Asphalt mixture performance and testing

Determining the effect of additives on hot mix asphalt performance through the testing of recovered composite mastic

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Abstract

As more and more recycled materials and additives are used in the manufacturing of hot mix asphalt (HMA), it has become rather meaningless to test bitumen sampled from the supply tank in the asphalt plant. Reclaimed Asphalt Pavement (RAP), Re-refined Engine Oil Bottoms (REOB), Ground Tire Rubber (GTR), Styrene-Butadiene (SB, SBS) polymer, and Polyphosphoric Acid (PPA) are materials commonly added to the HMA at various points during production. A standard method to determine their effect on HMA performance has been to extract and recover the binder for testing. This involves the use of solvents that may be hazardous to health and safety, and the process is generally speaking time consuming and laborious. The quality of extracted binder is also not guaranteed since solvent or filler may be left at the end of the process, or material such as polymer gel or rubber particulates may not pass through the filter feeding the rotary evaporator. Such issues have prevented the widespread use of extraction and recovery. A new method to determine the effects of additives on asphalt performance is proposed in this paper. A small quantity of mastic is separated from the mixture using a safe, fast and reliable physical process, without the use of any solvent. The material is called a composite mastic since it is comprised of all the components of the HMA except for the fine and coarse aggregates. Three tests are developed on a Dynamic Shear Rheometer (DSR) to test the composite mastic specimen to determine high, intermediate and low temperature properties. The high and low temperature properties provide the Performance Grade (PG) of the mixture and the intermediate temperature property is a newly developed fatigue index. It is shown that the method can determine the effect of additives on high and low temperature PG, and fatigue performance.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

Efforts to develop test methods and acceptance criteria for the control of the three main distresses in pavements are ongoing as industry practices continue to change. During the US Strategic Highway Research Program of the 1980s, a limited number of eight straight run bituminous binders were used to develop what is now embodied in American Association of State and Transportation Highway Officials (AASHTO) standard M 320 [1]. Originally meant to be a performance-based acceptance specification [2], it was generally recognized early on to have turned into a purchase specification with significant and continuing risks to user agencies. Case studies on early cracking showed that pavements of nearly identical designs, traffic, subgrades and climates can show significant variations in performance based on bitumen properties, perhaps related to additives at the asphalt plant (e.g., Reclaimed Asphalt Pavement (RAP), Reclaimed Asphalt Shingles (RAS), Recycled Engine Oil Bottoms (REOB) or other diluent oils), or issues such as overheating during production and placement of the asphalt [3-5].

The discordance between design and pavement performance for properly constructed pavements can largely be attributed to issues with respect to binder tests embodied in AASHTO M 320. First, conditioning of samples at both high temperatures, in the Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV), and low temperature in the Bending Beam Rheometer (BBR), has proven to be inadequate [3-10]. Materials recovered from pavements in early life have consistently shown to be harder and less able to relax stress in comparison to PAV residues [3, 5, 7, 10]. This must either be related to insufficient aging in the PAV, the introduction of deleterious additives, overheating during production, or a combination of such factors. In addition, conditioning at cold temperatures has shown to be a very effective way to separate superior from inferior materials, suggesting that the sampling and BBR conditioning protocols need to be improved [3-5, 8-11].

Second, a practical failure test for bitumen at intermediate temperatures has remained elusive [12-15]. Fatigue cracking is a complex phenomenon that is influenced by a significant number of variables. The original SHRP program thought that placing a limit on the bitumen loss modulus, $G'' = G^*\sin\delta$, should be effective for the control of fatigue, as it relates to the amount of dissipated energy during sinusoidal loading. Data obtained from the Zaca-Wigmore trial and from tests under controlled laboratory conditions suggested that an upper limit of 5.0 MPa on binder loss modulus could efficiently prevent the occurrence of cracking [16].

However, $G^*\sin\delta$ is obtained at low strain levels and as such energy is largely dissipated as heat, due to viscous flow, rather than through the formation of damage. Second, the stress state in between parallel plates and the continuous sinusoidal loading does not reflect how cracks open. Third, it seems that an upper limit of 5.0 MPa on $G^*\sin\delta$ actually promotes the wrong types of materials. Those binders that have both a low stiffness and low phase angle, due to phase separation, are known to show higher levels of ageing and cracking [17]. Finally, it is also recognized that thermal stress plays a rather important role in fatigue—a complex issue that is largely ignored [11, 18, 19].

In response to these early observations there have been a number of efforts to improve the specification. Work by one of us has focused on the development of the Double-Edge-Notched Tension (DENT) test to measure an approximate critical Crack Tip Opening Displacement (CTOD), which reflects strain tolerance in the ductile state [12-15]. The CTOD correlates with fatigue as binders that are more strain tolerant allow the pavement to flex before cracking starts and this reduces distress [15]. One drawback of the DENT is that it requires a significant amount of material. Using recovered bitumen, this creates problems with time, cost and safety concerns related to the handling of solvent.

In search of tests that use less time, cost and forgo the use of solvent, a new testing system referred to as UPTiM has been developed. UPTiM stands for Unified Performance Testing using incremental Methodology and m*, and meets industry needs for characterizing binders with various types of modifications [20-25].

The UPTiM protocol includes tests to determine the properties of tank-sampled and extracted bitumen, as well as mastic, which is defined here as the fine portion of the mixture with filler particles less than 250 μm in size. The mastic is physically separated from the asphalt mixture without the use of solvents and is referred to as a composite mastic since it includes all the effects from the additives on the bitumen. The process of preparing mastic involves heating the mixture to the level that does not change the properties of the material and is significantly faster and less costly than recovery of bitumen. In addition, the mastic better represents the material in the mixture since the process of recovering changes the level of blending of the original binder, RAP and other additives. UPTiM is based on a unified concept that applies to low temperature, high temperature and intermediate temperature tests on asphalt binder, mastic and mixture.

The UPTiM tests on both composite mastic and straight bitumen are performed on a Dynamic Shear Rheometer (DSR), require only a small amount of material and can be completed in a fraction of the time necessary to complete the AASHTO M 320 bitumen tests. UPTiM protocols provide equivalent results to existing new and old performance-related standards for unmodified bitumen while they differentiate between materials with different types and levels of modification.

The first objective of this study is to investigate the reliability of the UPTiM tests in determining properties of recovered bitumen. Second, the feasibility of using mastic as a replacement for bitumen recovery is investigated.

The scope of this study is to test extracted bitumen and recovered composite mastic from regular paving contracts in Ontario, Canada. Results from other studies are presented to complement the results. Binders were recovered and subsequently aged using the standard PAV procedure.

2. EXPERIMENTAL

2.1 Materials

A total of 18 binders and associated asphalt samples were used. The bitumen was extracted with toluene. The solution was twice fed through a centrifuge to remove fines prior to recovery. Solvent was carefully removed under a nitrogen atmosphere by using a rotary evaporator. Once the bulk of the solvent had been distilled, the temperature was increased in steps of 20 °C to a final 160 °C. The flask was left for an additional hour to make sure all solvent was removed. Unaged binder was tested at high temperatures and further aged in the PAV to provide material for testing at intermediate and low temperatures. Mastic was physically separated from the asphalt without the use of solvent.

Additional binders and mixtures were obtained for comparison from SPS10 sites constructed by the Missouri Department of Transportation, test cells from MnRoad constructed by the Minnesota Department of Transportation, and Accelerated Loading Facility lanes at the U.S. Federal Highway Administration in Virginia.

2.2 Standard Binder Performance Tests

AASHTO M 320 Specification Grading

The regular performance grades for the binders were determined according to procedures referenced in AASHTO standard M 320 [1]. The Performance Grade (PG) required for a location in North America is determined using high and low pavement temperature models [26-27] which are implemented in the software LTPPBind® [26, 28]. The grade is used commercially to trade and sell bitumen in North America but the grades have fallen short of being based on or related to performance. Binders of nearly identical M 320 grades can perform very differently due to differences in aging tendencies [3-11].

Double-Edge-Notched Tension Testing

Ductile failure properties were determined according to AASHTO TP 113-15 [29]. PAV residues were poured into silicone molds and conditioned at 15°C for 2 hours prior to testing. The energy under the curve was divided by the cross sectional area of the ligament and the specific total work of failure so obtained was plotted versus ligament length. The intercept of this straight line provided the specific essential work of failure which was divided by the net section stress to determine an approximate critical CTOD. Higher values give a binder more ability to stretch before failing and thus should reduce fatigue cracking. Additional background to this method is provided in previous publications [12-15].

2.3 UPTiM Binder and Mastic Performance Tests

The UPTiM tests for binder and mastic, which includes low temperature, intermediate temperature, and high temperature tests, are performed using a DSR [20-25, 30]. The tests are surrogates to low and high temperature performance grades (AASHTO R 29 [31]), high temperature grades with traffic bumping (compatible with LTPPBind V. 3.1 [28] and AASHTO M 332 [32]), intermediate grades (compatible with AASHTO R 29 for unmodified binders [31]), elastic recovery (AASHTO T 301 [33]), and the CTOD parameter (AASHTO TP 113 [29]). UPTiM tests for binder and mastic emulate current standards and are shown to have good correlation with the mixture tests [35-38].

UPTiM parameters are sensitive to the presence of additives and modifiers and differentiate between different types and amounts of polymer. The tests are performed using 8 mm diameter parallel plates and a 0.5 mm gap. While the tests on mastic are performed using 8 mm parallel plates and a 1 mm gap. A brief description of the UPTiM tests performed on binder and mastic in this study is given next.

Low Temperature UPTiM Test

The low temperature test, referred to as the Incremental Creep at Low Temperature (iCCL) test, is a creep test of 60 second similar to the BBR test (Figure 1). Tests can be performed at several increments of multiple subzero temperatures or at multiple stresses at a fixed subzero temperature (e.g., -5 °C). The duration of the test is about 30 minutes. The total deformation and slope of the creep curve is used to determine the continuous LTPG, similar to AASHTO R 29. Further details on the iCCL test can be found elsewhere [23, 38].

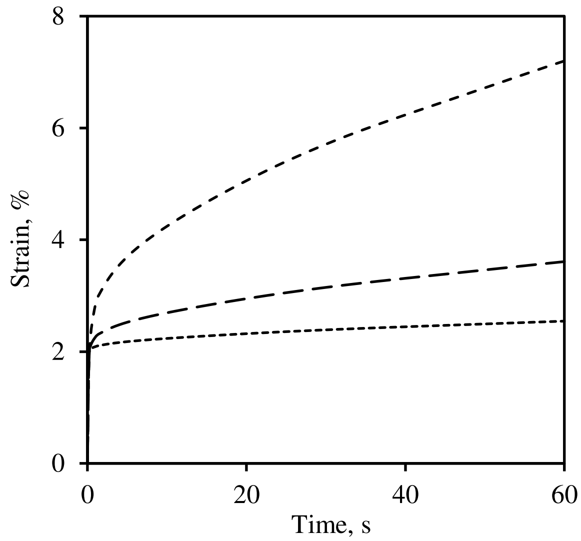

Figure 1. DSR Constant Shear (Creep) Load for iCCL Test Showing Strain (%) versus Time at 0 °C (top curve), -6 °C (middle curve), and -12 °C (bottom curve).

High Temperature UPTiM Test

The high temperature test determines the HTPG similar to M 320 for unmodified binders. For modified binders it provides traffic bumping similar to M 332 using LTPPBind V3.1. The test is performed at several temperature increments, each including 60 cycles of repeated 0.1 s load followed by 0.9 s rest period. The secondary slope of the permanent strain curve (m*) is used to determine the UPTiM parameters. The test duration is 30 min. Further details of the high temperature test can be found elsewhere [21, 22].

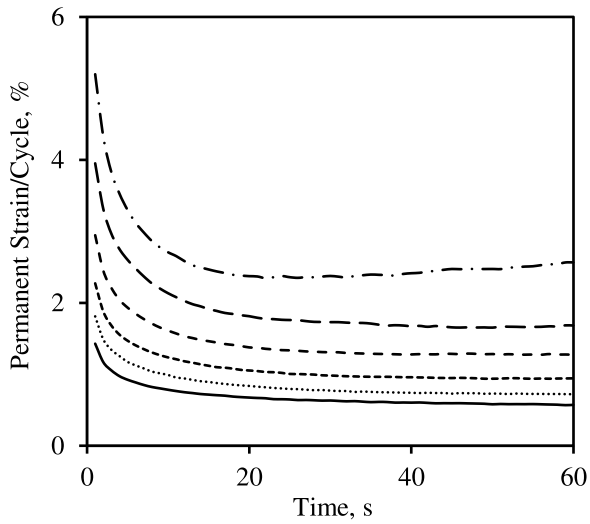

Figure 2. Permanent Strain per Cycle versus Time for 5 Increments of 1 °C from 17 °C (bottom solid curve) to 22 °C (top dashed curve) on a PG 64-28 Binder.

Fatigue UPTiM Test

The fatigue test for binder and mastic is referred to as FIT-B and FIT-C (Fatigue Test at Intermediate Temperature for Binder and Composite Mastic). The test is performed at several temperature increments, each including 60 cycles of repeated 0.1 s load followed by a 0.9 s rest period (Figure 2). The slope of the permanent strain curve at failure is used to determine the percentage elastic recovery, similar to ASTM D6084 [34] and the CTOD parameter of the DENT test (AASHTO T 113 [29]). The temperature at failure which is the temperature at which the material is most vulnerable to fatigue cracking is the intermediate temperature grade. This temperature is compatible to the SHRP intermediate temperature for neat binders and is lower or higher than the SHRP intermediate temperature for binders with additives and modifiers. The UPTiM fatigue test is sensitive to the type and level of modification and clearly shows the effects SBS, PPA, and REOB on fatigue performance. More details on the fatigue tests can be found elsewhere [24].

3. RESULTS

3.1 Standard Test Results

The standard binder test results for the 18 contract samples are provided in Table 1. The results for user agencies A-C are for contracts where extracted and recovered bitumen properties were used for acceptance of the asphalt. For user D the asphalt acceptance was based on tank-sampled properties.

Table 1. AASHTO R 29 Test Results for Bituminous Binders from 18 Ontario Contracts

User Agency	Design Grade	RAP, %	AASHTO M 320 Unaged and PAV			AASHTO TP 113 PAV
			HTPG, °C	LTPG, °C	ITPG, °C	DENT CTOD, mm
A	70-28	0	72.6	-35.0	11.6	32.1
	70-28	0	73.8	-36.1	9.5	24.5
	70-28	0	76.9	-34.0	12.7	27.5
	70-28	0	77.0	-34.1	11.9	27.6
B	64-28	0	67.2	-35.7	10.2	19.0
	64-28	0	71.3	-31.5	15.9	16.7
	64-28	0	76.3	-32.1	16	14.1
	64-28	0	74.1	-35.5	11.2	36.3
	64-28	0	72.7	-37.2	6.8	10.8‡
	64-28	0	71.2	-29.5	18.6	19.7
	64-28	0	73.5	-34.5	15.3	17.3
C	64-28	0	71.5	-39.4	6.4	40.3
D	58-28	15	72.8	-27.2†	25.4*	8.2‡
	58-28	15	61.6	-28.5	22	10.2‡
	64-28	0	61.5	-29.7	18.8	12.2‡
	64-28	0	62.8	-29.4	18.3	11.9‡
	58-28	15	63.3	-29.1	19.9*	11.1‡
	58-28	20	67.2	-28.3	22.5*	9.5‡

Note: † Single binder failed the LTPG requirement of -28°C. * Three binders failed the required 19°C ITPG. ‡ One binder from B and all six from D failed the 14 mm CTOD requirement. User D bases acceptance on tank-sampled bitumen properties.

3.2 UPTiM Test Results

The UPTiM test results at high temperatures, low temperatures, and intermediate temperatures, on recovered unaged and recovered PAV-aged binder, and on composite mastic are provided in Table 2. There are missing data in the table because not all of the extracted binders for these mixtures were kept for UPTiM testing.

4. DISCUSSION

4.1 Standard Binder Performance Tests

AASHTO M 320 Specification Grading

All the recovered binders were tested according to AASHTO R 29 [31] in order to determine their grades according to AASHTO M 320 [1]. The HTPG values listed in Table 1 show that these are generally close to the design for all of the user agencies but there are several outliers. User B has two contracts that have recovered HTPG values that are as much as 12.3 °C and 10.1 °C higher than what the contract documents specified. These correspond to about a four times higher high temperature stiffness than required. User D has one binder with a recovered HTPG of 72.8 °C, or about 14.8 °C higher than what the contract specified (the mix design lists 15 % RAP). Whether these significant differences are due to the presence of the RAP, overheating in the asphalt plant or some other issue is difficult to judge. Differences in ITPG are also considerable, ranging from a low of 9.5 °C to a high of 25.4 °C. The LTPG values for users A-C surpass the contract requirement of -28 °C by a good amount as these were also required to pass the more severe extended BBR protocol at the same low temperature. Only one of the LTPG values fails for user D, likely due to the quantity of RAP actually used in the asphalt mix. It should be noted though that several additional binders from this agency failed when conditioned for three days at cold temperatures. The results from these tests show that within this limited group of 18 binders there are significant deviations from the design and that therefore there will likely be significant differences in pavement performance. In Ontario there is no limit on the HTPG deviation from the design (samples only have to pass) and this might be a major reason for long term durability problems as with higher levels of modification comes risk for durability loss.

Table 2. UPTiM Test Results for 18 Ontario Bituminous Binders and Mastics

User Agency	Extracted Unaged			Extracted PAV-Aged			Composite Mastic		
	HTPG, °C	LTPG, °C	FI	HTPG, °C	LTPG, °C	FI	HTPG, °C	LTPG, °C	FI
A				79.2	-34.3	59	69.5	-36.9	25
	75.4	-33.9	81	71.6	-37.2	51	61.1	-39.0	33
	81.9	-33.1	136	82.1	-34.4	107	70.5	-37.0	29
							70.3	-37.3	30
B	67.8	-35.3	66	63.5	-36.8	48	59.0	-36.1	12
							60.3	-33.6	12
	71.2	-29.2	36	69.8	-30.4	47	65.1	-32.7	11
	75.8	-33.7	159	72.1	-37.1	101	64.9	-37.8	43
	66.7	-25.9	14	65.9	-27.0	22		-31.5	11
	68.9	-32.8	68	67.8	-34.9	53		-32.9	15
							65.2	-32.9	12
C							63.5	-40.3	28
D	71.0	-23.0	13	70.9	-24.4	2.4	67.3	-24.3	8.4
	66.1	-27.0	17	60.9	-30.9	17	59.5	-29.0	10
	63.0	-29.2	16	61.5	-30.2	23	60.3	-31.7	11
	63.3	-29.6	17	63.4	-29.3	24	57.2	-34.2	15
	64.3	-27.8	15	63.7	-27.6	25	62.0	-27.5	5.6
	65.5	-25.9	16	67.2	-25.7		64.4	-27.9	7.4

4.2 UPTiM Binder Performance Tests

Comparison of AASHTO R 29 and UPTiM Grades for 18 Ontario Binders

The AASHTO R 29 (M 320) performance tests were compared with the results from UPTiM testing. For the regular tests, recovered binders were used to determine the high temperature grades, followed by standard PAV aging and BBR and DENT testing to determine low temperature grades and CTOD properties. In contrast, the UPTiM protocol can use either recovered unaged, recovered PAV-aged, or straight mastic material from the mixture to determine low temperature, high temperature and fatigue properties. Figure 3 shows a comparison between the high temperature grades using AASHTO R 29 (Table 1) versus the UPTiM grades (Table 2) for unaged recovered binder, PAV-aged recovered binder and composite mastic.

It can be seen that for extracted and recovered binders (unaged and PAV-aged), the HTPG for AASHTO R 29 and UPTiM are rather close. The UPTiM HTPG using mastic, however, is about a grade lower than what it is for the recovered binders. This could be due to the differences between extracted material and composite mastic since the mastic recovery does not involve the use of solvent. Or, it could be due to binder-filler interactions that play a role in the UPTiM but that are absent from the straight binder tests. Similar data for the LTPG is shown in Figure 4. As is clear, UPTiM tests on extracted binders (unaged and PAV-aged) provide comparable LTPG with AASHTO R 29. The LTPG of mastic is slightly lower than that of the extracted binder for the same possible reasons as above.

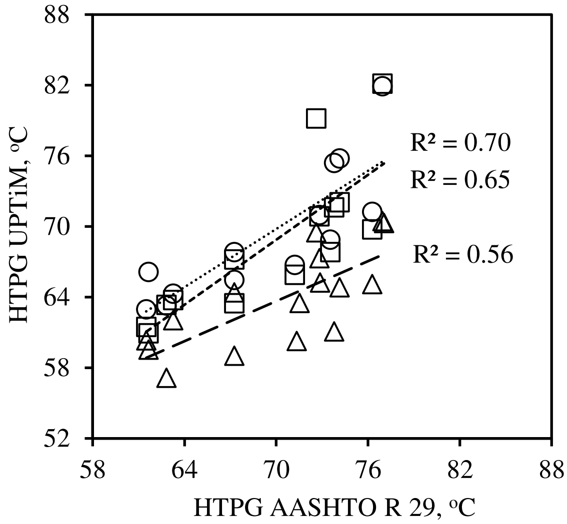

Figure 3. UPTiM HTPG for Recovered Binders and Mastics versus AASHTO R 29 Grades.
Note: Triangles are for UPTiM HTPG from unaged composite mastic test, squares are for UPTiM HTPG from unaged binder test, and circles are for UPTiM HTPG from PAV-aged binder test.

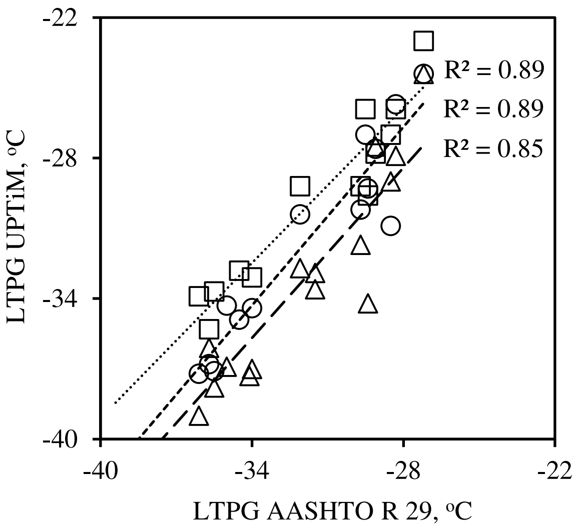

Figure 4. UPTiM LTPG for Recovered Binders and Mastics versus AASHTO R 29 Grades.
Note: Triangles are for UPTiM LTPG from unaged composite mastic test, squares are for UPTiM LTPG from recovered unaged binder test, and circles are for UPTiM LTPG from recovered PAV-aged binder test.

Comparison of Superpave and UPTiM for 41 Mixtures
Data for the 14 Ontario mixtures with PAV-aged recovered binder were complemented with data from ten SPS10 sites in Missouri (Missouri DOT), seven MnRoad mixtures (Minnesota DOT), and ten mixtures from a Federal Highway Administration Accelerated Loading Facility (FHWA ALF) fatigue study for examining the correlation between PAV-aged recovered binder and composite mastic for a wider range of mixtures from different locations.

Figure 5 shows the UPTiM HT PG for mastic versus that for the extracted and recovered binder while Figure 6 shows similar data for the LTPG. The data in Figures 5 and 6 indicate a very good correlation between HTPG and LTPG of the extracted and recovered binder and mastic properties over a wide variety of materials from varied sources. The standard error of difference between mastic and extracted binder grade is only 2.1°C for LTPG and it is 3.5°C for HTPG.

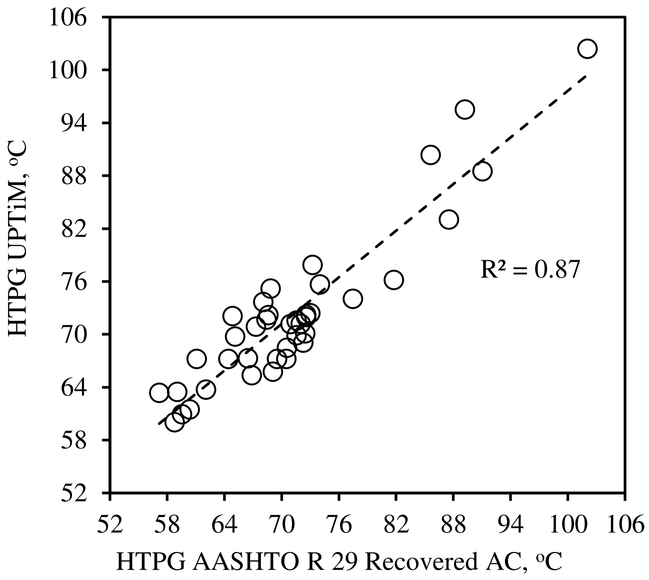

Figure 5. UPTiM HTPG for Mastic versus Extracted Binder (41 Samples).

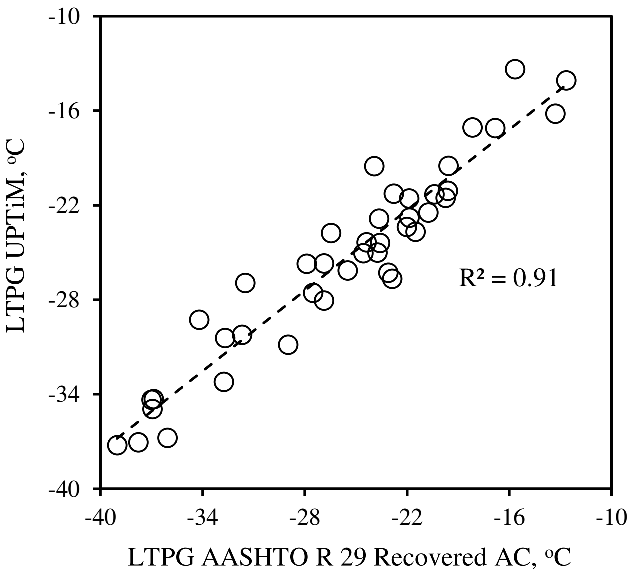

Figure 6. UPTiM LTPG for Mastic versus Extracted Binder (41 Samples).

From data presented in Figures 3-6, it can be concluded that the UPTiM mastic test protocol provides comparable grades to those obtained for extracted binders according to AASHTO standard R 29.

Comparison of UPTiM Fatigue Index and DENT

The UPTiM Fatigue Indices using extracted and recovered binder, PAV-aged recovered binder, and mastic were compared with the DENT CTOD parameter (for PAV-aged recovered binder) for 14 Ontario mixtures. Figure 7 shows the UPTiM Fatigue Indices (FI) versus the DENT CTOD values. It shows that the best correlation is for the unaged extracted and recovered binder ($R^2 = 0.96$). However, the correlation for the composite mastic is still relatively good ($R^2 = 0.76$). It appears that the UPTiM Composite Mastic Fatigue Index (FIT-C) has the same scale as DENT CTOD.

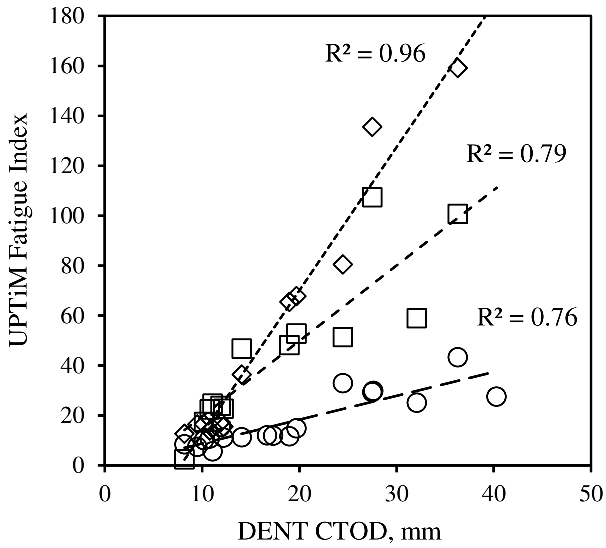

Figure 7. UPTiM Fatigue Index for Recovered Unaged, Recovered PAV-Aged, and Mastic versus DENT CTOD.
Note: Diamonds are for UPTiM on recovered unaged material, squares are for UPTiM on recovered PAV-aged material, and circles are for UPTiM on recovered composite mastic.

5. PRECISION AND BIAS

The number of UPTiM tests and the average coefficient of variation (COV) for each material type and test parameter (HTPG, LTPG, and FI) are listed in Table 3. A total of 78 tests were conducted on unaged extracted and recovered binder and 88 tests were performed on PAV-aged extracted and recovered binder (2 or 3 replicates for each material and test). The number of tests on composite mastics were about double the number of tests on extracted and recovered binders at 172 (3 or 4 replicates per material and test). Note that the mastic was recovered at two different times and the COV includes variability from the mastic recovery step. Overall, 392 tests were conducted using the UPTiM protocol. As is seen, the average COVs for HTPG and LTPG of the extracted and recovered binders are less than 1 %. The average COVs for HTPG and LTPG for PAV-aged extracted and recovered binders and composite mastic were also very impressive at around 2 %. The UPTiM fatigue test for unaged extracted and recovered binder had the lowest COV (10 %), while the COV of PAV-aged extracted and recovered binder and composite mastic were higher (13 % and 16 %, respectively). Overall, the variability of the HTPG and LTPG is a fraction of what is typically found for AASHTO R 29, showing that UPTiM high and low temperature tests are highly repeatable. The higher variability of the fatigue test is due to these being failure tests rather than low strain rheological tests. For this reason, more replicates may be conducted for FI tests.

Table 3. Coefficients of Variation for Each Test and Material Tested

Material	UPTiM HTPG		UPTiM LTPG (iCCL)		UPTiM Fit-B and Fit-C	
	COV, %	N	COV, %	N	COV, %	N
Unaged Extracted and Recovered	0.7	26	0.9	26	10	26
PAV-aged Extracted and Recovered	1.8	30	2.0	30	13	28
Recovered Composite Mastic	2.0	58	2.3	58	16	56

Future work with additional mastic and binder from contracts and trial sections will consider potential bias errors in this analysis. Effects of conditioning at both low and high temperatures will be assessed and may improve the accuracy of the specification in future.

6. SUMMARY AND CONCLUSIONS

In this study the reliability of the UPTiM tests for characterizing the high, low and intermediate temperature properties of bitumen was demonstrated by comparing UPTiM test results with those of AASHTO R 29 and AASHTO TP 113. In addition, the feasibility of using composite mastic, physically separated from the mixture, in place of extraction was examined by comparison of UPTiM mastic results with those obtained through AASHTO R 29 for extracted and recovered binder. The findings are as follows:

- The UPTiM binder tests provided nearly equivalent LTPG and HTPG values to AASHTO R 29 from testing either unaged or PAV-aged extracted and recovered binder.

- For the Ontario binders, UPTiM mastic tests provided LTPG and HTPG values that were slightly lower than those determined by testing extracted binder. This could be due to the differences between the composite mastic and extracted binder from use of solvents in the extraction process. However, the correlations between the high temperature and low temperature properties of recovered binder and mastic were strong using 41 materials from various studies.
- The relationship between the UPTiM Fatigue Index of unaged binder, PAV-aged recovered binder, or mastic with the DENT CTOD parameter indicate that the correlation is the best for unaged recovered binder ($R^2 = 0.96$). The correlation between the Fatigue Index of PAV-aged recovered binder and CTOD, and the correlation of the composite mastic fatigue index and CTOD are similar with $R^2 = 0.79$ and $R^2 = 0.76$, respectively.

Hence, it can be concluded that the UPTiM tests are capable of providing results similar to AASHTO R 29 and AASHTO TP 113 using unaged and PAV-aged bitumen as well as using mastic in a fraction of the time needed to perform current tests. It is also concluded that composite mastic testing is a safe, quick and reliable alternative to the testing of extracted and recovered bitumen. The mastic could be more representative of the binder in the mixture than extracted binder since there are is no solvent involved, which might change the molecular structure of the binder.

7. ACKNOWLEDGMENTS

The Ontario agencies that provided materials and funding for this work are hereby gratefully acknowledged.

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