.2**	**-4.8**
		9%	**2.75**	**0.470**	**79.5**	**78.9**	**0.65**	**16.6**	**23.9**	**-24.3**	**-16.5**	**-7.8**
76-22	**N.A.**	**0%**	**1.54**	**0.385**	**78.1**	**78.1**	**0.232**	**68.3**	**22.3**	**-27.0**	**-26.1**	**-0.9**

Rheological Indices Related to Brittleness and Durability

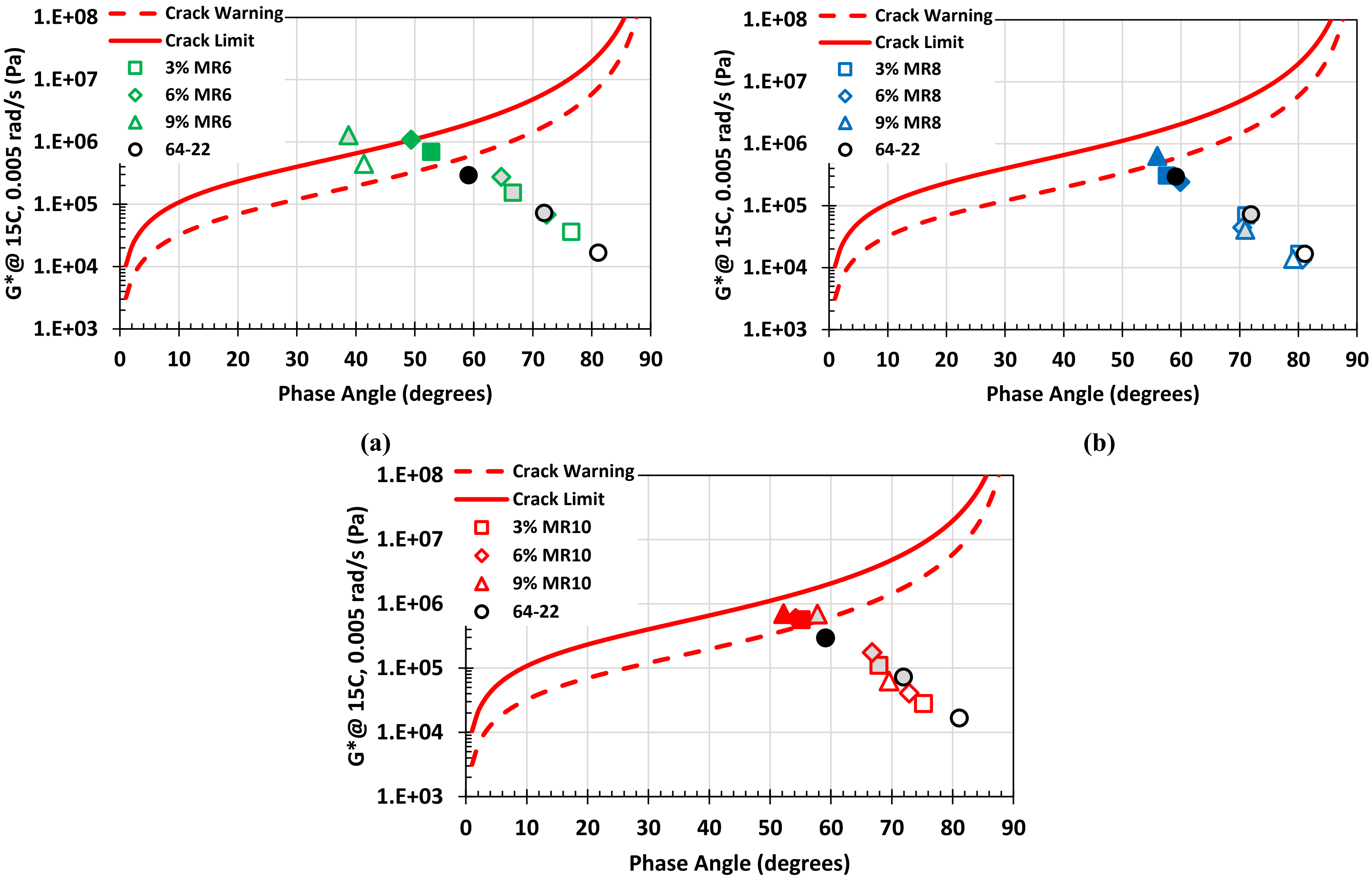
Glover-Rowe Parameter (G-R)

Glover et al. (2005) proposed the rheological parameter, G'/(η'/ G'), as an indicator of ductility based on a derivation of a mechanical analog consisting of springs and dashpots to represent the traditional ductility test. It has been well demonstrated that the Glover parameter is directly correlated to measured ductility. The Glover parameter can be calculated based on DSR frequency sweep testing results, making it much more practical than directly measuring ductility using traditional methods. Rowe (2011) re-defined the Glover parameter in terms of |G*| and δ based on analysis of a black space diagram as shown in Equation (1) and suggested use of the parameter $|G^*|\cdot(\cos\delta)^2/\sin\delta$, termed the Glover-Rowe (G-R) parameter in place of the original Glover parameter.

$$\frac{G'}{\eta'/G'} = \frac{|G^*|\cdot(\cos\delta)^2}{\sin\delta}\cdot\omega \tag{1}$$

A higher G-R value indicates increased brittleness. It has been proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 600 kPa corresponds to significant cracking based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2015).

The results for the G-R analysis are shown in Figure 3. Each of the asphalt binders were tested after different degrees of laboratory conditioning. Original, or no conditioning, is noted as the "open" symbols. Rolling Thin Film Oven (RTFO) is shown as the gray filled symbols. Twenty (20) hour conditioning in the Pressure Aging Vessel (PAV) is noted as the filled symbols. The G-R analysis indicates that the MR6 and MR10 modified asphalt binders migrate closer and into the Crack Warning/Crack Limit area of the Black Space at a greater rate than the unmodified PG64-22 asphalt binder. This indicates that the MR6 and MR10 modified asphalt binders are age hardening at a greater rate than the unmodified PG64-22 asphalt binder. Meanwhile, the MR8 material appear to have little to no impact on the age hardening progression due to the laboratory conditioning when compared to the unmodified PG64-22 asphalt binder.



(a)

(b)

(c)

Figure 3 - Glower-Rowe Parameter Evaluation at Varying Conditioning Levels; a) MR6 Material; b) MR8 Material; c) MR10 Material

Phase Angle Based Parameters

The asphalt binder phase angle has shown to be a good indicator of the healing and strain tolerance of asphalt binders (Christensen and Tran, 2018). However, at elevated temperatures, the influence of polymers may distort or exaggerate the asphalt binder performance. Therefore, to help negate this issue, the phase angle was measured at a shear stiffness (G*) of 10 MPa. It has been proposed by Anderson and Rowe (2015) that evaluating asphalt binders between a stiffness (G*) of 10 to 30 MPa helps to reduce stiffness dependency issues regarding loading rate and temperature. The measured phase angle at 10 MPa was then used to calculate the loss tangent value. Work conducted by Button et al., (1997) showed that higher loss tangent values at low testing temperatures indicates good resistance to fatigue cracking. Furthermore, Goodrich (1991) noted that the loss tangent "*... is an excellent indicator of whether an asphalt behaves as a brittle elastic solid or whether it maintains a viscous component*." The loss tangent is shown in Equation 2 and is defined as the ratio between the viscous to elastic modulus with higher loss tangent values indicating better resistance to cracking.

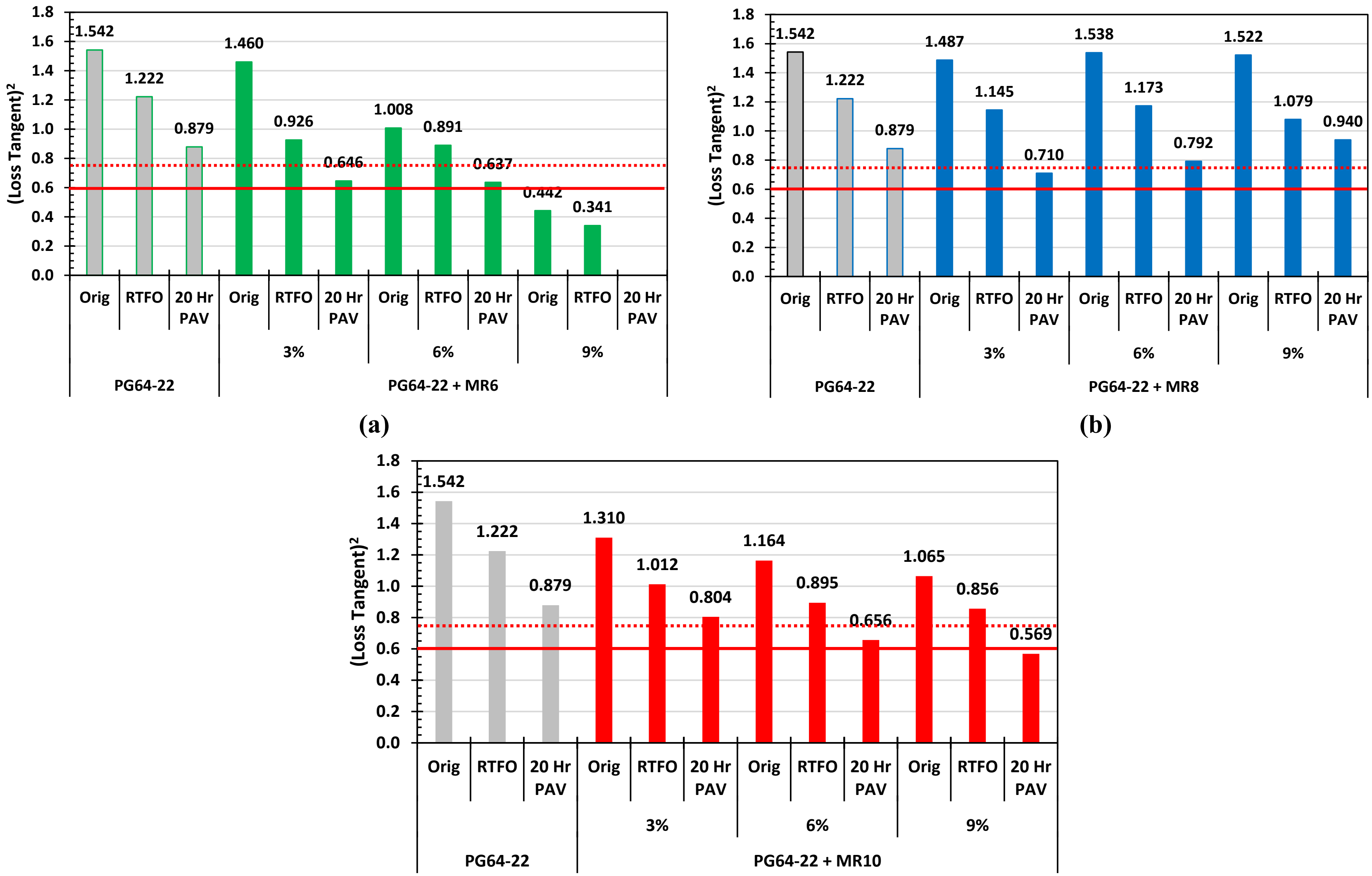
$$loss\ tangent = \frac{G''}{G'} = \tan\delta \qquad (2)$$

where,

G" = shear loss modulus; viscous component of G* of the asphalt binder
G' = shear storage modulus; elastic component of G* of the asphalt binder
δ = phase angle of the asphalt binder

For this study, the loss tangent was squared based on the NCHRP Project 9-59 observations of Christensen and Tran (2018) that showed a strong relationship of the δ^2 to the fatigue/fracture performance ratio (FPR). Bennert et al (2022) showed that the (Loss Tangent)^2 at G* = 10 MPa correlated well to laboratory cracking tests on various modified and unmodified asphalt binders, while also correlated well to observed fatigue cracking from asphalt airfield pavements and the FHWA ALF experimental sections. Higher (Loss Tangent)^2 at G* = 10 MPa values results in better fatigue cracking performance, while lower (Loss Tangent)^2 at G* = 10 MPa results in increased brittleness.

Figure 4 summarizes the results of the (Loss Tangent)^2 at G* = 10 MPa analysis. The general ranking of the plastic waste modified binders was extremely similar to that of the Glover-Rowe analysis. Once again, the MR6 and MR10 materials induced greater potential for fatigue cracking when compared to the unmodified PG64-22 asphalt binder. However, the MR8 material appears to even improve the (Loss Tangent)^2 at G* = 10 MPa over the unmodified PG64-22 asphalt binder at the higher dosage rates.



(a)

(b)

(c)

Figure 4 - (Loss Tangent)^2 at G* = 10 MPa Analysis at Varying Conditioning Levels; a) MR6 Material; b) MR8 Material; c) MR10 Material

Double Edge Notched Tension (DENT) Test – AASHTO TP113

The Double Edge Notched Tension (DENT) test has also been proposed for characterizing binder fatigue fracture resistance. The DENT test was developed by Queen's University in Canada and modified and adapted for intermediate temperature testing by the FHWA (Andriescu et al., 2004). The DENT was conducted in accordance with AASHTO TP113, *Determination of Asphalt Binder Resistance to Ductile Failure Using Double-Edge-Notched Tension (DENT) Test*. The DENT test utilizes the concept of fracture mechanics to evaluate the ductility of asphalt binders. The critical tip opening displacement (CTOD), which has been found to be a good indicator of fatigue resistance (Christensen and Tran, 2018) was used to compare to the mixture fatigue cracking.

Figure 5 shows the DENT test results conducted at a test temperature of 25°C and conditioned for 20 hours in the PAV. The addition of the MR6 and MR10 materials appears to reduce the CTOD value, while the MR8 seems to slightly improve the DENT performance when compared to the unmodified PG64-22. The PG76-22 asphalt binder is also shown as a comparison with the elastomeric properties of the SBS polymer clearly providing superior performance over the plastic waste modified asphalt binders.

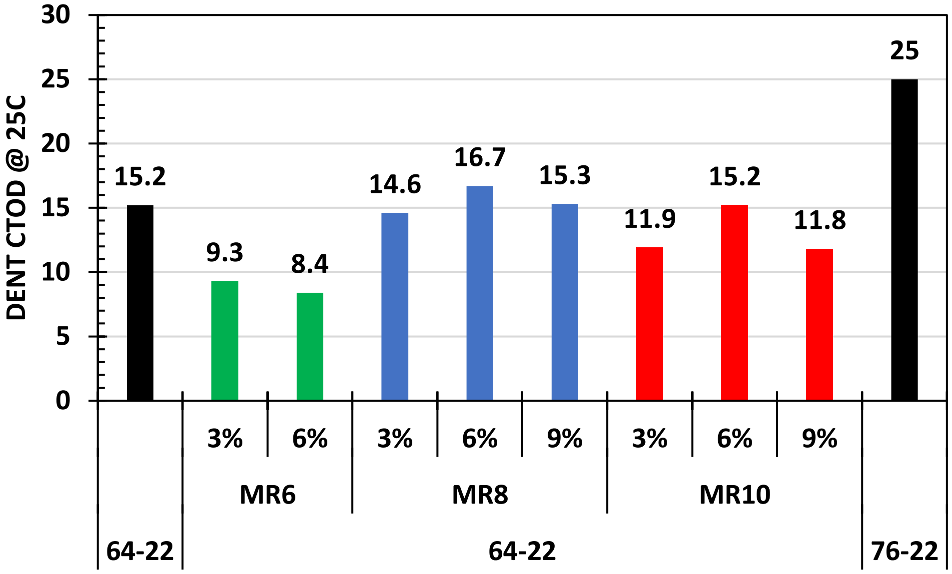


Figure 5 - Double Edge Notched Tension Test (DENT) Results

Asphalt Binder Cracking Device (ABCD) – AASHTO T387

The Asphalt Binder Cracking Device (ABCD) was utilized to evaluate the low temperature critical cracking temperature (T_{cr}) of the asphalt binders due to thermally induced (cooling) stress. The ABCD T_{cr} is primarily controlled by the coefficient of thermal contraction (CTC) of the asphalt binder. The CTC controls the rate of volumetric change in the asphalt binder, thereby controlling the rate of thermal stress development. An asphalt binder with a higher CTC may be subjected to larger strains compared to low CTC asphalt binders before cracking failure is observed. Work conducted under NCHRP Project 9-60 showed that the asphalt binder's CTC affects non-load related cracking (Elwardany et al., (2019)). To better interpret the ABCD data, Elwardany et al., (2019) recommended normalizing the ABCD T_{cr} using the stiffness-based low temperature grade from the bending beam rheometer (BBR) test (Tc = 300 MPa). This was recommended for two reasons;

1. The T_C (S = 300 MPa) is highly correlated with the glass transition temperature, T_g. Modifiers like REOB will actually help to reduce the T_g. Therefore, normalizing the ABCD T_{cr} using T_C (S = 300 MPa) should improve the sensitivity of the ABCD cracking data to REOB-type modification that reduces T_g.
2. Since the T_C (S = 300 MPa) is already a part of the PG grading system, it is simpler to use than the actual T_g value, which would require sophisticated measurement equipment outside of conventional asphalt binder test equipment.

Therefore, Elwardany et al., (2019) proposed the parameter ΔT_f, described below.

$$\Delta T_f = T_C(S) - T_{cr} \tag{3}$$

where,

$T_C(S)$ = low temperature PG grade from BBR Stiffness
T_{cr} = ABCD low temperature critical cracking temperature

The ΔT_f parameter is combined with the ΔT_c parameter from the low temperature BBR testing to provide a performance space for evaluating the potential for non-load associated cracking. The results of this analysis are shown below as Figure 6. Values plotting to the right of the line as proposed as "good performing" while values to the left have a greater potential for cracking. The results of the NCHRP 9-60 approach once again show that the addition of the MR8 material had a negligible to slight improvement in the non-load associated cracking resistance when compared to the MR6 and MR10 materials.

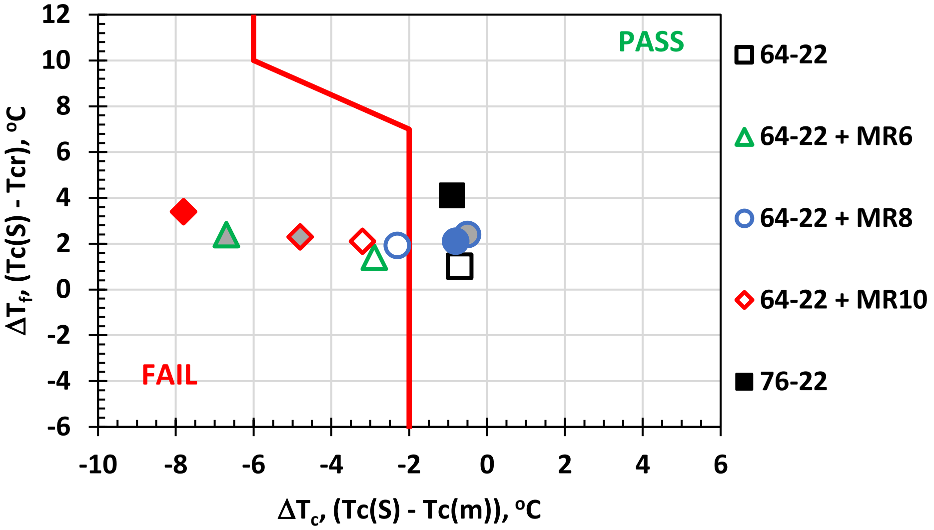


Figure 6 - Results of the ABCD Testing and NCHRP 9-60 Analysis Approach to Evaluate Potential for Non-Load Associated Cracking Potential

Asphalt Binder Testing Summary

The asphalt binder analysis of the plastic waste modified asphalt binders showed that the thermoplastic waste material (MR8) may have a beneficial impact on reducing the impact of age hardening on the intermediate and low temperature cracking performance while showing little to no change in the high temperature performance. Meanwhile, both the polyolefin (MR6) and co-block plastic (MR10) waste materials significantly increased the high temperature stiffness of the modified asphalt binders. Unfortunately, both the MR6 and MR10 were found to detrimentally impact the intermediate and low temperature fatigue performance of the asphalt binders and increase the rate of age hardening witnessed from the varying levels of laboratory conditioning. These results were used to select the MR8 to advance into the asphalt mixture evaluation phase of the study. Dosage rates of 6 and 9% by total weight of the asphalt binder were selected as both of these dosage rates showed a potential to help reduce the impact of aging on the cracking performance of the asphalt binders.

PHASE 2 – ASPHALT MIXTURE TESTING

Using the asphalt binder testing as a guide, an ummodified PG64-22 asphalt binder was modified with the thermoplastic (MR8) waste plastic at two dosage rates; 6 and 9% by weight of the asphalt binder. Along with an unmodified PG64-22 and an SBS modified PG76-22 asphalt binder, a 9.5 mm nominal maximum aggregate size asphalt mixture was produced in the laboratory and evaluated for its respective stiffness, rutting, fatigue and low temperature cracking, and moisture damage potential performance. The asphalt mixture was designed at design gyration level of 75 gyrations and air void content of 4.0%. An optimum asphalt content of 6.1% and the design voids in mineral aggregate (VMA) of 17.1% were determined for the asphalt mixture. Recycled asphalt pavement (RAP) was not included in the asphalt mixture so only the impact of the asphalt binder could be evaluated. For the rutting evaluation, the asphalt mixtures were short-term oven aged (STOA) conditioned for two hours loose at the compaction temperature of the asphalt binder as determined using the rotational viscosity data. Meanwhile, specimens produced for the cracking evaluation were evaluated after both STOA and long-term oven aged (LTOA) conditioning. The LTOA conditioning incorporated conditioning the loose asphalt mixture at 135°C for 24 hours. Prior work by the researchers have indicated that this aging condition mirrors the rheological changes of the asphalt binders found in the New York/New Jersey area after twelve to fifteen years of service life (Bennert et al, 2017). All test specimens were compacted to an air void level of 6.0 +/- 0.5% air voids to simulate typical in-place air void levels found in the New York/New Jersey area.

Stiffness Evaluation

The stiffness characteristics of the asphalt mixtures were evaluated by measuring the dynamic modulus and phase angle properties in uniaxial compression using the Asphalt Mixture Performance Tester (AMPT) following the method outlined in AASHTO T378, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The data was collected at three temperatures; 4, 20, 35 and 45°C using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz. Test specimens were evaluated under both STOA and LTOA conditions.

The collected modulus values of the varying temperatures and loading frequencies were used to develop dynamic modulus master stiffness curves and temperature shift factors using numerical optimization of Equations 1 and 2. The reference temperature used for the generation of the master curves and the shift factors was 20^{o}C.

$$\log\left|E^*\right| = \delta + \frac{\left(Max - \delta\right)}{1 + e^{\beta + \gamma\left\{\log\omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \tag{1}$$

where:

$|E^*|$ = dynamic modulus, psi
ω_r = reduced frequency, Hz
Max = limiting maximum modulus, psi
δ, β, and γ = fitting parameters

$$\log\left[a(T)\right] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{2}$$

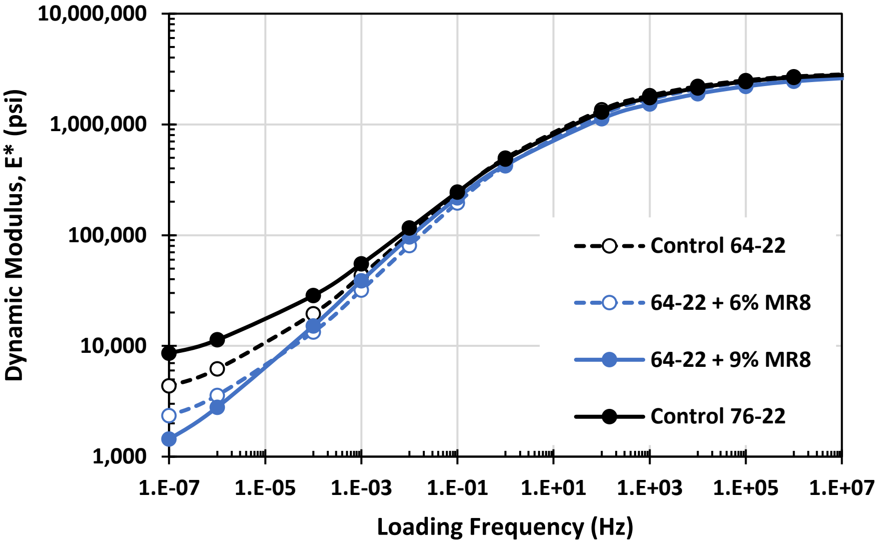
where:

a(T) = shift factor at temperature T
T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as a fitting parameter)

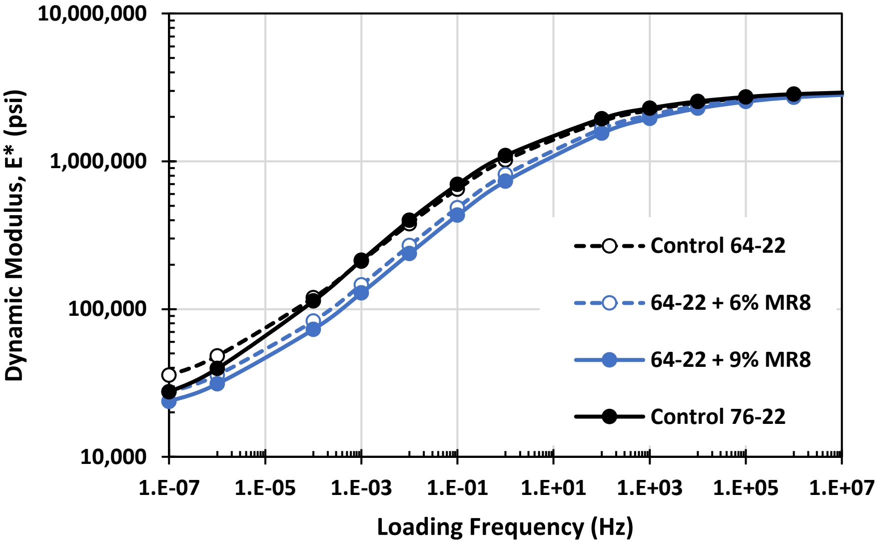
,

The results of the dynamic modulus testing are shown as Figure 7. Figure 7a provide the resultant master stiffness curves for the STOA conditioned asphalt mixtures. At the STOA condition, the asphalt mixture have very similar dynamic modulus properties at the low temperature (high loading frequencies) and intermediate temperature (middle range of loading frequencies) test conditions. However, at the higher test temperatures (low load frequencies), separation between the mixtures initiates. The PG76-22 asphalt binder resulted in the highest stiffness values while the MR8 modified mixtures had the lowest stiffness values.

After the mixtures were LTOA conditioned, both of the thermoplastic waste plastic (MR8) modified asphalt mixtures showed lower stiffness magnitudes throughout most of the master curves (Figure 7b). Special attention is placed on the intermediate and low temperature area of the master curve as lower dynamic modulus values within this range typically results in better fatigue cracking performance. Therefore, the dynamic modulus master curves would suggest that at elevated aging conditions, the MR8 material may actually provide some level of resistance to aging when compared to the unmodified PG64-22 and SBS modified PG76-22 materials.



(a)



(b)

Figure 7 - Dynamic Modulus Master Curves at a) Short-term Oven Aged Condition (STOA); b) Long-term Oven Aged Condition (LTOA)

Rutting Evaluation

Four different test methods were utilized to evaluate the rutting potential of the plastic waste modified asphalt mixtures; 1) Asphalt Pavement Analyzer, 2) Hamburg Wheel Tracking Testing; 3) Asphalt Mixture Performance Tester (AMPT) Flow Number and 4) High Temperature IDT Strength. The Asphalt Pavement Analyzer test was conducted in accordance with AASHTO T340, *Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt*

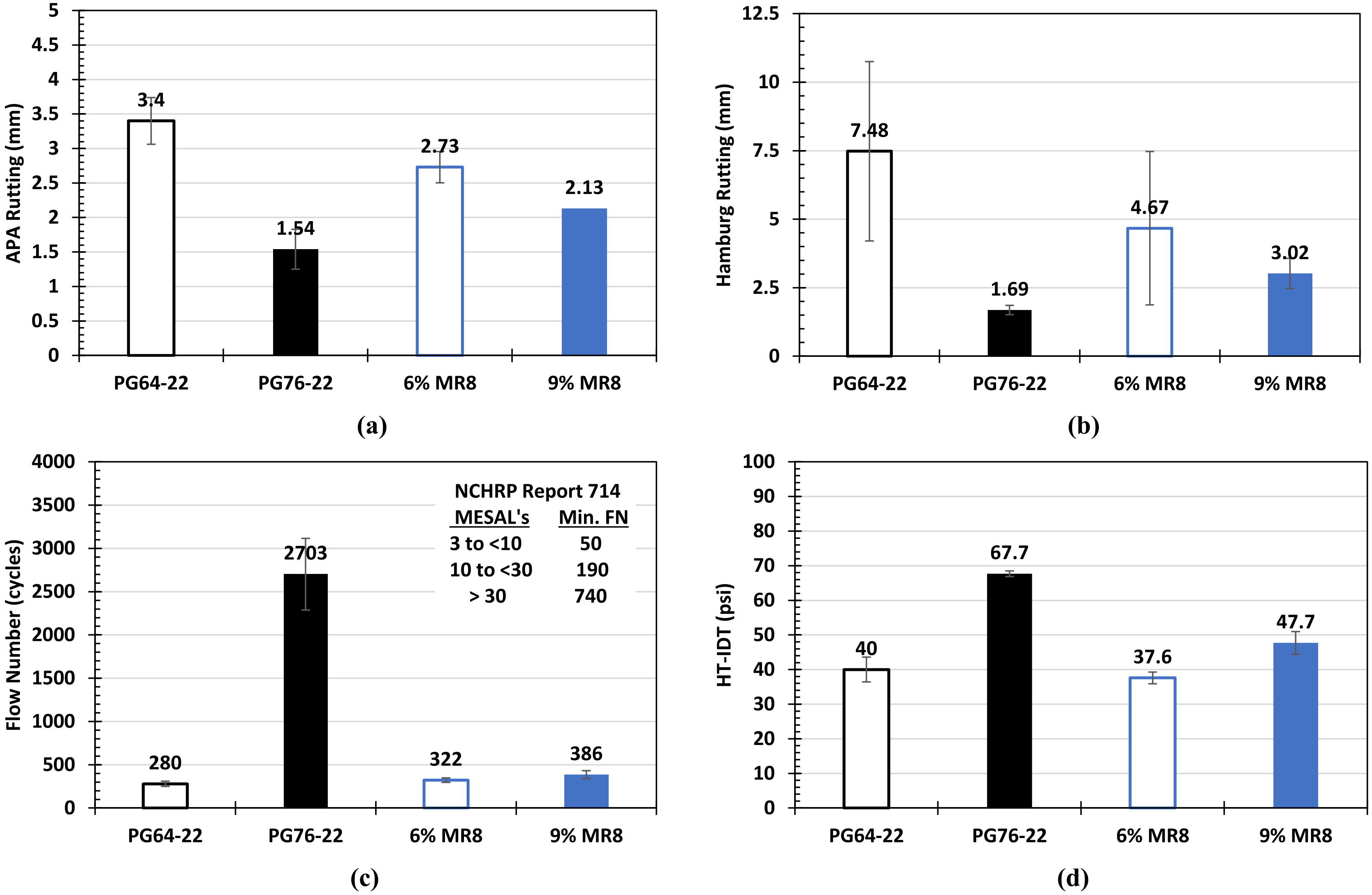
(HMA) Using the Asphalt Pavement Analyzer, at a test temperature of 64°C. A hose pressure of 100 psi and wheel load of 100 lbs were used to load the compacted specimens until 8,000 loading cycles had completed. The final rutting measured at 8,000 cycles was used for comparison purposes.

The Hamburg Wheel Tracking test was conducted in accordance with AASHTO T324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures*, at a test temperature of 50°C. A 158 lb steel wheel load was applied at 52 passes per minute with deformation of the specimens recorded at each loading cycle. The recorded data was used to measure the permanent deformation after 20,000 cycles. The shape of the deformation vs loading cycle curve was also used to determine the Stripping Inflection Point, which is theorized to determine the onset of moisture damage in the asphalt specimen.

The Asphalt Mixture Performance Tester (AMPT) Flow Number parameter was determined in accordance with AASHTO T378, *Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT).* The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 54°C, which corresponds to New Jersey's average 50% reliability high pavement temperature at a depth of 20 mm according the LTPPBind 3.1 software. These testing parameters (temperature and applied stress) conform to the recommendations currently proposed in NCHRP Project 9-33, *A Mix Design Manual for Hot Mix Asphalt.* Testing was conducted until a permanent vertical strain of 5% or 10,000 cycles was obtained.

Lastly, the High Temperature Indirect Tensile Strength (HT-IDT) test method was utilized to evaluate the rutting potential of the different asphalt mixtures. The HT-IDT follows the general testing guidelines noted in AASHTO T 283, *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage*, and highlighted in NCHRP Report 673 (Advanced Asphalt Technologies, 2011). The HT-IDT test is conducted at a test temperature 10°C below the average, 7-day maximum pavement temperature, 20 mm below the pavement surface at a 50% reliability as determined by LTPPBind Version 3.1. For typical New Jersey conditions, this results in a HT-IDT test temperature of 44°C.

The asphalt mixture rutting results are shown in Figure 8. The laboratory results all trend in a very similar manner; 1) the SBS modified PG76-22 asphalt mixture achieved the best rutting resistance of the four asphalt mixtures; 2) the unmodified PG64-22 asphalt mixture resulted in the lowest resistance to laboratory rutting; and 3) the addition of the MR8 material appears to slightly improve the rutting resistance of the asphalt mixture. In fact, the data suggests that the higher dosage rate, 9% by weight of asphalt binder, resulted in better rutting resistance than the 6% dosage rate. The results would indicate that a slight benefit in rutting resistance may be observed when utilizing the MR8 plastic waste material.



(a) (b)

(c) (d)

Figure 8 - Rutting Evaluation Results a) Asphalt Pavement Analyzer; b) Hamburg Wheel Tracking Test; c) AMPT Flow Number; d) High Temperature IDT Strength

Fatigue Cracking Evaluation

Five different test methods were used to address the fatigue cracking potential of the asphalt mixture with and without the plastic waste material. These included; 1) SCB Flexibility Index, 2) Overlay Tester, 3) IDEAL-CT Cracking Index, 4) Disk-Shaped Compact Tension Test, DC(T), and 5) Flexural Beam Fatigue. The SCB Flexibility Index test was conducted in accordance with AASHTO T393, *Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test (I-FIT).* The test procedure was conducted at a test temperature of 25^{o}C and a loading rate of 50 mm/min. The fracture energy (G_f) and the post-peak slope (S) were calculated from the load vs displacement measurements and used to calculate the Flexibility Index (FI) parameter.

The Overlay Tester was conducted in accordance with NJDOT B-10, *Overlay Test for Determining Crack Resistance of HMA*. The test specimens were tested at a 25^{o}C test temperature with a maximum, cyclic displacement of 0.63 mm. The cycle time of 10 seconds (5 seconds loading, 5 seconds unloading) using a triangular waveform was conducted until specimen failure, defined as 93% reduction in Initial Load, was achieved.

The IDEAL-CT Cracking Index was measured in accordance with ASTM D8225, *Standard Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. The IDEAL-CT test was conducted at a test temperature of 25^{o}C and at a displacement rate of 50 mm/min. The analysis is similar to that of the SCB Flexibility Index, where the fracture energy (G_f) and the post-peak slope (S) to determine the Cracking Tolerance Index value. However, unlike the SCB Flexibility Index, the post-peak slope location from the IDEAL-CT Index test is determined at the constant 75% of the peak load on the load vs displacement graph.

The flexural fatigue properties of the asphalt mixtures were evaluated using AASHTO T321, *Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending*. The applied tensile strain levels used for the fatigue evaluation ranged between 400 to 1000 micro-strains, depending on the asphalt mixture evaluated. Samples used for the Flexural Beam Fatigue test were compacted using a vibratory compactor designed to compact brick samples of 400 mm in length, 150 mm in width, and 100 mm in height. After the conditioning and compaction was complete, the samples were trimmed to within the recommended dimensions and tolerances specified under AASHTO T321. The test specimens were evaluated at a test temperature of 15^{o}C using a sinusoidal waveform in strain-controlled mode of loading with a loading frequency of 10 Hz.

Lastly, the low temperature cracking resistance of the asphalt mixtures were evaluated using the Disk-Shaped Compact Tension test DC(T) in accordance with ASTM D7313, *Standard Test Method for Determining Fracture Energy of Asphalt Mixtures Using the Disk-Shaped Compact Tension Geometry*. The DC(T) test is run in crack mouth opening displacement (CMOD) control mode at a rate of 1 mm/min. The displacement gauge mounted at the notch opening controls the rate at which the crack grows. The test temperature at which the DC(T) was conducted is +10^{o}C from LTPPBind determined low temperature PG grade at a 98% reliability. For New Jersey conditions, this results in a DC(T) testing temperature of -12^{o}C.

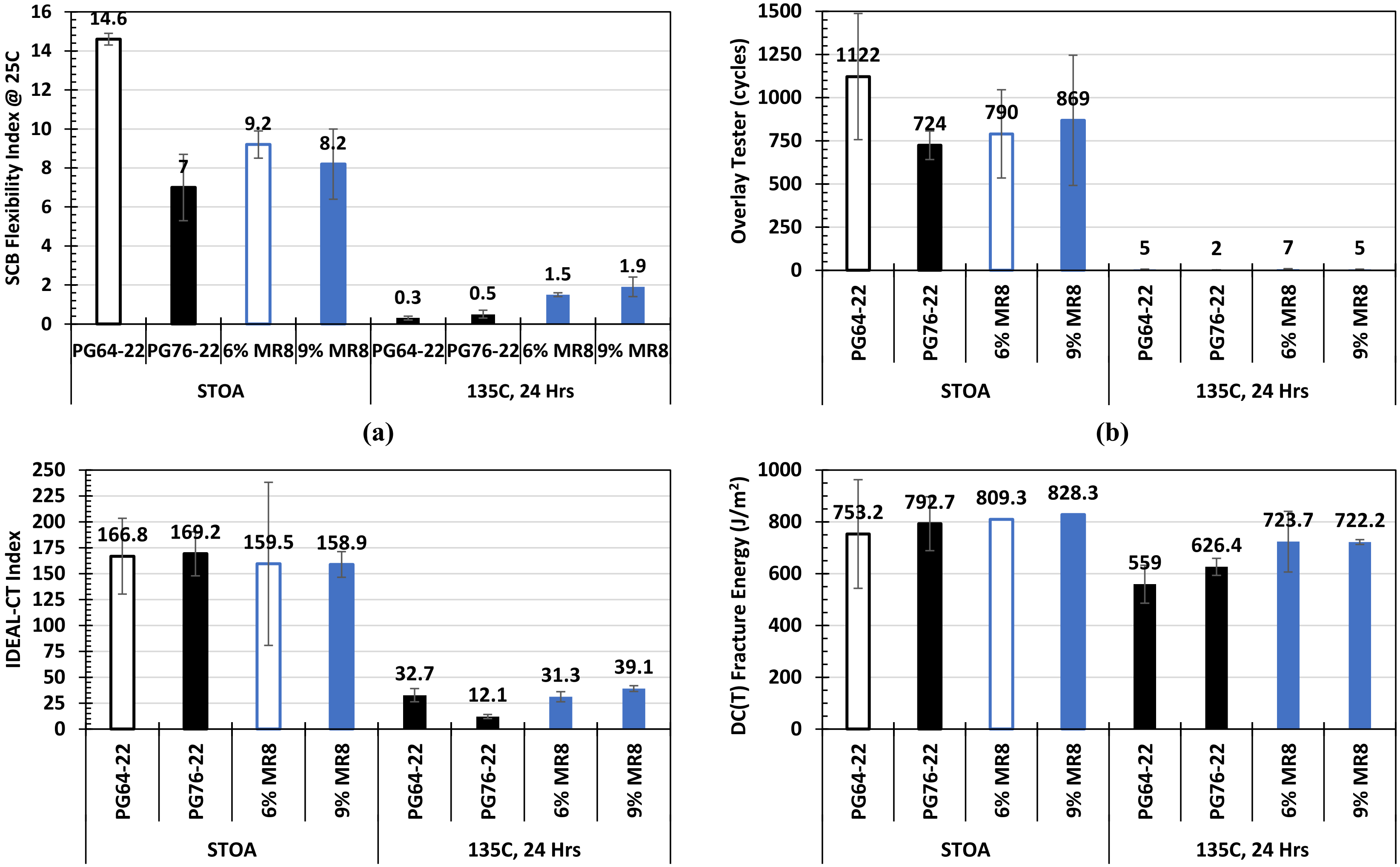
The fatigue cracking properties of the asphalt mixtures can be found in Figures 9 and 10 for both the short-term oven aged (STOA) and long-term oven aged (LTOA) conditions. When evaluating the fatigue properties at the STOA condition, in general, the MR8 modified asphalt mixtures show cracking properties similar to the unmodified PG64-22, and even at times, the SBS modified PG76-22 asphalt binder. The Overlay Tester, SCB Flexibility Index and DC(T), all tests known to evaluate the crack propagation mode, showed that the MR8 modified asphalt mixtures behaved very similar to unmodified PG64-22 and SBS modified PG76-22 at the STOA condition. Meanwhile, the IDEAL-CT Index and Flexural Beam Fatigue tests, known as crack initiation mode tests, show that the SBS modified PG76-22 generally had better results followed by the unmodified PG64-22 and MR8 modified asphalt mixtures.

When the asphalt mixtures were LTOA conditioned to simulate highly aged asphalt mixtures, the MR8 modified asphalt mixtures actually performed the best overall. Although the magnitude of the cracking values was relatively low in the SCB Flexibility Index and Overlay Tester, and may be arguable hard to make a rational conclusion, both the DC(T) and the Flexural Beam Fatigue test results showed that after significant aging, the MR8 modified asphalt mixtures achieved the best fatigue cracking performance. Meanwhile, the IDEAL-CT Index results showed similar performance with the MR8 modified asphalt mixtures resulting in a slightly better performance. The improved performance of the MR8 modified asphalt mixtures at LTOA conditioning suggests that the addition of the waste thermoplastic material may provide a means to reducing the negative impact of aging on asphalt mixtures.

Moisture Damage Potential

The moisture damage potential of the asphalt mixtures was intended to be evaluated using two test methods/parameters; 1) Tensile Strength Ratio (TSR) from AASHTO T283 and 2) Stripping Inflection Point from the Wet Hamburg Wheel Tracking test. However, a Stripping Inflection Point was not observed for any of the asphalt mixtures evaluated. Therefore, the moisture damage potential was solely based on the TSR value. The TSR was determined in accordance with AASHTO T283, *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-induced Damage*. The test method describes the procedure for specimen saturation, freeze-thaw cycling and measuring the indirect tensile strength of the conditioned and unconditioned asphalt mixtures.

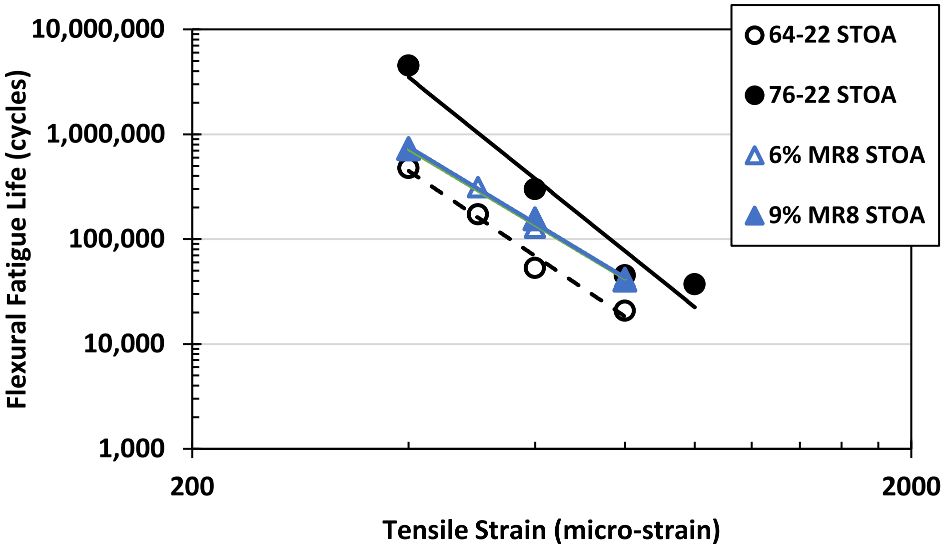
The final test results for the TSR evaluation are shown as Figure 11. The test results show that all four of the asphalt mixture met the minimum requirement of 80% TSR. However, Figure 11a also shows that both of the MR8 modified asphalt mixtures achieved TSR values greater than the unmodified PG64-22 and the SBS modified PG76-22. And although the results of the 6% MR8 asphalt mixture could be noted as being statistically equal to the PG64-22 and PG76-22, the results of the 9% MR8 asphalt mixture clearly outperformed that of the other three asphalt mixtures. A closer look at the indirect tensile strengths (Figure 11b) show that the addition of the thermoplastic waste plastic reduces the tensile strength at 25^{o}C. This may indicate that the addition of the thermoplastic material reduces some of the stiffening/age hardening that is occurring during the loose mix and compacted specimen conditioning associated with AASHTO T283 test method.



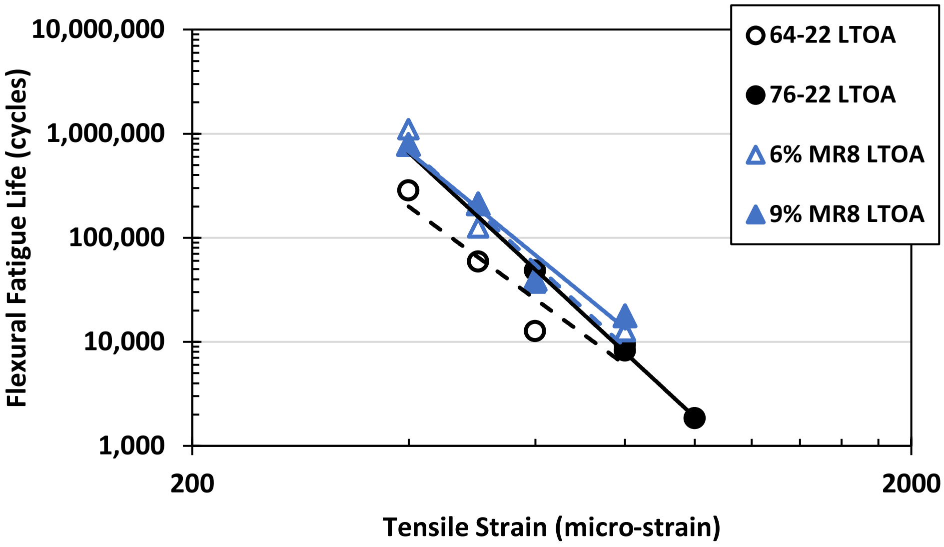
(a) **(b)**

(c) **(d)**

Figure 9 - Fatigue Cracking Test Results; a) SCB Flexibility Index; b) Overlay Tester; c) IDEAL-CT Index; d) DC(T) Fracture Energy at -12ºC

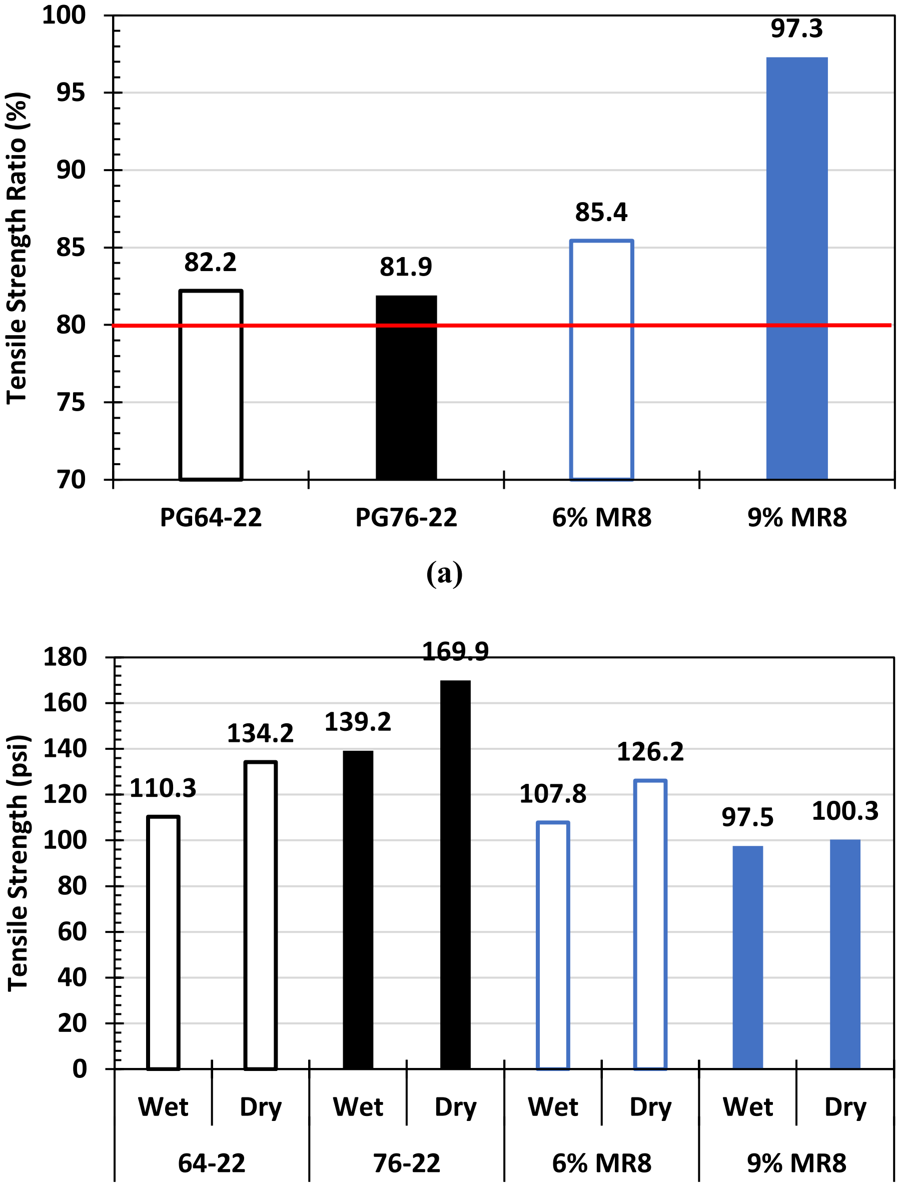


(a)



(b)

Figure 10 - Flexural Beam Fatigue Results; a) Short-term Oven Aged; b) Long-Term Oven Aged



(a)

(b)

Figure 11 - Tensile Strength Ratio Results from AASHTO T283 Moisture Damage Potential Evaluation; a) Tensile Strength Ratio (TSR) Values; b) Indirect Tensile Strength Measurements for Wet (Conditioned) and Dry (Unconditioned) Specimens

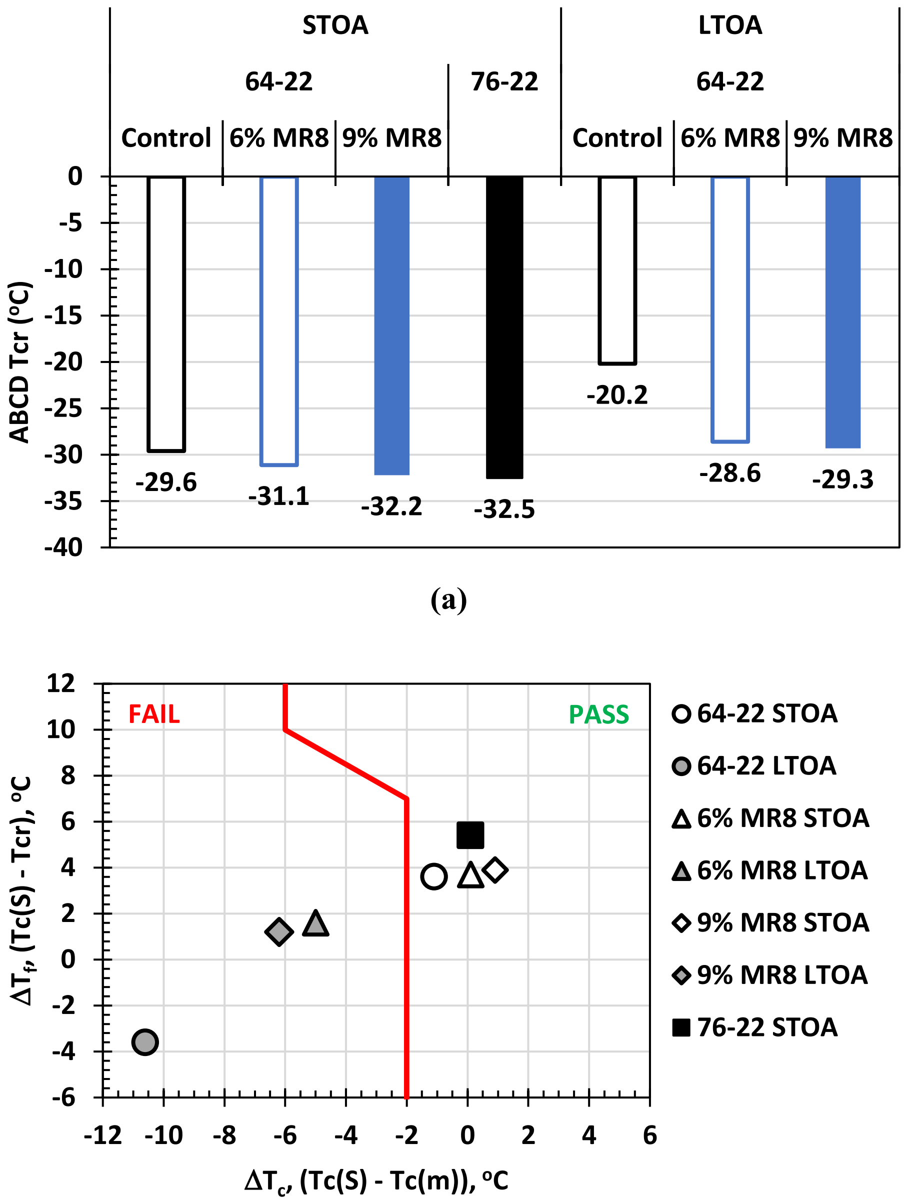
Evaluation of Extracted and Recovered Asphalt Binders

The asphalt mixtures properties indicated that the thermoplastic waste plastic may provide additional benefit to the cracking properties of the asphalt binders. To help validate this hypothesis, the asphalt binders from each of the asphalt mixtures was extracted and recovered in accordance with AASHTO T164, *Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)* and ASTM D5404, *Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator*, respectively. Table 2 summarizes the performance grading results. The data clearly shows that when comparing the thermoplastic plastic waste (MR8) modified asphalt mixture to the Control PG64-22 asphalt mixture, the thermoplastic material provided a level of aging resistance as shown with the change in low temperature PG grade properties of the asphalt binders. When comparing the STOA to LTOA low temperature PG grade properties, the unmodified PG64-22 "lost" 12.1^{o}C on the low temperature PG grade due to the laboratory loose mix conditioning. Meanwhile, the thermoplastic waste plastic modified mixtures showed an average "loss" of 6.4^{o}C, approximately 50% less. This would indicate that the addition of the thermoplastic material aids in resisting oxidative aging in the asphalt binder. Unfortunately, data was not available for the SBS modified PG76-22 asphalt mixture after LTOA conditioning.

The recovered asphalt binders were also evaluated using the Asphalt Binder Cracking Device (ABCD) to provide additional assessment of the cracking/fracture toughness of the recovered asphalt binders. Figure 12 shows the results of the ABCD critical cracking temperature. In Figure 12a, the ABCD critical cracking temperature shows similar values for the recovered asphalt binders after STOA loose mix conditioning. However, the test data indicates that the thermoplastic modified mixtures resulted in a much greater critical cracking temperature than the unmodified PG64-22 after LTOA loose mix conditioning. This agrees with the low temperature PG grade observations noted earlier and demonstrates the ability of the thermoplastic material to aid in resisting oxidative aging of the asphalt binders. Utilizing the NCHRP 9-60 analysis approach shown in Figure 12b, the recovered asphalt binders from the STOA conditioned mixtures were all grouped in the "Passing" zone. After LTOA conditioning, the recovered binders migrated in the "Failing" zone, as would be somewhat expected due to the level of aging applied to the loose mixtures. However, the magnitude of change was much greater for the recovered asphalt binder of the unmodified PG64-22 as opposed to the thermoplastic modified recovered binders. Once again this illustrates the potential benefit of utilizing thermoplastic waste plastic as a modified in asphalt mixtures.

Table 2 - Extracted and Recovered Asphalt Binder Properties from Mixture Study

Base Binder	Plastic Waste Type	Dosage Rate by Weight of Binder (%)	Mixture Conditioning	High Temperature PG Grading (As-Recovered)			Inter. PG Grade (ºC)	Low Temperature PG Grading (As-Recovered)		
				High Temp PG	MSCR @ 64C			Stiffness (ºC)	m-value (ºC)	ΔTc (ºC)
					Jnr (1/kPa)	% Rec				
64-22	N.A.	N.A.	STOA	71.7	1.646	2.0	23.1	-26.0	-24.9	-1.1
			LTOA	97.3	0.013	72.1	27.3	-23.8	-12.8	-11.0
	MR8	6%	STOA	73.4	1.185	4.5	22.4	-27.4	-27.5	0.1
			LTOA	96.7	0.013	75.0	24.1	-27.0	-22.0	-5.0
	MR8	9%	STOA	73.2	1.179	6.0	22.6	-28.3	-29.2	0.9
			LTOA	97.4	0.016	78.3	23.2	-28.1	-21.9	-6.2
76-22	N.A.	N.A.	STOA	85.1	0.066	80.7	23.5	-27.1	-27.2	0.1



(a)

(b)

Figure 12 - Asphalt Binder Cracking Device (ABCD) Critical Cracking Temperature (Tcr) Test Results

CONCLUSIONS OF STUDY

An extensive laboratory study was conducted to evaluate different waste plastics used as an asphalt binder modifier. Three waste plastics types, polyolefin, thermoplastic and co-block plastic, were preblended in the same base asphalt binder at varying percentages. Asphalt binder rheological and fracture-based properties were measured and an optimum plastic waste and dosage rate was selected for asphalt mixture evaluation. The asphalt mixture testing consisted of stiffness, rutting, cracking and moisture damage potential testing at early life and late life aged conditions. The results of the study showed;

1. Both the polyolefin (MR6) and co-block plastic (MR10) waste materials are highly prone to phase separation from the liquid asphalt binder. Meanwhile, the thermoplastic waste plastic (MR8) showed little to no separation at the dosage rates evaluated in the study. Therefore, the use of waste plastics preblended in asphalt binders should be consistently agitated when in storage to ensure separation will not occur. Otherwise, a compatibilizer-type additive may be required to limit separation.
2. Both the polyolefin and co-block plastic waste materials resulted in shifting the performance grade properties of the asphalt binder warmer than the base PG64-22 asphalt binder used for blending. This resulted in improvements in the high temperature performance grade but detrimentally impacting the low temperature grade performance of the plastic waste modified asphalt binders. In contrast, the thermoplastic waste plastic was found to have little to no impact on the high temperature performance grade of the asphalt binder but did slightly improve the low temperature property of the asphalt binders.
3. Rheological asphalt binder parameters, such as the Glover-Rowe parameter and the (Loss Tangent)^2 at $G^* = 10$ MPa, showed that the thermoplastic waste plastic may aid in reducing the impact on aging on the fatigue performance of the asphalt binders. Slight improvements were found over the base PG64-22 asphalt binder, while both the polyolefin and co-block waste plastic showed to be detrimental to the both of these rheological parameters.
4. Fracture-based asphalt binder testing once again showed that the addition of the thermoplastic waste plastic may provide benefit as the asphalt binder undergoes oxidative/thermal aging. Slight improvements were shown in the CTOD parameter of the DENT test while the NCHRP 9-60 approach showed the thermoplastic waste plastic to perform as well as the base PG64-22 and the SBS modified PG76-22 asphalt binders.
5. The asphalt mixture testing was conducted on two baseline asphalt binders, an unmodified PG64-22 and an SBS modified PG76-22, along with two preblended thermoplastic waste asphalt binders that were found to be good performers from the asphalt binder portion of the study; 6% MR8 and 9% MR8. Stiffness properties, rutting resistance, fatigue cracking resistance and resistance to moisture damage were evaluated under a variety of test methods.
6. The asphalt mixture stiffness, as determined using the dynamic modulus, showed that the thermoplastic materials were able to achieve lower stiffness values after LTOA conditioning. This is extremely important as age hardening is one of the primary mechanisms for load and non-load associated cracking. The fact that the thermoplastic material may resist age hardening would greatly improve the ability for asphalt mixtures to resist non-load and load associated cracking.
7. The asphalt mixtures were evaluated using a variety of rutting-related performance tests. Overall, the SBS modified PG76-22 asphalt mixture was found to achieve the best resistance to permanent deformation while the unmodified PG64-22 asphalt mixture had the lowest resistance. The addition of the thermoplastic waste plastic slightly improved the rutting resistance over the base PG64-22 asphalt mixture.
8. The fatigue cracking performance was found to be highly dependent on the level of conditioning induced on the asphalt mixtures and the mode of the cracking test. The

thermoplastic modified asphalt mixtures performed better when evaluated under the crack propagation tests and LTOA condition while the SBS modified and unmodified PG64-22 was found to perform better at the crack initiation and STOA condition.

9. The moisture damage potential was found to be adequate for all four asphalt mixtures evaluated. However, the addition of the thermoplastic waste plastic did result in higher TSR values while reducing the measured indirect tensile strengths.

Overall, the study indicated that not all waste plastic materials are suitable for the wet process approach to modifying asphalt mixtures. Both the polyolefin (MR6) and co-block plastic (MR10) waste plastics were found to be highly susceptible to separation and reduced the fatigue cracking potential of the asphalt binder. It is recommended that future studies be conducted using a dry process (i.e. – adding the waste plastic directly into the drum or pug mill at the asphalt plant) to evaluate if this is a more suitable means of introducing polyolefin and co-block waste plastics into asphalt mixtures. This study appears to show that thermoplastic waste plastics, like the MR8 material evaluated in this study, are suitable for wet process applications and can provide a benefit to the overall performance of the asphalt mixture when compared to the base asphalt binder it is introduced to.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Bennert; data collection: Bennert, Ericson, Haas, Cytowicz, Wass and Tulanowski; analysis and interpretation of results: Bennert, Ericson, Haas and Cytowicz; draft manuscript preparation: Bennert; All authors reviewed the results and approved the final version of the manuscript.

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