COMPREHENSIVE EVALUATION OF WARM MIX ASPHALT MOISTURE SUSCEPTIBILITY

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ABSTRACT

The Ministry of Transportation of Ontario (MTO) has implemented optional use of Warm Mix Asphalt (WMA) technology on Ontario's highways and roads since 2012. Many types of WMA technologies have been successfully used to produce and place over one million tonnes of WMA in Ontario's provincial highways to date with proven environmental, economical and safety benefits. However, there are still concerns with moisture resistance of WMA mixes due to lowered production and placement temperatures.

To address the aforementioned concern, MTO and the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo have partnered under MTO's Highway Infrastructure Innovation Funding Program (HIIFP) to evaluate the moisture susceptibility of WMA through a laboratory testing program. The program includes Hamburg wheel tracking test, tensile strength ratio (TSR) using two conditioning methods of Moisture Induced Stress Tester (MIST) and AASHTO T283, and stripping by static immersion tests.

Mixtures for this study were produced using two Performance Graded Asphalt Cement (PGAC) sources, three types of WMA additives, and three aggregate types. This paper presents the laboratory test results and evaluates the effects of several WMA additives on moisture resistance of typical Ontario Superpave mixes. The paper further attempts to determine if there is a correlation between the results from the Hamburg test, TSR, and static immersion test.

Keywords: moisture susceptibility, hot mix asphalt, warm mix asphalt, MIST, swell, Evotherm, Rediset, Sonnewarmix, static immersion

INTRODUCTION

The Ministry of Transportation of Ontario (MTO) has implemented the optional use of Warm Mix Asphalt (WMA) on Ontario's highways and roads since 2012. Many types of WMA technologies have been successfully used to produce and place over one million tonnes of WMA on Ontario's provincial highways with proven environmental, economical and safety benefits including (Tabib et al., 2014):

- Reduced Green House Gas (GHG) emissions at the asphalt mixture production plant and during paving operations,
- Reduced fuel consumption at the asphalt mixture plant,
- Improved workers' health and safety due to reduced asphalt fumes and lower mix temperature at paving sites,
- Improved compaction and joint quality,
- Less potential to crack due to reduced asphalt binder aging,
- Facilitating longer haul distances from the production facility to the paving site, and
- Potential for higher reclaimed asphalt pavement (RAP) content.

Despite the aforementioned benefits of WMA, there are still concerns with warm mix technologies in Ontario, including (Tabib et al., 2014):

- Effectiveness of different technologies,
- Ensuring long term performance and resistance to moisture damage,
- Restrictions/adjustments at the asphalt plant – production of WMA may require adjustments to the burner and flights. Some plants encounter clogging of material on the conveyor belts when they lowered their production temperature,
- Combination with antistrip additive – when used need to ensure that the WMA additive is compatible with the antistrip additive.

Scope and Objectives

MTO and the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo have partnered under MTO's Highway Infrastructure Innovation Funding Program (HIIFP) to evaluate the moisture susceptibility of WMA through a comprehensive laboratory testing program, particularly the ability of AASHTO T283 conditioning method (known as "modified lottman") to detect moisture susceptibility of WMA compared to Moisture Induced Stress Tester (MIST), Hamburg Wheel Tracking Test (HWTT), and stripping by static immersion test.

EXPERIMENTAL PLAN

A combination of qualitative and quantitative laboratory test methods was used to evaluate the effect of several WMA additives on moisture resistance of typical Ontario Superpave mixtures. The variables included two grades of PGAC, three types of WMA additives, and three different aggregate sources. The main objective of this assessment was to establish a reliable ranking system for moisture susceptibility of WMA mixtures and determine if there is a correlation between the results from the Hamburg test, Tensile Strength Ratio (TSR), and static immersion test.

Materials and Specimen Preparation

Modified binder prototypes were produced following a consistent approach using a single source of PG 58-28 and 58-34 (polymer-modified) base asphalt binders in combination with three types of warm mix additives. More information on additives used is given in TABLE 1. Additive types were selected based on the preliminary literature review, availability to the paving industry, a survey performed in 2015 by CPATT-UW on Canadian usage of WMA (Varamini & Tighe, 2015), and guidance from MTO. For each additive, the supplier's recommended dosage rate (as listed in TABLE 1) were used to treat molten base binders with different types of additives.

TABLE 1 Warm Mix Asphalt Additive Information

WMA Additive	Type	Colour	Addition rate (% by binder weight)	Physical State at 25ºC
Evotherm® 3G	Chemical (Fatty amine derivative)	Amber Dark	0.3	Liquid
Rediset® LQ	Chemical (Surfactant blend)	Brown	0.5	Liquid
SonneWarmix™	Wax/Organic	Brown	1.0	Solid

Three aggregate sources were used in this study: trap rock diabase, referred to as aggregate "A", granite, referred to as aggregate "B", and dolomite sandstone, referred to as aggregate "C". Aggregate types and sources were selected based on the MTO's past experience and historical records on their composition and their susceptibility to moisture damage. All aggregate types are listed in the MTO's Designated Sources for Material (DSM) for use in the premium asphalt mixes. More information on aggregate mineralogy and physical properties are listed in TABLE 2. Composition of each aggregate type was determined by using Bruker X-ray fluorescence (XRF) analyzer at MTO's Bituminous Laboratory. For this test, 50-grams of material retained on different sieve sizes were batched and crushed using two types of crushers to achieve a fine powder passing 75-µm sieve size for XRF analysis. Given in TABLE 2, XRF analysis verified that type B and C aggregates contain a relatively higher percentage of silicon dioxide (SiO_2) compared to type A, indicating that types B and C are more susceptible to moisture damage than type A aggregate.

Each aggregate blend consisted of premium 12.5 mm coarse aggregate, and crusher fines (washed, and unwashed) to meet physical requirements of premium Superpave 12.5 mm mixture as per Ontario Provincial Standard Specification, as given in TABLE 2. Asphalt mixtures were produced in the CPATT's laboratory at the University of Waterloo. All mixtures were short-term aged prior to testing using a forced draft oven: HMA mixtures (control) for 4 hours at 135ºC as per AASHTO R30 and WMA mixtures for 2 hours at field compaction temperatures as per AASHTO R35.

Testing Procedures

Binder Characterization

The Superpave PGAC binder specification according to AASHTO M320 (AASHTO, 2010) was followed to characterize each modified binder used to produce warm mix asphalt mixtures. This was to ensure recommendations provided by the additive suppliers were appropriate for this study and all binders are exhibiting similar high and low temperature performance grades and the targeted PG grades were not adversely affected by the additives.

TABLE 2 Asphalt Mixtures Properties

Property		12.5 mm maximum size OPSS[1] Requirement	Aggregate		
	Sieve Size (mm)		Type A[2] Blend	Type B[3] Blend	Type C[4] Blend
Gradation (% Passing)	12.5	90 – 100	96.7	94.8	98.1
	9.5	45 – 90	83.6	79.6	87.3
	6.7	-	65.3	64.6	-
	4.75	45 – 55	55.0	55.0	62.9
	2.36	28 – 58	45.3	42.8	45.4
	1.18	-	30.6	32.6	33.1
	0.600	-	19.8	23.8	25.7
	0.300	-	12.2	13.2	12.8
	0.150	-	7.2	5.9	6.7
	0.075	2 – 10	4.0	3.0	3.1
N_{des} (%G_{mm})		96.0	96.0	96.0	96
N_{ini} (%G_{mm})		≤ 89.0	88.8	89	88.9
N_{max} (%G_{mm})		≤ 98.0	97.2	97	97.6
Air Voids (%) at N_{des}		4.0	4.0	4.0	4.0
Voids in Mineral Aggregate, VMA (% minimum)		14.0	14.7	14.3	14.3
Voids Filled with Asphalt, VFA (%)		65 – 75	73.2	72.2	71.3
Dust Proportion, DP		0.6 – 1.2	1.0	0.7	0.7
Asphalt Cement Content (%)		-	4.7	5.0	4.9
Silicon dioxide Content by X-ray Fluorescence, passed 75-µm (% of weight)		-	42.5	57.0	46.5

Note: [1]OPSS is Ontario Provincial Standard Specification, [2]Type A is trap rock diabase, [3]Type B is pink granite, and [4]Type C is Dolomite Sandstone.

Moisture Sensitivity

Moisture sensitivity of compacted mixtures was quantified as the percentage of tensile strength retained after conditioning which is referred to as the Tensile Strength Ratio (TSR). The tensile strength was determined by using the Indirect Tensile Strength (IDT) apparatus in accordance with ASTM D6931-12, “Standard Test Method for Indirect Tensile Strength of Bituminous Mixtures” (ASTM, 2012). Two moisture conditioning alternatives were considered for this study to evaluate the resistance of mixtures to moisture damage: (1) AASHTO T283 conditioning, and (2) moisture conditioning performed by MTO’s Moisture Induced Stress Tester (MIST) as per ASTM D 7870-13, “Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure” (ASTM, 2013). The strength testing was performed by applying an axial force at a rate of 50 mm/min until the maximum load was reached.

MIST conditioning was performed at MTO’s Bituminous laboratory by applying 3500 cycles of 276 kPa pore pressure at 50°C. Pore pressure cycling was applied immediately after specimens in the chamber reached a conditioning temperature of 50°C. This temperature was maintained by the equipment. After cycling, specimens were cooled to 25 ± 1°C in a water container for 2 hours prior to IDT testing. To further evaluate the moisture susceptibility of asphalt mixtures, the change in density (also known as “swelling”) was calculated for each specimen after MIST conditioning. Swelling was calculated by using Equation 1, by measuring Bulk Relative Density (BRD) of each specimen before and after MIST conditioning.

$$swell\ (\%) = \left(\frac{BRD_{initial} - BRD_{after\ MIST}}{BRD_{initial}}\right) \times 100 \tag{1}$$

To assess quality of chemical compatibility and bonding between binder and aggregate, static immersion test was performed at MTO's bituminous laboratory in accordance with LS-285, "Method of Test for Stripping by Static Immersion" (MTO, 2011). For this test, 100 grams of dry coarse-aggregate blend was prepared by mixing 50 grams of aggregate retained on 9.5-mm sieve size, 35 grams of retained on 6.7-mm sieve, and 15 grams of retained on 4.75-mm sieve size. The aggregate blend was placed in an oven at specified temperature prior to mixing with 4.0 ± 0.1 grams of heated asphalt binder. The loose mixture was then transferred to a 600-mL beaker to allow cooling to room temperature. After cooling, the beaker was filled with distilled water to the ¾ full mark,, sealed, and placed into a water bath at 49 ± 0.5°C for 24 hours. The beaker was then removed and placed under an illuminated magnifier for evaluation of the extent of retained asphalt coating on the aggregate as a percentage.

RESULTS

The Superpave PG binder specification according to AASHTO M320 (AASHTO, 2010) was used to characterize each modified binder. It can be seen from Figure 1 that the PG grades were not adversely affected by warm mix additives.

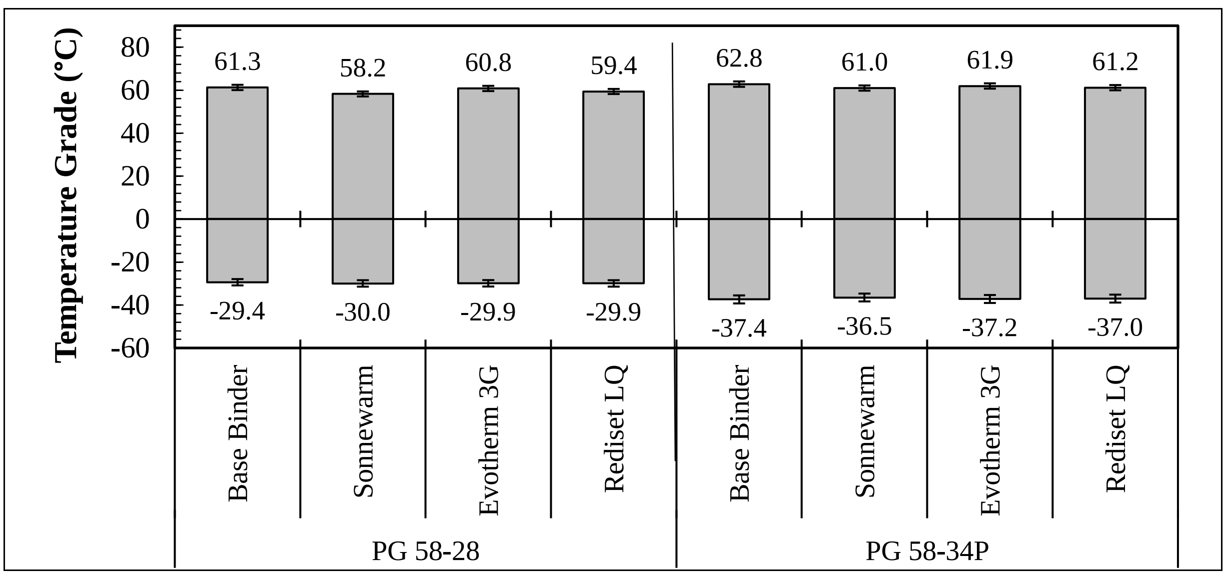


FIGURE 1 Continuous Performance Grade of Asphalt Binders Treated with Warm Mix Additives

Moisture Sensitivity

The resistance of compacted mixtures to moisture damage in terms of indirect tensile strength ratio was evaluated by employing two moisture conditioning protocols: (1) vacuum saturation followed by one freeze-thaw cycle as per AASHTO T283 procedure, and (2) moisture conditioning performed by MIST. Figure 2 presents the IDT strength test results for dry, T283 and MIST conditioned specimens containing different aggregate and additive types. In all figures, error bars represent one standard deviation from the average value of triplicate samples tested, with TSR results shown above the bars of each conditioning protocol.

Although addition of warm mix additives resulted in lower tensile strength for both dry and wet strengths, some of these additives (i.e. Evortherm 3G and Rediset LQ) seemed to have anti-stripping properties that improved TSR values as shown in Figure 2. TSR values also suggest that Sonnewarmix may not have such anti-stripping properties. The remaining concern is the reduction of dry and wet tensile strengths for mixes with warm mix additive compared to control mix. Figure 2 illustrates relatively good correlation between TSR values obtained by using T283 and MIST conditioning protocols. However, MIST protocol caused the most severe moisture damage compared to T283 protocol in a much shorter time. MIST protocol requires approximately six hours to complete while T283 conditioning requires two to three days.

In general, TSR values obtained from T283 and MIST conditionings suggest that Evotherm 3G provided higher level of resistance to moisture damage when used with PG58-28 compared to Rediset LQ and Sonnewarmix. Furthermore, it was observed that TSR values of all WMA mixtures are more than threshold of 80% specified by MTO, except for the mix with Sonnewarmix and PG58-28. However, in all cases higher TSR values were obtained because the dry IDT dropped more than the drop in wet IDT due to the effect of the warm mix additive.

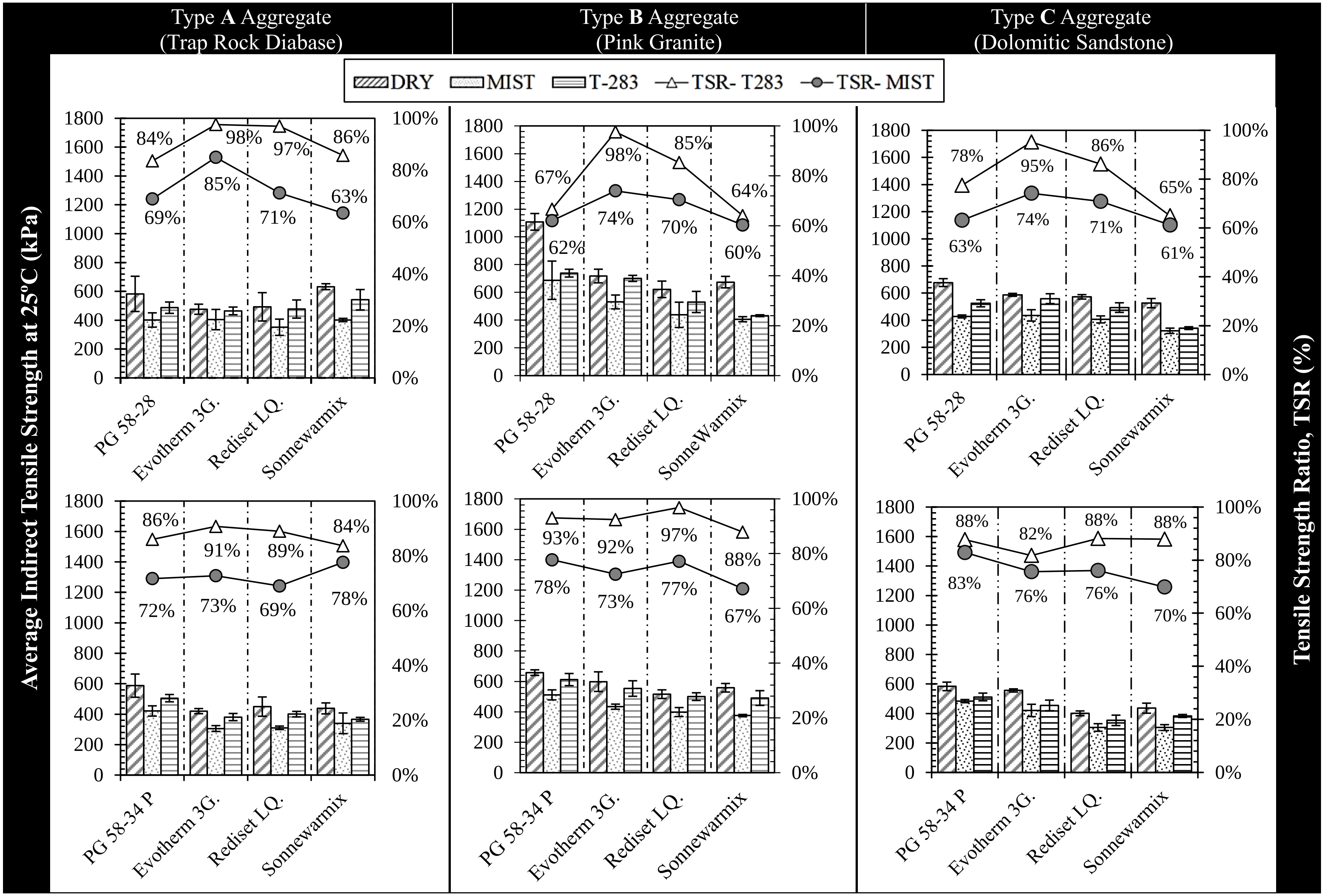
The correlation of TSR values obtained from T283 and MIST was further studied as shown in Figure 3. A relatively good correlation (R^2 value of 0.87) was observed between the two conditioning protocols for HMA samples. A poor correlation (R^2 value of 0.48) was observed for WMA samples.

Furthermore, an interaction plot as shown in Figure 4 was generated by using Minitab© statistical software. IDT shown in Figure 4(A) indicate that mixtures containing the PG 58-28 binder had higher strength compared to PG 58-34P mixtures. The analysis of variance (ANOVA) presented in Table 3 confirms that binder type, aggregate type, warm mix additive, and conditioning protocol are significance parameters in tensile strength variation.

TABLE 3 Analysis of Variance (ANOVA)

Source	**DF[1]**	**Adjusted SS[2]**	**Adjusted MS[3]**	**P-Value[4]**	**Statistically Significance**
Aggregate	2	558,142	279,071	0.000	**YES**
Binder	1	32,942	32,942	0.000	
Additive	3	652,805	217,602	0.000	
Conditioning	1	249,83	249,833	0.000	
Aggregate – Binder Interaction	2	83,585	41,792	0.000	**YES**
Aggregate – Additive Interaction	6	40,528	6755	0.000	**YES**
Aggregate – Conditioning Interaction	2	6751	3376	0.103	NO
Binder – Additive Interaction	3	83,989	27,996	0.000	**YES**
Binder – Conditioning Interaction	1	1,237	1,237	0.358	NO
Additive – Conditioning Interaction	3	3,763	1,254	0.461	NO

[1]Degree of Freedom, [2]Adjusted Sum of Squares, [3]Adjusted Mean of Squares, [4]P-Value is the probability of $|T_{observed}|>t_{critical}$ at significance level of 95% (α=0.05)



1 **FIGURE 2 Effect of WMA on Moisture Sensitivity of Superpave 12.5mm Mixtures**

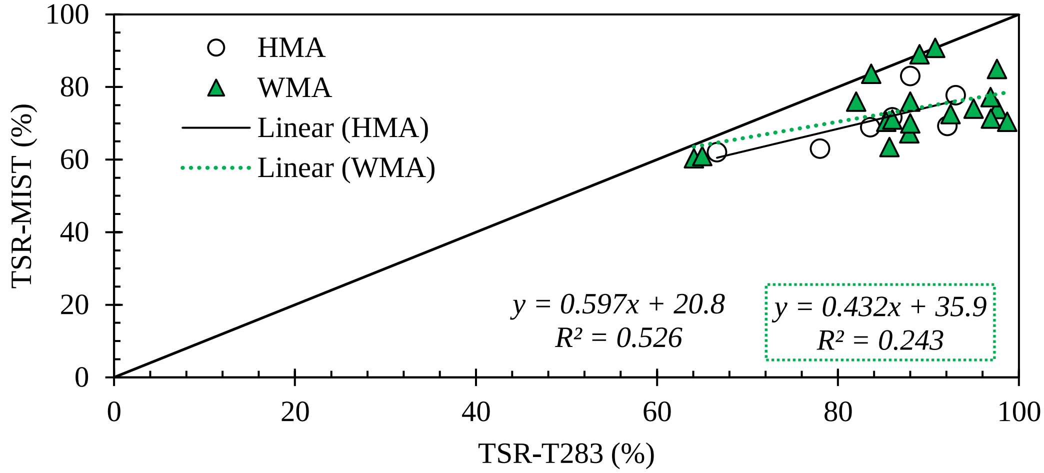


FIGURE 3 Correlation between TSR values obtained after T283 and MIST conditioning Protocols

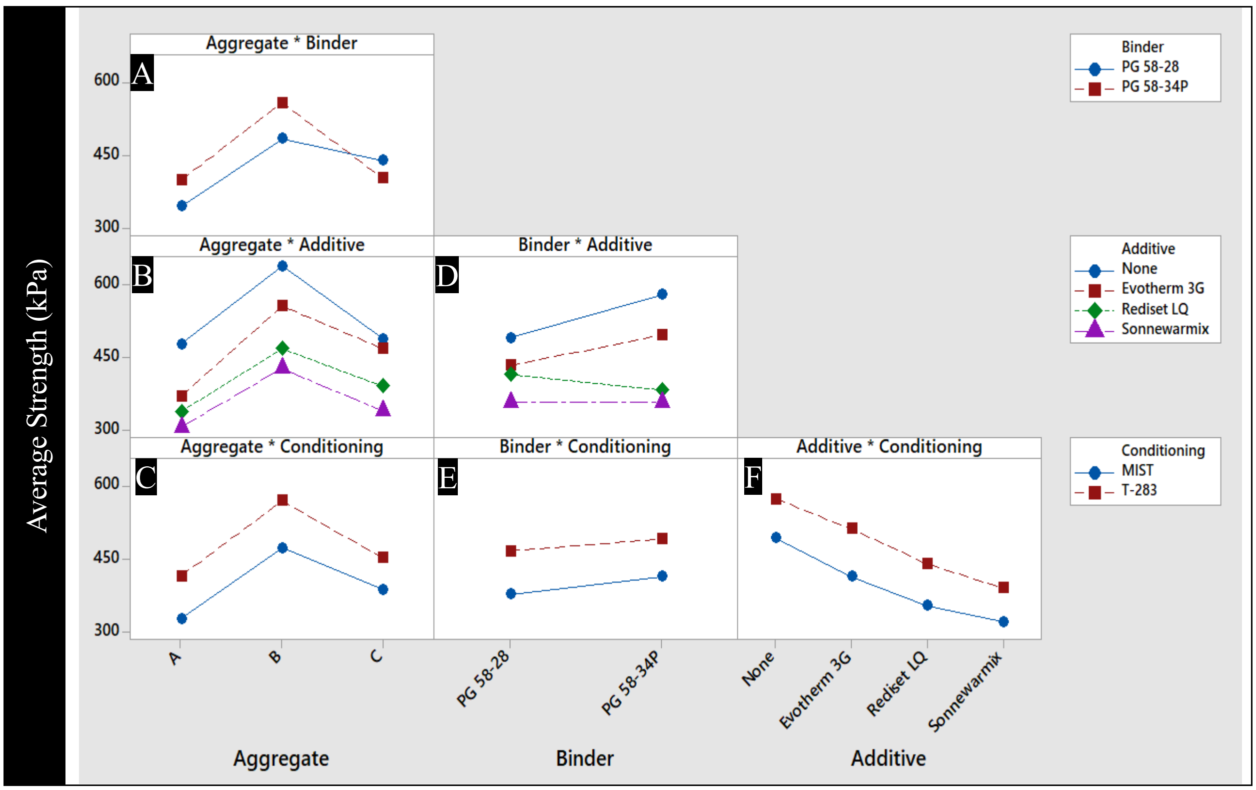


FIGURE 4 Interaction Plot for Indirect Tensile Strength for HMA and WMA Mixtures Containing Different Types of Warm Mix Additives, Aggregates, and Asphalt Binders

To further evaluate the moisture susceptibility of asphalt mixtures, change in density (also known as "swelling") was calculated for each specimen after MIST conditioning and then normalized with respect to those values obtained from the control mixtures by using Equation 2. Figure 5 shows an example of swelling observed in the laboratory.

$$Swell\ Ratio(\%) = \left(\frac{Average\ Swell\ of\ Modified\ Mix}{Average\ Swell\ of\ Control\ Mix}\right) \times 100 \qquad (2)$$

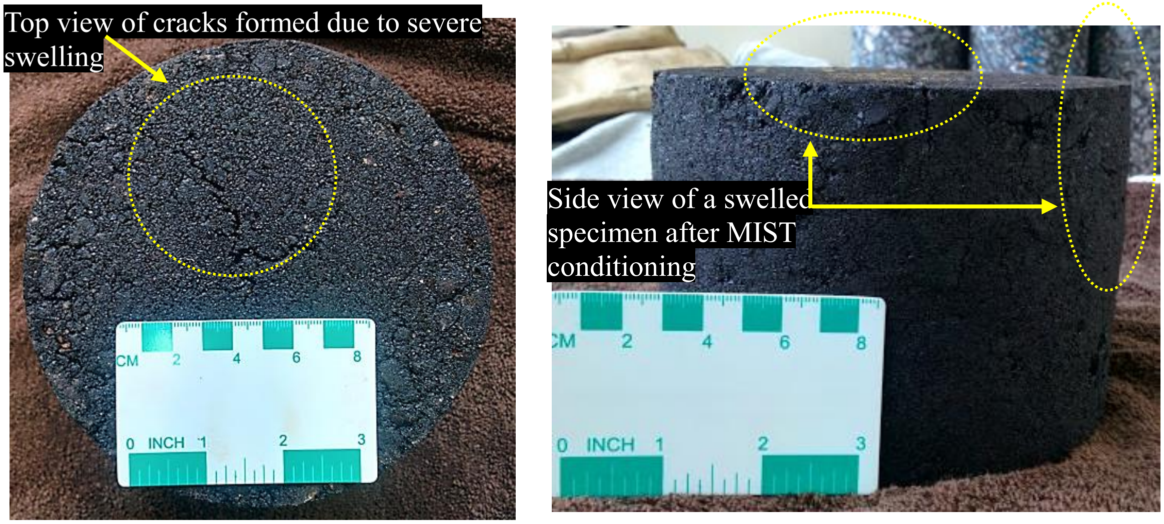


FIGURE 5 Severe Specimen Swelling Observed After MIST Conditioning

Figure 6 shows the swelling results along with TSR data. In general, it was observed that Evotherm 3G and Rediset LQ effectively reduced swelling by 23% to 40% for all mixtures regardless of the aggregate type and asphalt binder grade. However, Sonnewarmix was observed to cause an increase in swelling for all mixtures after MIST conditioning. Observed swelling for aggregate type B was higher than the other two aggregates.

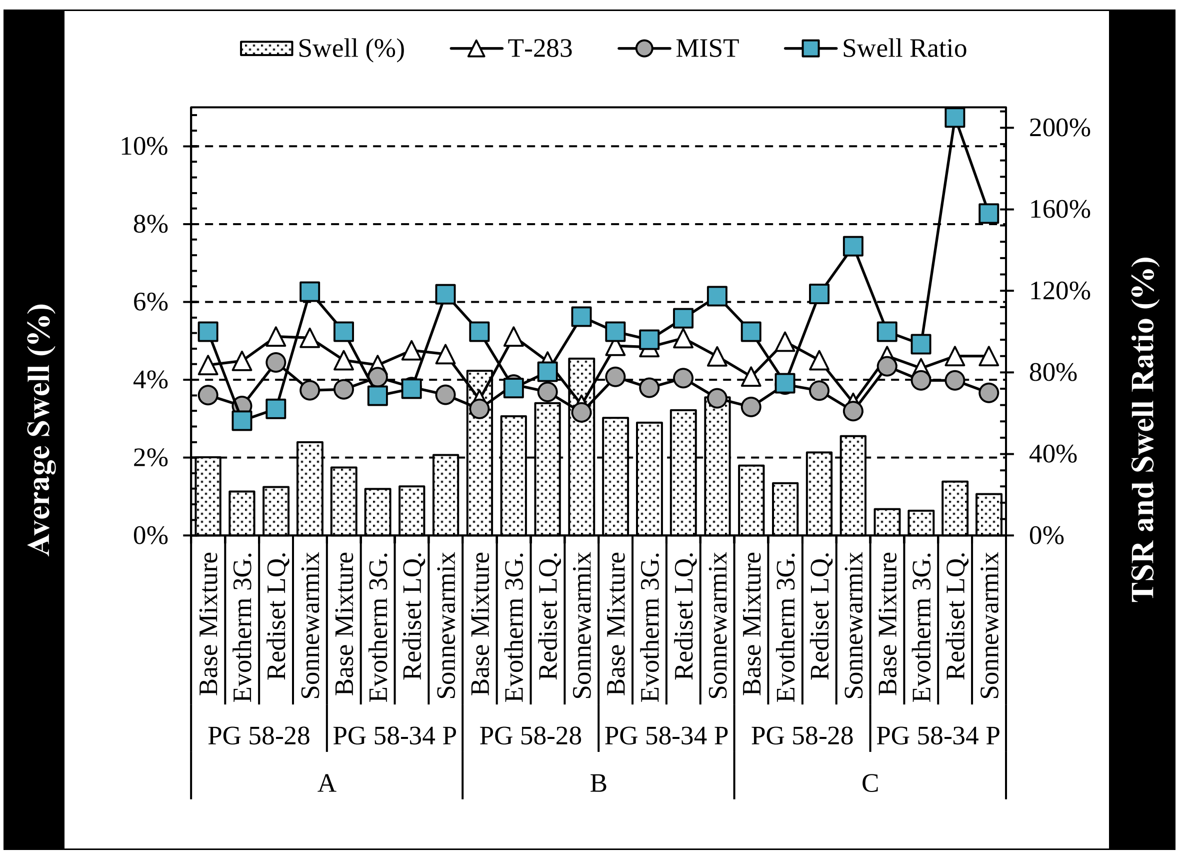
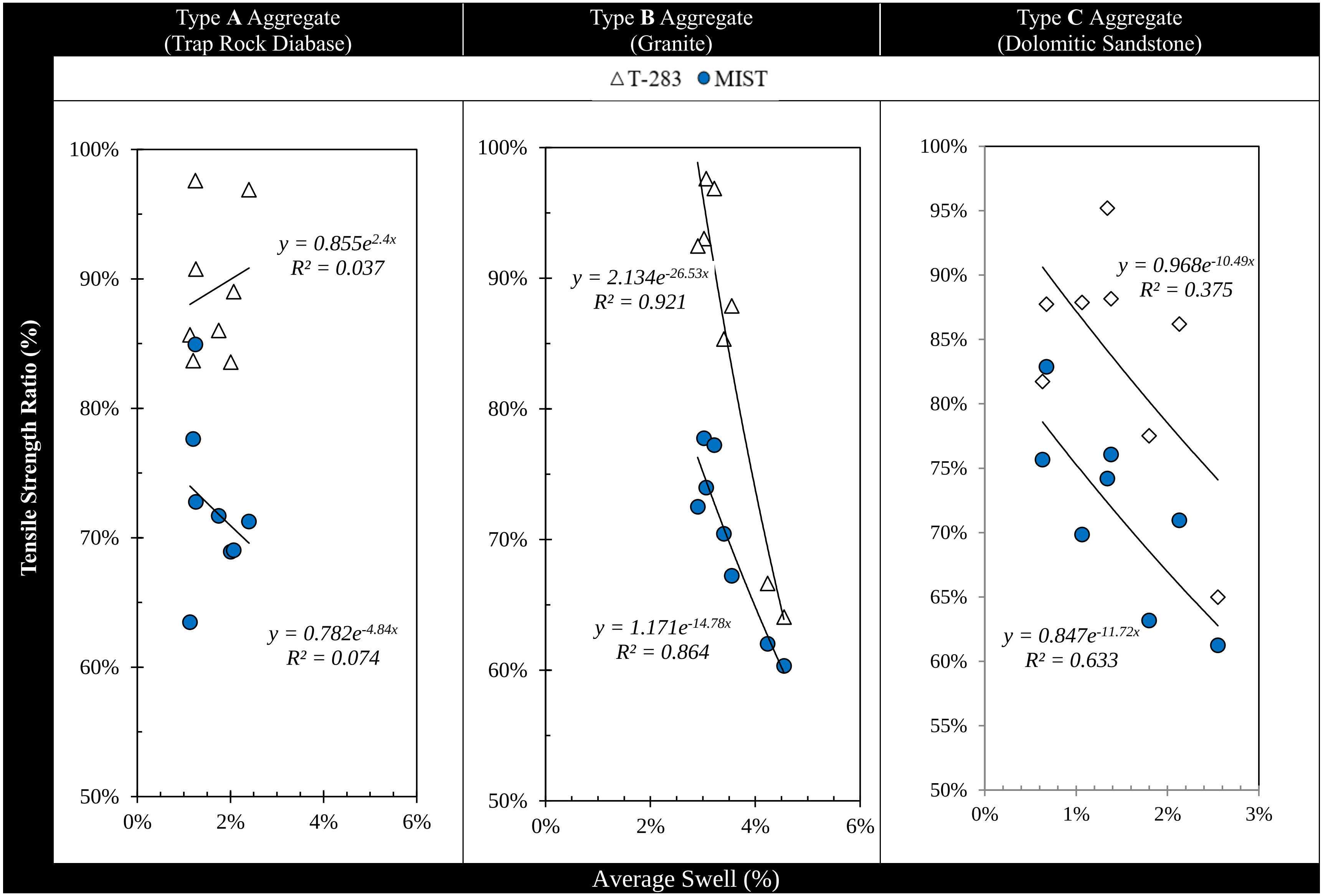


FIGURE 6 Comparison of TSR Ratio Determined After T283 and MIST Conditioning With Swell Ratio

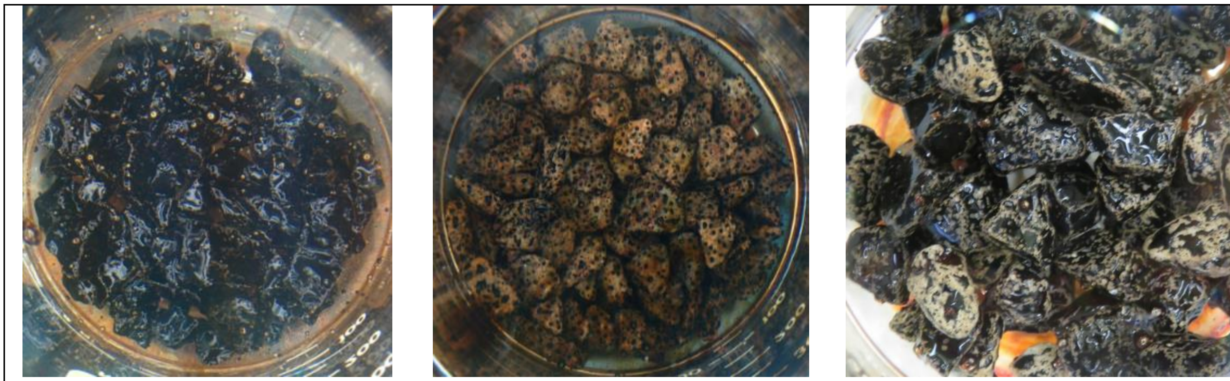
The relationship between the mixture's TSR was compared to the average swell percentage using an exponential function (Figure 7) that yielded the best fit. No correlation was found between TSR and MIST conditioning with the swell percentage for mixtures containing aggregate type A. A relatively moderate to strong coefficient of determination (R^2) was found for aggregate types of B and C.

To assess chemical compatibility and bonding between modified binders and aggregates, static immersion test was performed at MTO Bituminous laboratory. For this test, it was observed that all combinations with type A aggregate resulted in an average percent retained coating of more than 95 percent as shown in Figure 8(a) which was expected, as aggregate type A was known as not susceptible to stripping. Combination of type B aggregate and PG 58-28 base binder resulted in severe stripping as shown in Figure 8(b). Retained aggregate coating of 55 percent was observed for combination of PG 58-28 and aggregate C, as shown in Figure 8(c). Severe and slight stripping were observed when Sonnewarmix additive was used with Types B and C aggregates and PG 58-28, as shown in Figure 8(d) and (e), respectively. This suggests the requirement of anti-striping agent when Sonnewarmix is used with an aggregate source with known history of moisture susceptibility. This recommendation was further validated by adding an anti-stripping additive (PaveBond® LITE) and more than 95% retained aggregate coating was observed.

Results obtained from static immersion test imply that the use of Evotherm 3G and Rediset LQ in combination with pink granite and dolomitic sandstone significantly improved the retained coating to over 90%. Figure 8(f) shows an example of retained coating observed after Evotherm 3G was used in combination with pink granite.



1 **FIGURE 7 Relationship Between TSR Determined Using T283 and MIST Conditioning, and Average Swell**



(a) PG58-28 + trap rock diabase (>95% retained coating)

(b) Base PG58-28 + pink granite (10% retained coating)

(c) Base PG58-28 + dolomitic sandstone (55% retained coating)

(d) PG58-28 + Sonnewarm + granite(10% retained coating)

(e) PG58-28 + Sonnewarm + dolomitic sandstone (65% retained coating)

(f) PG58-28 + Evotherm + granite (>95% retained coating)

FIGURE 8 Static Immersion Test (LS-285) Visual Rating

The TSR results obtained from T283 and MIST conditioning were further examined for correlation with percent retained coating obtained from static immersion testing. As shown in Figure 9, a good to moderate correlation (R^2 value of 0.89 for WMA and 0.48 for HMA) was observed for TSR results obtained from T283 conditioning and retained coating. However, the correlation between TSR results obtained from MIST conditioning and retained coating was found to be relatively less than TSR conditioning (R^2 value of 0.53 for WMA and 0.24 for HMA). The correlation between retained coating and MIST swell was found to be moderate for both HMA and WMA mixes.

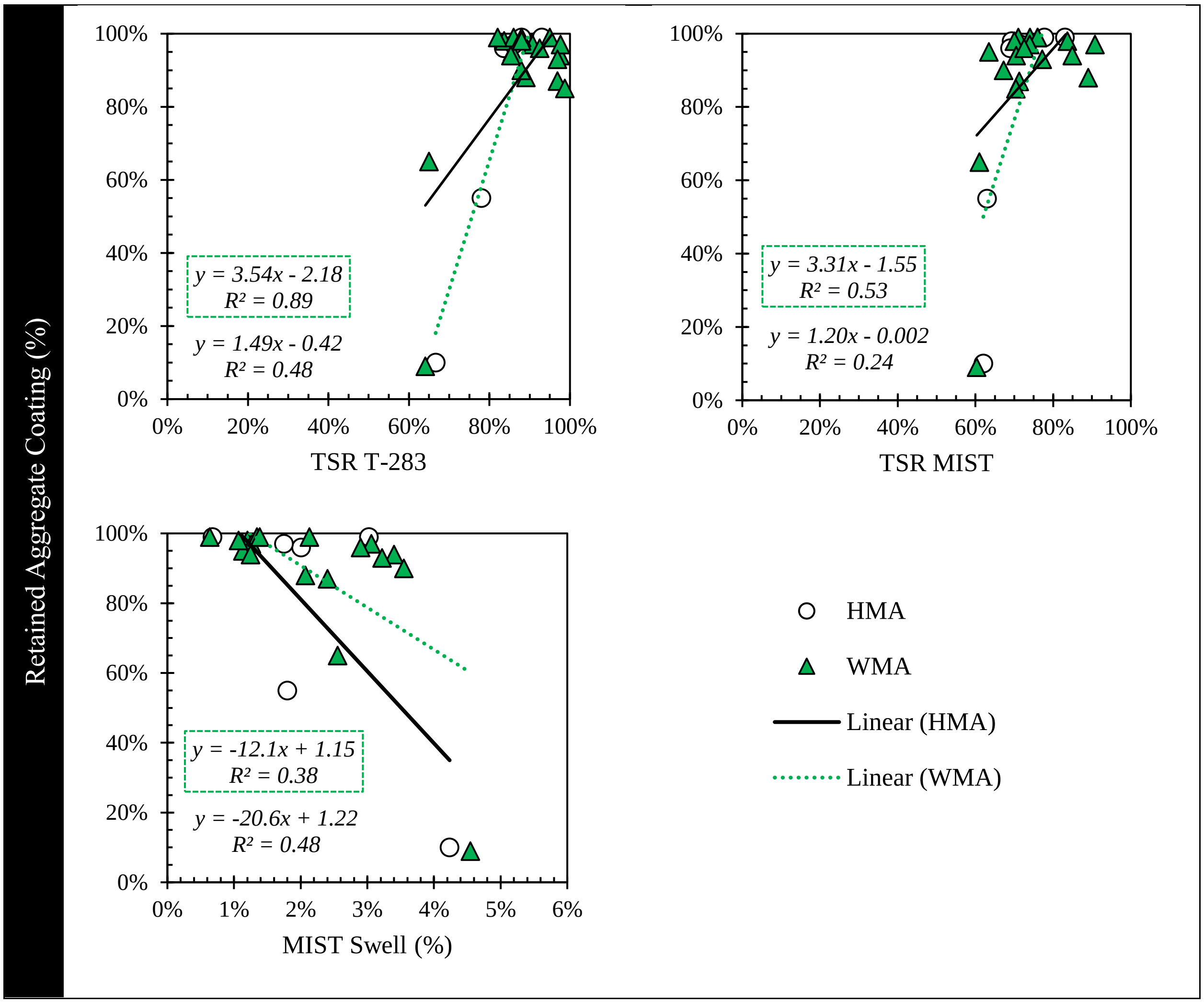


FIGURE 9 Relationship between Static Immersion Test (LS-285) and TSR and MIST Results

HWT test was used to measure rutting susceptibility of asphalt mixtures combined with moisture susceptibility by tracking a 705 N load hard-rubber wheel across the surface of gyratory compacted specimens submerged in a hot water bath at 50°C. Test results of Hamburg rutting test for the various WMA mixtures are presented graphically in Figure 10.

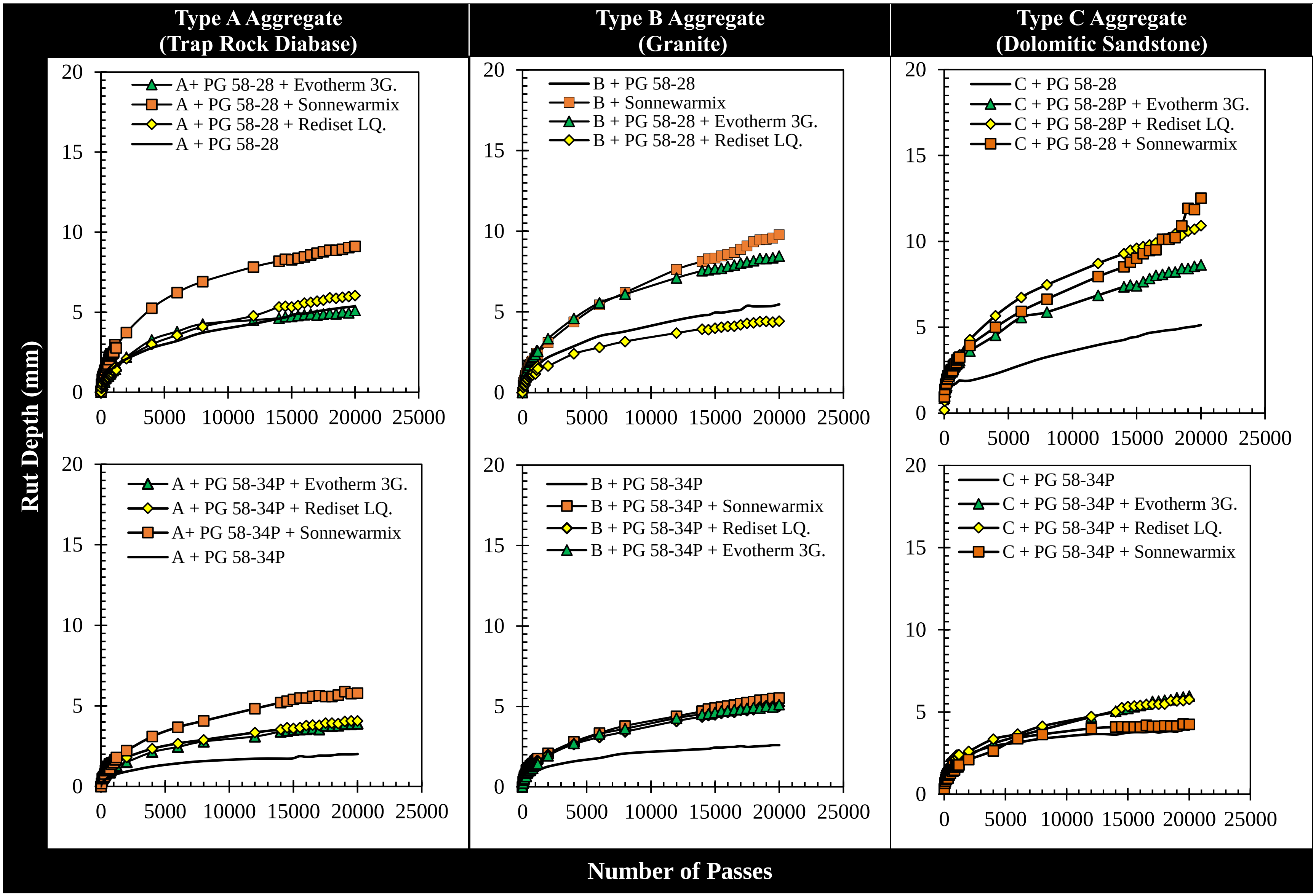
The resistance of all mixtures to rutting was visually compared and the following trends were observed.

1. Addition of warm mix additives in general resulted in a slight increase in rut depth with some exceptions where the warm mix additive performed equivalent to the control mix, as shown in Figure 10.
2. It was observed that mixtures containing Sonnewarmix provided the least level of resistance to rutting. This was hypothesized to be related to the melting point of this wax type additive which causes asphalt mixture to behave relatively softer at the testing temperature of 50°C and lower the resistance to rutting. However, the melting point of this additive was reported by the manufacturer to be 80°C on the Material Safety Data Sheet (MSDS) determined by using ASTM D-127 test method. No further testing was performed to verify this

temperature. Excessive rutting for this mix could be due to moisture damage which was also implied by other tests in this study.

3. For all mixtures, use of warm mix additives in combination with polymer modified asphalt binder (PG 58-34P) resulted in increased resistance to rutting compared to the same with unmodified PG 58-28. This suggests using a polymer modified binder may improve the rutting and stripping performance of WMA and HMA mixtures.

It should be noted that none of the mixtures exhibited stripping inflection point. But, two mixtures exhibited severe visual stripping in the wheelpath after completion of the Hamburg rutting test: (1) conventional HMA containing PG 58-28 and type B aggregate, and (2) WMA mixture containing Sonnewarmix with PG 58-28 and type B aggregate. Furthermore, these mixtures did not exhibit such visual stripping after being treated by a liquid anti-stripping agent.



1 **FIGURE 10 Hamburg Wheel Track Results on Superpave 12.5mm Mixture**

For a better systematic evaluation, previously presented test results were ranked in ascending order as listed in TABLE 4 for each combination of aggregate and binder type: first for the best performance and last for the weakest performance. Then, for each mixture, a total rank was calculated by adding ranks from each test.

TABLE 4 Mixture Moisture Susceptibility Rankings

Aggregate Type	Binder Grade	Additive Type	TSR T-283 (%)	Rank	TSR MIST (%)	Rank	MIST Swell (%)	Rank	Percent Coating (%)	Rank	HWTD Depth	Rank	Overall Rank[1]
Trap Rock Diabase	PG 58-28	Control	84	2	69	3	2.10	3	98	1	5.37	2	11
		Evotherm 3G.	98	1	85	1	1.13	1	98	1	5.12	1	5
		Rediset LQ.	97	3	71	2	1.25	2	87	3	6.05	3	13
		SonneWarmix	86	4	63	4	2.40	4	95	2	9.02	4	18
	PG 58-34P	Control	86	3	72	3	1.75	3	95	3	2.03	1	13
		Evotherm 3G.	91	1	73	2	1.20	1	97	2	3.99	2	8
		Rediset LQ.	89	2	69	4	1.26	2	88	4	4.07	3	15
		SonneWarmix	84	4	78	1	2.70	4	98	1	5.77	4	14
Pink Granite	PG 58-28	Control	67	3	62	3	4.23	3	10	3	5.47	2	14
		Evotherm 3G.	98	1	74	1	3.06	1	97	1	8.22	3	7
		Rediset LQ.	85	2	70	2	3.40	2	94	2	4.43	1	9
		SonneWarmix	64	4	60	4	4.55	4	9.0	4	9.79	4	20
	PG 58-34P	Control	93	2	78	1	3.20	2	99	1	2.59	1	7
		Evotherm 3G.	92	3	73	3	2.90	1	96	2	5.12	3	12
		Rediset LQ.	97	1	77	2	3.22	3	96	2	5.02	2	10
		SonneWarmix	88	4	67	4	3.55	4	90	2	5.52	4	18
Dolomitic Sandstone	PG 58-28	Control	78	3	63	3	1.80	2	55	3	5.13	1	12
		Evotherm 3G.	95	1	74	1	1.34	1	98	1	8.64	2	6
		Rediset LQ.	86	2	71	2	2.13	3	98	1	10.9	3	11
		SonneWarmix	65	4	61	4	2.55	4	65	2	12.5	4	18
	PG 58-34P	Control	88	1	83	1	0.67	2	99	1	3.93	1	6
		Evotherm 3G.	82	2	76	2	0.63	1	99	1	4.25	2	8
		Rediset LQ.	88	1	76	2	1.38	4	99	1	5.77	3	11
		SonneWarmix	88	1	70	3	1.07	3	98	2	5.98	4	13

[1]The lower the ranking, the better the anticipated resistance to moisture damage

CONCLUSIONS

The following conclusions can be drawn:

1. Statistical analysis of TSR values suggest that MIST conditioning protocol is capable of discriminating different mixtures in terms of resistance to moisture damage better than T283 in a much shorter testing period.
2. The MIST Swelling showed an excellent correlation with TSR after MIST for strippable aggregates (i.e., types B and C).
3. Results of static immersion test were found to be correlating well with TSR values obtained after T283 conditioning protocol. A moderate correlation was observed between static immersion and TSR after MIST conditioning.
4. Hamburg rutting test showed that addition of warm mix additives in general resulted in decreased level of resistance to rutting with some exceptions.
5. WMA additives used in this study were found to be effective in improving moisture susceptibility in some combinations; except for SonneWarmix. However, all IDT values dropped with the addition of each warm mix additive.
6. The analysis of variance (ANOVA) confirmed that the binder, warm mix additive and conditioning are significant sources in indirect tensile strength variation.

FUTURE RESEARCH OPPORTUNITIES

Conditioning would have a significant impact on asphalt cement and its characteristics since binder is a thermorheological material whose property is influenced by temperature. In the process of a freeze-thaw cycle, keeping the specimens at a constant temperature of 60°C in the bath for 24 hours has an important impact on asphalt cements that might exhibit various behaviors in terms of their instinct physical properties such as viscosity. It would be interesting to determine the impact of a specific temperature at which binders have the same physical property to compare the moisture damage resistance of various binders containing different PGAC grading. To compare the performance of various binders against moisture damage, finding an equiviscous temperature, the temperature at which binders have a specified viscosity may be effective. Also, effect of warm mix additives should be studied on mechanical properties of mixtures by performance-based testing such as dynamic modulus, flow number, semi-circular bend and disk-shaped compact tension tests.

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