Benchmarking AC Mixes for Stripping Potential and Establishing Required Measures for Ensuring Sustainable Pavement Structures

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Abstract

Manitoba has been adding liquid anti-stripping agents (LAS) into asphalt concrete (AC) mixes, containing moisture susceptible aggregates, to improve their resistance to stripping and thereby, reduce the extent of premature damage to pavements. The province requires a minimum wet to dry tensile strength ratio (TSR) of 70% for acceptance of AC mixes. However, some sources have aggregates for which the available LAS do not provide the desired TSR. In addition, the specified minimum TSR may not ensure adequate long-term resistance to stripping because the specified TSR does not target any minimum indirect tensile strength (ITS), specifically in wet condition. This study was undertaken to benchmark aggregates from different areas of the province in terms of TSR and wet ITS; recommend the desired minimum TSR and wet ITS values for acceptance of AC mixes with and without using an anti-stripping agent (LAS agent or hydrated lime); set the condition and threshold for using hydrated lime, and recommend the process of adding the hydrated lime for producing sustainable AC mixes.

The analysis of available test data indicates that a minimum TSR of 70% and wet ITS of 350 KPa would be acceptable targets to ensure adequate anti-stripping performance of AC mixes in Manitoba. A suitable LAS agent and/or hydrated lime may be used if any of the above stated criteria are not met for any feasible aggregate combination. A minimum TSR of 60% seemed to be a reasonable target when an anti-stripping agent (LAS or lime) is used, provided that the wet ITS does not fall below 350 KPa. Hydrated lime should be used if the desired TSR of 60% and/or the desired wet ITS of 350 KPa could not be met with any LAS. This paper presents the details of test data, case studies, their assessment, basis for the specified thresholds and recommendations.

Introduction

The performance of an asphalt pavement structure is depicted by several limiting values of observed or expected distresses including cracking, rutting and moisture related stripping. The stripping in AC mixes results from the loss of bond between aggregate and asphalt binder in the presence of moisture, which causes reduction of pavement service life. The most desirable options to improve the stripping resistance of AC mixes are the provision of good quality aggregates that do not have high affinity to moisture, reduced air voids (increased compaction) and improved pavement drainage. However, the stripping of asphalt binder from the aggregate surfaces in the presence of moisture is a complex phenomenon. As mentioned by Yonn and Tarrer[1], the primary factors that contribute to moisture-related stripping in an AC mix include: physical and chemical properties of both the aggregate (e.g., surface characteristics and mineral composition) and asphalt binder (e.g., chemical composition, surface tension and viscosity). In addition, construction methods and external environmental factors contribute to stripping in AC mixes making it a more complex phenomenon. The stripping mechanisms can be grouped into three types: 1) mechanical, 2) chemical and (3) thermodynamic. The mechanical mechanism refers to the quality of adhesion of asphalt binder to aggregates. It is dependent on how well the asphalt binder intrudes into the aggregate pores and surface irregularities to ensure a strong mechanical interlock. The chemical mechanism involves chemical reactions among asphalt binder, aggregate surface and water, which primarily depends on surface charges and pH of the mixture. The thermodynamic mechanism refers to the ability of different asphalt binders to lubricate and coat aggregate surfaces. It depends on the viscosity and surface tension of asphalt binder, and AC mixing temperature[2].

A well designed and compacted homogeneous asphalt mixture, placed on a good quality aggregate base layer and constructed as well as maintained to minimize moisture penetration into AC layer and/or water ponding on the underlain base layer can help in reducing the stripping potential. However, construction issues and pavement distresses are not fully avoidable and aggregate base materials with good drainage quality are not always available. These lead to water ingress from pavement surface and as well as from the bottom of AC surface. As more free moisture is available at the bottom of AC layer, the stripping generally starts from the AC layer bottom surface, i.e., stripping is generally a bottom-up phenomenon. It is then manifested as disintegration and crumbling of AC mixture. However, at early stage, it can start at pavement surface due to interaction of traffic load and moisture.

There is an increased potential of stripping in cold climate with freeze/thaw exposure, specially in early spring when pavement surface and top part of base layer undergo repeated freezing and thawing while the lower part of pavement structure still remains frozen. Repeated traffic loads on moisture saturated pavement aggravates the issue. In addition, the mineralogy and chemical composition of the aggregates that are used in AC mixes can contribute to stripping. Hydrophilic i.e., water-loving aggregates, which tends to be acidic, are more susceptible to cause stripping. Hydrophobic i.e., water-repelling aggregates provide better resistance to stripping. Any plastic dust or clay adhered to the aggregate particles also prevent proper adhesion of asphalt binder with aggregates and contribute to stripping[3,4]. Therefore, challenges exist in some areas of Manitoba and elsewhere to economically source or process aggregates that will ensure good resistance to stripping. An anti-stripping agent is generally added to AC mixes to improve the adhesion between the binder and aggregates and thereby, preventing undesirable extent of moisture-induced premature damage to AC layer and ensuring sustainability of pavement structures.

When the aggregate for AC mixes is the driver of stripping issues, the primary approach to improving the resistance to moisture related damage in AC mixes is to enhance the adhesion between the asphalt binders and aggregates[5,6]. Anti-stripping agents are typically used to enhance the adhesion between the asphalt binder and aggregate as they facilitate physical adsorption or chemical reactions between the asphalt binder and aggregate[5,7]. Different types of anti-stripping agents are available in North America and elsewhere around the globe including hydrated lime, portland cement, liquid anti-stripping agents, warm mix additives and polymer modifiers that are added to asphalt binders. Hydrated lime is considered to be a highly effective inorganic additive for improving the resistance to moisture related damages in AC mixes. However, no single additive can ensure adequate resistance to stripping or moisture related damage for all variation of aggregate types and compositions as well as environmental exposures. The selection of an appropriate anti-stripping agent or the combination of agents depends on their field trial performance, visual assessment of binder coating and loss of coating or debonding, and laboratory test results. The primary test methods used by different agencies include: 1) Modified Lottman Test as per AASHTO T283 that determines the change in tensile strength of an AC mix when exposed to moisture and expressed in terms of TSR; 2) Hamburg Wheel Tracking Test (HWTT) as per AASHTO T324, which measures the susceptibility of AC mixes to moisture damage in terms of magnitude of rutting and/or the number of wheel passes to Stripping Inflection Point (SIP); 3) Static Immersion Test as per AASHTO T 182 to evaluate the moisture susceptibility of asphalt-aggregate mixes through visual estimation of remaining asphalt coated surface area after submersion in water for 24 hours; and 4) Boiling Test as per ASTM D3625, which allows for a rapid visual assessment of loose AC mix for the amount of asphalt stripped aggregates after boiling in water at 100 °C for 10 minutes.

Manitoba has been conducting testing for TSR for nearly two decades with special focus on aggregates available in the south-western part of the province and limited number of static immersion testing. Several anti-stripping agents have been used with mixed success/failure performance experiences: good

performance with some low TSR values and poor performance despite the desired TSR threshold of 70% were met. In addition, Methylene Blue Test (MBT) was conducted on some aggregates to detect the presence of plastic fines in the fine aggregates and their impacts. Therefore, an in-depth assessment is being carried out to re-establish the specification requirements. This paper presents the details of the test data, case studies, their assessment, process of benchmarking and establishing targets, and the preliminary recommendations.

Background

Manitoba has evaluated many anti-stripping agents over the last two decades or more. Based on the laboratory tests and field trial results, the province approved a number of anti-stripping agents to address the stripping issues. Anti-stripping agents are mostly used for aggregates in south-western area of the province. The province set the minimum TSR requirement as 70% for acceptance of AC mixes considering the limitation in the quality of aggregates and achievable values using the readily available anti-stripping agents that can be easily introduced into asphalt mix production. The currently approved products and maximum dosage (as a percentage of asphalt binder) are listed in Table 1.

Table 1. Manitoba approved anti-stripping agents

Product Name/ Type	Dosage Rate	Manufacturers / Suppliers
Hydrated Lime		
Morlife 5000	0.5%	Ingevity Corporation
Pave Bond Lite	0.5%	
Evotherm M1	0.5%	
Zycotherm	0.1%	Zydex Incorporated
Zycotherm-EZ	0.1%	
Redicote C-2914	0.5%	Nouryon
Warmgrip N1	0.5%	
Adhere 77-00	0.5%	Road Science - Arkema
Adhere LOF-65-00	0.5%	

However, some sources have aggregates for which the available LAS do not provide the desired minimum TSR value. There have been cases of reduced dry strength with the use of certain LAS for some aggregates. In addition, the specified minimum TSR has not always provided the desired field performance because the specified minimum TSR does not target any minimum ITS (which is also called IDT strength), specifically in wet condition. To overcome these issues, Manitoba reassessed some historical trials, AC mix design and quality control/assurance/acceptance tests data to provide new recommendations for AC mix requirements to better address the stripping issues. This paper presents the results of analyses and tentative recommendations for changes to relevant specifications.

Findings from Literature Review

According to Hossain and Roy[8], stripping-related moisture damage is considered as a major distress of asphalt pavements and plays an important role in pavement design and construction. Moisture damage in AC due to stripping can result from adhesive failure (failure of the bond between the asphalt binder and the aggregate), cohesive failure (failure within binder itself), or combination of both adhesive and

cohesive failures, resulting in a reduction of asphalt mix stiffness. Moisture damage negatively affects the performance and serviceability of AC pavements by accelerating the formation of potholes or promoting delamination between pavement layers and load related distresses such as rutting, cracking and raveling. Yoon and Tarrer[1] found that there is no strong correlation between aggregate physical properties such as pore volume and surface area, and the stripping potential. Aggregates that have high electrostatic surface charges or introduce high pH to water are more susceptible to stripping, due to dissociation of acidic components in asphalt, by creating electrical repulsion between asphalt and aggregate (two negatively charged) surfaces. It was found that the effectiveness of amine-base anti-strip additives decreases as the pH of water increases, whereas the effectiveness of hydrated lime remained constant, independent of the pH of the contacting water. According to Huang et al.[9], asphalt binder that is high in phenolics, ketones and nitrogen bases have a high resistance to stripping. Aggregate sources with more silica content such as granite are more prone to stripping when compared to limestone sources with less silica content. Further, the absorption of asphalt binder in the pores of aggregate particles are better at resisting moisture damage than the coated asphalt binder on smooth aggregate surface. Surface free energy (SFE) test showed that asphalt binders (both polymer modified and non polymer modified) exhibit negligible decrease in cohesiveness when amine-based anti-strip additive is added. Conversely, there was an increase in the ability of asphalt binder to coat the surface of aggregate when amine ASA was added to limestone, granite and gravel aggregates.

Modified Lottman test (AASHTO T283) is a commonly used test for moisture susceptibility of compacted AC mixes. The TSR is generally used as the parameter for the evaluation of moisture damage potential. The TSR requirements vary among state and provincial agencies, with some agencies also requiring a minimum tensile strength. Alberta Transportation do not require LAS to be added to a mix when a minimum TSR of 75% is met. Mixes that do not meet the minimum TSR target have to be treated with LAS at a dose between 0.3% and 0.5% by weight of binder. The treated mix is considered to be suitable if the TSR value is 60% or higher and has improved over the TSR value of untreated mix[10]. Georgia DOT allows TSR values less than 80% as long as the TSR is at least 70% and all dry tensile strength values exceed 690 KPa (100 psi)[11]. South Carolina DOT requires a minimum TSR value of 85% and a minimum wet ITS of 448 KPa[12]. Oklahoma DOT requires a minimum ITS of 517 KPa (75 Psi) for their Superpave Mix using PG 76-XX binder, a minimum mix design TSR of 80% and field mix TSR of 75% for all binders[13]. Kandhal et al.[14] recommended a minimum TSR of 70% when using AASHTO T283 to determine moisture susceptibility.

Kennedy and Anagnos[15] investigated the wet-dry ITS values for evaluating moisture susceptibility of asphalt mixes. It was concluded that mixtures with TSR less than 70% are moisture susceptible and mixtures with ratios greater than 70% are relatively resistant to moisture damage. The study also indicated that consideration should be given to the absolute values of the retained strength. Lottman[16] compared the TSRs of laboratory produced AC specimens to field cores and noticed a slight stripping in the field cores when the wet to dry ITS ratio is at 0.80. As the ratio decreased further, more severe stripping was observed.

With a test for surface free energy, Huang et al.[9] found that amine-base LAS can improve moisture damage resistance of the asphalt-aggregate combination by reducing the free energy, which is released in the presence of moisture. This is consistent with the increase in TSR values when amine-base LAS was added to limestone, granite and gravel aggregates combined with both polymer modified and non modified asphalt binders. Amirkhanian et al.[12] evaluated the effect of amine-based LAS and hydrated lime on stripping resistance of asphalt pavement in South Carolina. It was found that the wet ITS values of all mixes, regardless of aggregate source, were greater than the South Carolina DOT (SCDOT) minimum wet ITS requirements of 448 KPa when LAS or hydrated lime were used. There were no significant differences

in dry ITS values between hydrated lime and different types of amine-based LAS, regardless of aggregate sources. However, there were significant differences in wet ITS values between hydrated lime and amine-based LAS for certain aggregate sources. Some LAS-aggregate combinations produced TSR values of less than the SCDOT's minimum requirement of 85%. This emphasizes the importance of selecting the most effective anti-stripping agent for each aggregate source. With Hamburg Wheel-Tracking Test (HWTT), Huang et al.[9] found that aggregates from gravel and granite sources are more prone to moisture-related stripping than the aggregate from limestone sources, with gravel being the worst. The study also found that the addition of amine-base LAS can delay the occurrence of SIP, suggesting an improvement in moisture resistance.

Kandhal[4] also suggested that anti-stripping agents (both liquid and lime additives) should not be specified across the board in all asphalt mixes as an insurance. Some anti-stripping agents are aggregate and asphalt specific and, therefore, may not be effective, and could be detrimental at times. Al-Saffar et al.[5] found that a low dose (0.25-0.5%) of silane LAS have the best improvement in TSR results (92.9%-94.9%) when compared to untreated asphalt mixture with a TSR of 80.5%. However, the TSR values start to decline (88.9%-91.3%) with larger dose (0.75-1.0%). This stresses the importance of using specific LAS dosages to yield optimal TSR values.

The static immersion and the boiling are also two common tests on loose AC mixes to evaluate their moisture resistance. These tests visually quantify asphalt binder that is stripped from the aggregate surfaces. They give early indications of the effectiveness of lime and liquid anti-strip agents on moisture susceptibility of AC mixes. The Methylene Blue test (MBT) determines the aggregate quality by quantifying harmful clays in fine aggregate[8,9]. Kandhal et al.[14] performed a statistical analysis on aggregate test data that included sand equivalent value, plasticity index and methylene blue value (MBV). By comparing with AASHTO T283 and HWTT, it was found that MBV of fine aggregate has the best correlation with stripping.

Objectives, Scope and Significance

Stripping is a common phenomenon in different areas of Canada and elsewhere. The AASHTO T283 is the most widely used test method for assessing the sensitivity of aggregates to stripping. The selected TSR value for the acceptance of AC mixes varies from 70 to 85% among the highway jurisdictions. A few US agencies specify a minimum wet (conditioned specimens) ranging from 413 to 483 KPa depending on the asphalt binder high temperature grade. A LAS is commonly used when the minimum TSR requirement is not met for any aggregate. Few agencies also use hydrated lime alone or in combinations with LAS. However, Manitoba is still facing challenges to establish reasonable acceptance criteria that will provide satisfactory performance of AC mixes with moisture susceptible or water loving aggregates. The main objectives of this study were to:

i) Benchmark aggregates from different areas of the province in terms of TSR and wet ITS;
ii) Establish and recommend the desired minimum TSR and wet ITS values for AC mix acceptance without using any anti-stripping agent;
iii) Establish and recommend the acceptable minimum TSR and wet ITS values when an anti-stripping agent (LAS agent or hydrated lime) is required;
iv) Set the condition when hydrated lime should be used, if no additional change in AC mix design is considered; and
v) Recommend the process of adding the hydrated lime, where applicable.

Historical AC mix design, trial and research test data, local field performance experience and case studies are the primary basis for the analysis presented in this paper. The objective of this paper is to present the details of data, case studies, their assessment, basis for the specified thresholds and recommendations for sharing knowledge with interested participants. The resulting recommendations are expected to enhance the performance of AC surfaced provincial highways/roads and contribute to sustainability of all relevant resources including natural and processed materials.

Research Methodology and Test Methods

For this study, test data for moisture related stripping potential of aggregates covering a period from 2015 to 2026 were assembled, which included:

1. Testing for dry and wet ITS and TSR as per *AASHTO T283 "Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage"*. This test gives an indication of how much the dry tensile strength of an AC mix changes when exposed to moisture, which is considered to provide valuable information about moisture related stripping. The results of testing on 180 AC mix samples are included in the study.
2. Rut depth and number of wheel passes to SIP in accordance with *AASHTO T324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures".* A low number of wheel passes to SIP and/or large rut depth to SIP provide indication of susceptibility of AC mixes to stripping when exposed to moisture and traffic loads. This test was completed at 45 °C temperature at a research/investigation level on limited number of AC mix samples.
3. Static-Immersion Test as per *AASHTO T 182 "Standard Method of Test for Coating and Stripping of Bitumen-Aggregate Mixtures".* This test is used to evaluate the resistance of an asphalt binder coated aggregates to stripping through visual estimation of the percentage of surface area that remain coated with asphalt binder after the immersion in water for 24 hours at 49±0.5 °C. The remaining binder coated area should be ≥95% to be acceptable. This test was also conducted on few samples at a research/investigation level.
4. Methylene Blue Test as per *AASHTO T 330 "Standard Method of Test for The Qualitative Detection of Harmful Clays of the Smectite Group in Aggregates Using Methylene Blue."* This test is used to estimate the amount of harmful clays and organic matter that are present in aggregates in terms of Methylene Blue Value (MBV). A high value of MBV indicates that a large amount of clays and/or organic material is present in the aggregate sample, which could cause stripping of asphalt binder from aggregate surface. Table 2 shows the ranges of MBV for different levels of expected performance of aggregates. This test was also completed on several aggregate samples for research/investigation purposes, specifically when no available liquid antistripping agent provided satisfactory TSR.

Specific gravity (SG) and water absorption of aggregates are two important physical properties. A low SG of aggregates generally indicates the presence of lightweight particles. Alternatively, a high water absorption generally indicates that aggregates are porous and could be susceptible to moisture related stripping, especially in freeze-thaw climates. Most aggregates from sources in south-western Manitoba, where moisture-related stripping is a major concern, exhibit low SG and high water absorption, mainly

due to the presence of lightweight and porous shale particles. Accordingly, this study also included an analysis to understand the impact of varied SG and water absorption on moisture related stripping performance of AC mixes.

Table 2. MBV ranges for varying expected performance

MBV Range (mg/g)	Expected Performance
< 6	Excellent - Suitable for use in HMA and concrete
7 – 12	Marginally Acceptable - May require monitoring
13 – 19	Problems or Possible Failures - Additional testing is required
≥ 20	Failure - Not recommended for HMA or concrete

The results of these testing were used to assess how good the available aggregates in different areas of the province are in terms of their resistance to moisture-related stripping without and with the use of different LAS agents and hydrated lime. The analysis of data, together with local field performance experience, allowed for setting the thresholds of TSR, wet ITS and the number of wheel passes as well as rut depth to SIP that can be used for acceptance of AC mixes. These data were also used to set the conditions i.e., the trigger values of TSR and wet ITS for using an anti-stripping agent.

Aggregate Sources and Properties

The AC mix samples that were tested for moisture related stripping potential included aggregates from different sources across the province. The general aggregate types were pit run gravel, limestone bedrock and granite bedrock with varying mineralogy. There have been no wide-spread moisture related stripping issues or reported concerns for AC mixes containing aggregates from sources that are located in the eastern and northern part (regions) of the Province. There are some concerns with gravel aggregates from sources located in the Parkland-Interlake region. However, the stripping issue is a major concern for the gravel aggregate sources located in south-western Manitoba. The regional map of the province is shown in the Appendix.

Bedrock granite aggregates are generally clean (free of natural dust, clay and organic matter), hard, strong and relatively impervious. They do not absorb significant amount of water and do not undergo significant degradation, abrasion and freeze-thaw damage or weathering. These properties generally make them suitable for highway construction. However, some inferior quality granites do also exist (especially, in the outer layer of bedrock crop) in the eastern area of the province, but no such source is known to exist in northern region. Therefore, testing for stripping potential of AC mixes with granite aggregates were limited to few sources that are available in the eastern area.

The quality of aggregates from limestone quarry varies depending on the composition of sedimentary rock materials located in different parts of the province. Given the number of sources that are being used for highway construction projects, a good number of tests were conducted for moisture susceptibility of AC mixes containing quarried limestone aggregates.

Gravel aggregates from pits are the primary sources materials for AC mix production for Manitoba highway construction projects. The quality of aggregates and their composition vary widely among different areas of the province with generally well performing AC mixes in south-eastern and northern areas of the province. Some moisture susceptibility issues were observed with aggregates in the Parkland-

Interlake area. However, limited data are available due to limited number of asphalt paving project over the last several years. The major problem exists with aggregate sources located in the south-western Manitoba, resulting in significant moisture related damage experiences and major concerns. Therefore, the majority of testing for potential moisture susceptibility of AC mixes focused on the AC mixes containing aggregates from gravel sources, with special focus on aggregates from sources located in the south-western part of the province.

AC Mix Properties

The testing for potential moisture susceptibility of aggregates was conducted on AC mix samples prepared as part of mix design as well as mix design verification and on samples collected from field for mix verification. The dust contents (% passing the 0.075 mm sieve) varied from 2.6 to 5.6%.

Test Results and Analysis

As stated earlier, TSR tests were carried out on 180 samples, whereas the HWT, MBV and Static-Immersion tests were carried out on select samples for research/investigation purposes to determine which anti-stripping agents and their combinations provide the expected performance. The province accepts AC mixes without any anti-stripping agent if they exhibit TSR of ≥70%. If the TSR is lower, an approved anti-stripping agent should be used. However, this TSR requirement is not always met even after the addition of LAS. In addition, simply meeting a TSR of 70% does not necessarily ensure a good performance. Manitoba has not specified yet any requirements for HWT wheel passes and rut depth (but developed some preliminary recommendations), MBV and Static-Immersion in the specification. This section presents summaries and analysis of different tests data for recommending new acceptance criteria and their limiting values.

HWT Test Results

A number of HWT tests were conducted on different AC mixes and details of those test results are included in a different paper presented in this conference. The summary of those test results is presented in Table 3 and discussed below. A case study also included HWT test results.

Mixes # 1 and 2 had 10% and 20% RAP, respectively. The rut depths to SIP are small (≤6.0 mm, which is Manitoba's proposed target for Bit. B mixes). However, the number of wheel passes to SIP is very low (significantly less than 8,000 wheel passes, which is Manitoba's proposed target for Bit. B mixes with 58-XXP asphalt binder) for Mix #1, indicating a potential for stripping. The number passes to SIP is moderate (slightly less than 8,000 wheel passes) for Mix #2, indicating low or no stripping potential. These two mixes had wet ITS of 366 KPa and 367 KPa (TSR of 76.9% and 74.1%), respectively. Mix #3 with a LAS agent exhibited well over 13,000 wheel passes to SIP with a small rut depth and had a wet ITS of 484 KPa. This mix is expected to provide very good resistance to stripping.

Mixes #4, #5 and #6 had 0%, 15% and 25% RAP, respectively and contained a LAS agent. All three AC mixes exhibited over 8,000 wheel passes with ≤6.0 mm rut depth to SIP. However, rut depths to SIP slightly exceeded 6.0 mm mark for 15% and 25% RAP AC mixes indicating some potential issues with moisture susceptibility. These three mixes exhibited TSR values of 59.8%, 64.0% and 62.2% together with wet ITS of 365 KPa, 348 KPa and 346 KPa, respectively. Mix #7 with gravel and Mix #8 with limestone aggregates

also exhibited >8,000 wheel passes to SIP with low rut (≤6.0 mm) depths to SIP. Mix # 7 had a wet ITS of 417 KPa and no testing for TSR was done for Mix #8.

Mix #9 withstood >15,000 wheel passes to SIP. The exhibited rut depth to SIP exceeded 6.0 mm, but at a high number of when passes. This mix had a wet ITS of 373 KPa and TSR of 72.2%. Mix #10a with hydrated lime and a liquid anti-stripping agents withstood a higher number of passes to SIP than Mix#10b with a LAS agent only. Both mixes (#10a and #10b) seemed to have met the resistance to moisture stripping requirements (≤6.0 rut depths and >8,000 wheel passes to SIP) based on HWTT results. However, the wet ITS of Mix #10a and #10b were 469 KPa and 252 KPa with TSR values of 60.9% and 50.2%, respectively. These indicate that hydrated lime has improved the moisture-related stripping resistance; however, the HWTT result related to stripping resistance of Mix #10b does not match well with the wet ITS and TSR values. These tests and results need further verification.

Table 3 . Summary of HWTT results

Mix ID	Mix Type	Binder Grade	Hamburg Wheel Test (AASHTO T324)					
			Test Temp. (°C)	Number of passes to SIP	Rut depth to SIP (mm)	Stripping/ Creep Slopes	No. of Passes	Rut Depth (mm)
1	Bit B	PG 58-37P	45	4807	3.54	3.64	13153	12.50
2	Bit B	PG58-37P	45	7533	4.15	4.78	15885	12.50
3*	Bit B	PG 58-37P	45	13261	3.16	5.01	20000	8.28
4*	Bit. B	PG 58-34P	45	8796	4.02	6.96	16222	12.50
5*	Bit B	PG 58-34	45	9661	6.16	4.57	13818	12.50
6*	Bit B	PG 58-34	45	10466	6.25	4.68	18691	9.07
7*	Bit B	PG 58-34P	45	9720	5.21	5.92	16372	12.50
8	Bit B	PG 58-37P	45	9788	5.29	4.63	16560	11.81
9	Bit B	PG 58-34P	45	15852	6.89	2.99	20000	8.41
10a**	Bit B	PG58-34P	45	14010	3.66	4.92	20000	8.87
10b*	Bit B	PG 58-34P	45	11126	4.12	3.73	19471	11.41
11	SP12.5-C	PG58-37P	45	-	-	-	20000	4.49
12	SP12.5-D	PG64-34P	45	-	-	-	20000	2.28
13	SP12.5-D	PG 58-34P	45	16057	3.09	4.03	20000	3.89
14	SP12.5-C	PG 58-37P	45	15114	5.31	8.73	20000	10.59
15	SP12.5-D	PG 64-34P	45	-	-	-	20000	2.81
16	SP12.5-D	PG 64-34P	45	-	-	-	20000	2.52
17	SP19-C	PG58-34	45	16915	4.92	3.85	20000	6.66
18	SP19-D	PG64-37P	45	-	-	-	20000	3.10
19	SP19-D	PG 58-34P	45	16734	6.92	4.33	20000	7.22
20	SP19-C	PG 58-34	45	-	-	-	20000	3.46
21	SP19-D	PG 64-34P	45	-	-	-	20000	2.80
22	SP19-D	PG 64-34P	45	-	-	-	20000	2.43

**Mix with a liquid anti-stripping agent; **Mix with lime plus a liquid anti-stripping agent.*

White cell= gravel aggregates; yellow cell: limestone aggregates; grey cell= granite aggregates.

Among the SuperPave AC mixes, only the Mix #19 (Class D SP19.0) exceeded 6.0 rut depth to SIP, but with a high number of wheel passes. This mix had a wet ITS of 361 KPa (TSR = 71.5 %). The HWT test results as discussed above may indicate that a wet ITS of less than 375 KPa could be an indicator of moisture related stripping, although the HWT test results for few mixes indicated no stripping issues even though the wet ITS values are slightly below the 375 KPa mark.

Correlations of ITS and TSR with aggregate specific gravity and water absorption

Figures 1 and 2 show the variation of ITS with the variation of specific gravity and water absorption of aggregates, respectively, for AC mixes with no anti-stripping agent. These two figures show that the dry ITS slightly decreases with increased specific gravity and it increases with increased water absorption. Alternatively, the wet ITS slightly increases with increased specific gravity and it negligibly decreases with increased water absorption. These correlations are negligible to very poor, indicating that the tensile strengths do not depend much on the aggregate specific gravity or water absorption for properly designed AC mixes. These may imply that the tensile strengths are dependent on the chemical composition of aggregates, and the bonding between asphalt binder and aggregate particles.

Figure 1. Correlation between ITS and aggregate specific gravity

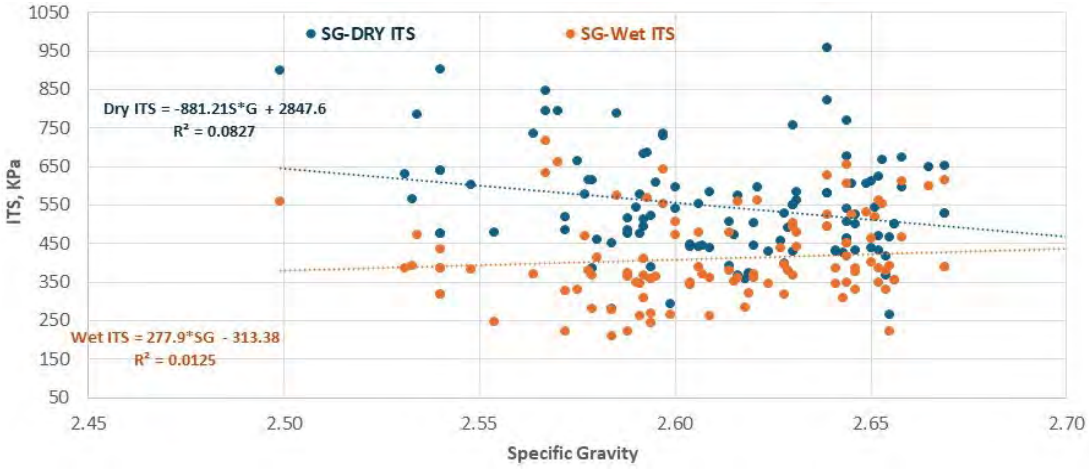
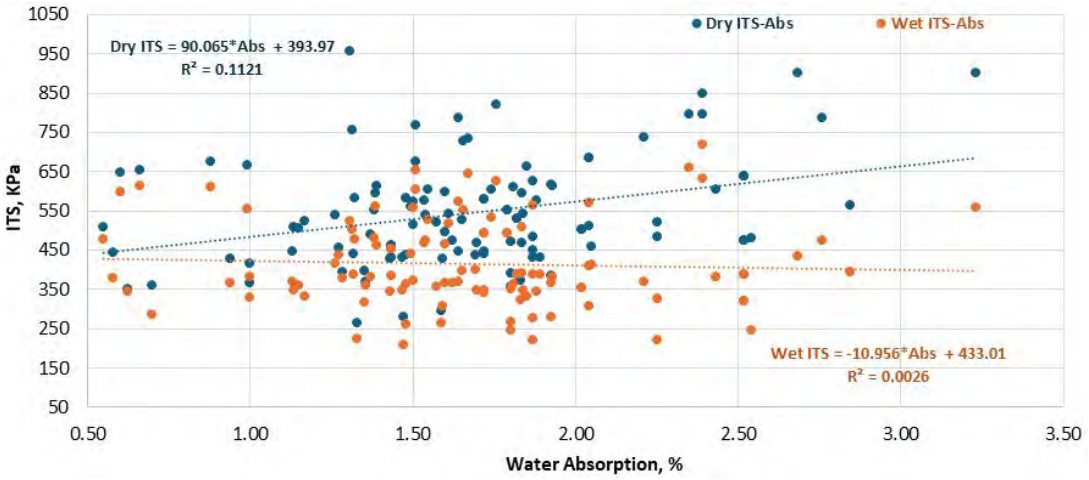


Figure 2. Correlation between ITS and aggregate water absorption



In contrast, Figures 3 and 4 show that TSR has some correlations with both of specific gravity and water absorption; where TSR increases as the specific gravity increase and it decreases as the water absorption increases. These indicate that no one should simply rely on the TSR because a high TSR is possible with low values of both dry and wet strengths and field performance of such AC mixes (with low strengths) have been poor.

Figure 3. Correlation between TSR and aggregate specific gravity

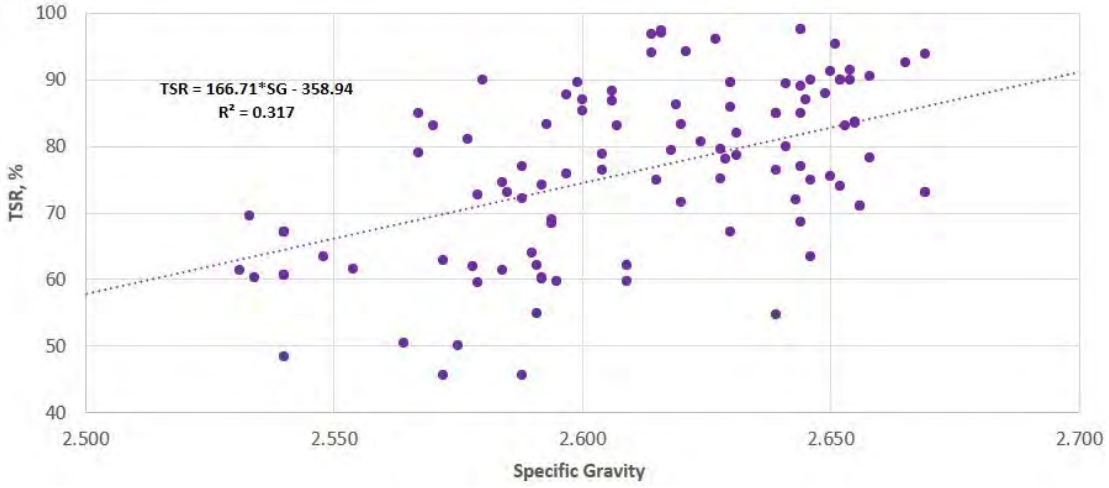
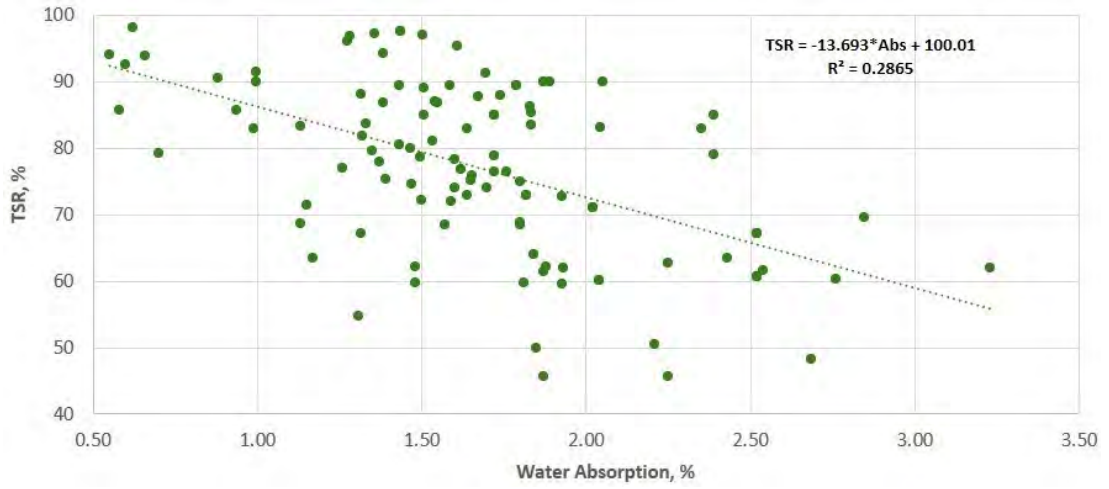


Figure 4. Correlation between TSR and aggregate water absorption



ITS and TSR Test Results: No Anti-stripping Agent

Table 4 shows the dry as well as wet strengths and TSR of AC mixes with different aggregates (granite, limestone and gravel), separated by regions. It also shows the specific gravity and water absorption of those aggregates including the minimum, maximum and average values. As shown in the table, the dry and wet strengths of granite aggregates in south-eastern Manitoba varied from 428 to 653 KPa and 367 to 614 KPa with average values of 546 KPa and 474 KPa, respectively. The single AC mix containing granite aggregates from northern area exhibited a dry and wet ITS of 351 KPa and 344 KPa, respectively, with aggregates having a very high specific gravity (2.814) and low water absorption (0.62%). Despite such low

dry and wet ITS values, the TSR was 98.1%, which is very high. These results indicate that a high TSR is possible despite the ITS is low, specially in wet condition, and a low water absorption does not always mean a high resistance to stripping.

Table 4. Summary of ITS and TSR test results for AC mixes

Statistics	Dry strength, KPa	Wet strength, KPa	TSR, %	Specific Gravity	Absorption, %
Granite: South-Eastern Area (Eastern Region)					
Minimum	428	367	74	2.614	0.55
Maximum	653	614	93	2.669	0.94
Average	546	474	86	2.639	0.69
Granite: Northern					
One Sample	351	344	98.1	2.814	0.62
Limestone: South-Eastern Area (Eastern Region)					
Minimum	426	347	71	2.567	1.26
Maximum	848	718	91	2.669	2.39
Average	581	477	82	2.641	1.75
Limestone: Northern Region					
Minimum	428	308	72	2.643	0.58
Maximum	469	380	86	2.735	1.70
Average	447	345	77	2.677	1.29
Limestone: Parkland-Interlake Region					
Minimum	426	349	81	2.600	1.50
Maximum	578	473	87	2.645	1.62
Average	515	431	83	2.615	1.55
Gravel: South-Eastern Area (Eastern Region)					
Minimum	398	317	75	2.597	1.350
Maximum	735	644	97	2.641	1.800
Average	498	419	83	2.617	1.560
Gravel: Northern Region					
One Sample	374	322	86.2	2.619	1.83
Gravel: Parkland-Interlake Region					
Minimum	508	332	63	2.644	1.13
Maximum	524	477	93	2.646	1.17
Average	516	386	75	2.645	1.15
Gravel: South-Western Area (Western Region)					
Minimum	266	209	46	2.499	0.88
Maximum	901	611	100	2.658	3.23
Average	529	381	74	2.593	1.74

For the AC mixes with limestone aggregates from south-eastern area, the dry and wet strengths ranged from 426 to 848 KPa and 347 to 718 KPa with average values of 582 KPa and 477 KPa, respectively. The range of dry (428 to 469 KPa) and wet (308 to 380 KPa) as well as the average dry (447 KPa) and wet (345 KPa) strengths were lower in northern area (based on limited test data) than in the southern area indicating some issue with the limestone aggregates in northern sources. In Parkland-Interlake area, limestone aggregates exhibited a dry and wet strength of 426 to 578 KPa and 349 to 473 KPa, respectively.

The dry and wet strengths of AC mixes with gravel aggregates from south-eastern Manitoba varied from 398 to 735 KPa and 317 to 644 KPa with average values of 498 and 419 KPa, respectively. The single AC

mix containing gravel aggregates from northern area exhibited a dry and wet ITS of 374 KPa and 322 KPa, respectively, with a very good TSR of 86.2%. This once again indicates that a high TSR is possible despite the strengths are low and there were many AC mixes that fell in this category. The dry and wet strengths of AC mixes with gravel aggregates from Parkland-Interlake area ranged from 508 to 524 KPa and 332 to 477 KPa, respectively. The average dry and wet strengths were 516 KPa and 386 KPa, respectively. The dry and wet strengths of AC mixes with gravel aggregates from south-western area had the most variability. They ranged from as low as 266 to 901 KPa and 209 to 611 KPa with average dry and wet ITS values of 529 KPa and 381 KPa, respectively.

The TSR values exceeded 70% for all AC mixes containing granite and limestone aggregates, and gravel from south-eastern areas, regardless of their wet strengths. Such high TSR values for aggregates from these sources resulted in good impression about the quality of aggregates and less focus on moisture related performance evaluation.

AC mixes with limestone aggregates generally provide good resistance to stripping, although the ITS values can vary depending on the bedrock strata and AC mix constituents including aggregate composition, air voids in AC mixes, effective asphalt binder contents, binder grade and as compacted density. None of the available LAS is known to improve the ITS of AC mixes containing limestone aggregates. Manitoba used LAS in two AC mixes containing limestone aggregates. The wet ITS increased from 349 to 359 KPa for one mix (Bit. B) and it decreased from 494 to 458 KPa for the other mix (SP12.5). Any minor concerns with low ITS and/or TSR should be addressed through the selection of aggregates and AC mix combinations. Limestone from source(s) with major concern should not be used for AC mix production.

Table 4 shows that the ITS of AC mixes with granite aggregates from south-eastern area had moderate variation with a good average values. For AC mixes with gravel aggregates from south-eastern area, both dry and wet strengths also had moderate variation with a good average values. These data indicate the presence for some poor quality granite and gravel aggregate sources in this area, but majority of sources are probably good. The highest variation of ITS values was noted for AC mixes with gravel aggregates from the south-western area. Although the average dry strength was good, the average wet ITS was low. These indicate a wide spread issue with aggregates from this area. AC mixes with gravel from Parkland-Interlake, and gravel and granite from northern areas also exhibited low or low ranges of wet ITS with a low single or average values. To assess the extent of low wet strength issues, the test data were divided into three groups considering the average and range of wet ITS values, sample size and regional experiences with different aggregate sources.

Group 1 (Limestone sources): AC mixes with aggregates from all limestone sources;

Group 2 (Sources with low concerns): AC mixes with granite and gravel aggregates from south-eastern and northern areas; and

Group 3 (Sources with major concerns): AC mixes with gravel from Parkland-Interlake and south-western areas.

Table 5 shows the percentile distribution of wet ITS values at six benchmarks: <250 Pa, <300 KPa, <350 KPa, <375 KPa, <400 KPa and ≥400 KPa for each of the three groups. As shown in the table, 13.5%, 33.3% and 33.3% of wet strengths fall in <350 KPa mark for Group #1, #2 and #3, respectively. 21.6%, 50.0% and 55.6% of wet strengths are below the 375 KPa mark for these three groups, respectively. For Groups #1

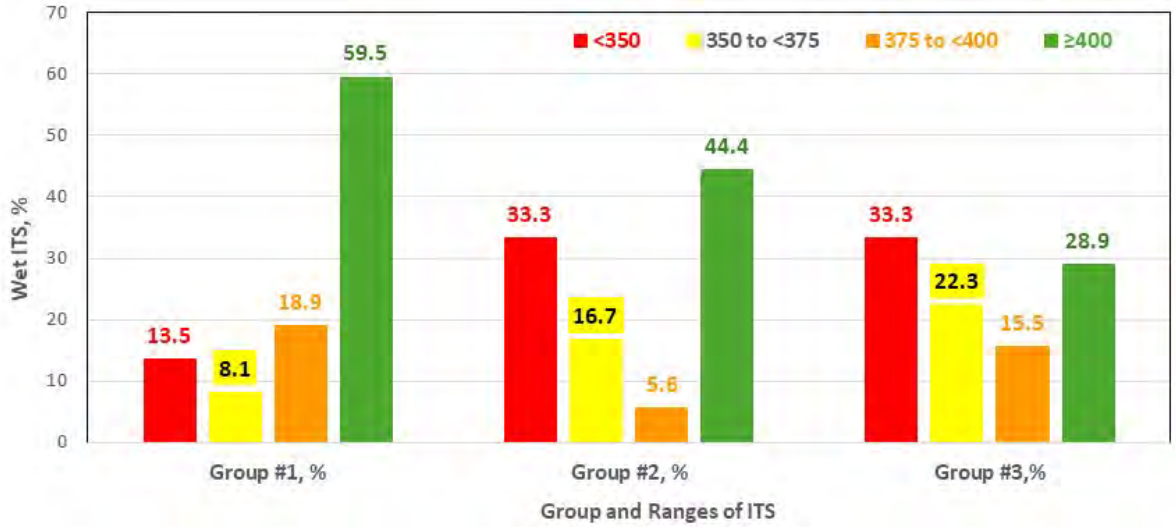
and #2, no wet ITS falls below 300 KPa mark. In Group #3, 11.1% of wet ITS falls below 250 KPa mark and 22.2% falls below 300 KPa mark, further indicating major issues with the relevant aggregate sources.

Table 5. Summary of wet ITS values for three groups

Wet ITS, KPa	Group #1, %	Group #2, %	Group #3,%
<250	0.0	0.0	11.1
<300	0.0	0.0	22.2
<350	13.5	33.3	33.3
<375	21.6	50.0	55.6
<400	40.5	55.6	71.1
≥400	100.0	100.0	100.0

Figure 5 graphically shows the percentages of wet ITS values in four ranges: <350 KPa, 350 to <375 KPa, 375 to <400 KPa and ≥400 KPa. These ranges were created considering the HWTT test data and the corresponding wet ITS values, and rated as red (high concern), yellow (moderate concern), orange (low concern) and green (no concern), respectively. In Group 1, 13.5% of wet ITS values fall in red category, 8.1% fall in yellow category, 18.9% fall in orange category and 59.5% fall in green category. In Group 2, 33.3% of wet ITS values fall in red category, 16.7% fall in yellow category, 5.6% fall in orange category and the rest 44.4% fall in green category. In Group 3, 33.3% of wet ITS values fall in red category, 22.3% fall in yellow category, 15.5% fall in orange category and only 28.9% fall in green category.

Figure 5. Percentile distribution for wet ITS ranges (no anti-stripping agent)



ITS and TSR Test Results: LAS Added

Table 6 shows the percentile distribution of wet ITS values after the addition of LAS into the AC mixes with aggregates from sources that showed low TSR values when tested without LAS. The values were again divided into four ranges <350 KPa, 350 to <375 KPa, 375 to <400 KPa and ≥400 KPa values, which are rated as red (high concern), yellow (moderate concern), orange (low concern) and green (no concern), respectively. As shown in the table, the wet ITS of 30.8% of AC mixes still fell in the red category even

after the addition of LAS agents. Wet ITS of 7.7% AC mixes fell in yellow, another 7.7% fell in orange and the rest 53.8% fell in green categories. In total, 60.8% of wet ITS were ≥375 KPa mark after treatment with LAS agents. None of the wet ITS values were below 250 KPa after the treatment with LAS agents. 23.1% of wet ITS values were between 250 KPa and <300 KPa, and 7.7% were between 300 KPa and <350 KPa. The 7.7% wet ITS values that fell between 350 KPa and <375 KPa could be improved to ≥375 KPa or even ≥400 KPa with minor adjustment to aggregate combination (e.g., by small reduction of the proportion of natural fines) in addition to the use of an appropriate LAS agent. The other 7.7% that fell between 300 KPa and <350 KPa could be improved to ≥375 KPa with some adjustment to aggregate compositions together with the addition of an appropriate LAS agent or using hydrated lime. The 23.1% cases that fall below 300 KPa mark even after the addition of a LAS agent may require special consideration such as the addition of hydrated lime and/or major changes to aggregate compositions with or without an LAS agent. All these percentage values reflect the percentages of AC mixes that had TSR of less than 70% with virgin aggregates (no LAS agents)

Table 6 also shows that even though the treated mixes achieved wet strengths of ≥400 KPa, the TSR could be as low as 63%. No performance issue has been identified with such AC mixes. Therefore, the required minimum TSR should be reduced to 60% when an anti-stripping agent is used. Hydrated lime should be used if the wet ITS falls below 375 KPa or 350 KPa and/or TSR falls below 60% after addition of LAS agent(s).

Table 6. Percentile distribution for different ranges of wet ITS values (LAS added)

ITS	AC mixes with LAS				Same AC mixes with no LAS		
Category	Wet strength, KPa	Wet strength, % in the range	Dry strength, KPa	TSR, %	Wet strength, KPa	Dry strength, KPa	TSR, %
Red	<350	30.8	320-509	50-90	221-452	438-644	46-98
Yellow	350 to <375	7.7	472-539	61-78	247-267	480-503	53-62
Orange	375 to <400	7.7	475-529	72-80	….371….	…..737…..	….50…..
Green	≥400	53.8	450-822	63-95	322-504	374-757	48-89

ITS and TSR Test Results: Hydrated Lime Added

Hydrated lime was used in two projects. No appreciable improvement to wet ITS was noted when fed into the mixing plant because lime did not have enough time to react. A case study is presented later in the paper that included addition into the mixing plant and pre-treatment of aggregate in the laboratory. Such pre-treatment can practically be done during aggregate production. The other alternative is to have the blended aggregates and lime materials go through pugmill, which gives lime a time to react and enhance the resistance to moisture related stripping.

MBV, ITS and TSR Test Results

Table 7 shows the ITS values of two AC mixes with aggregates that had methylene blue values of 4.4 mg/g (Mix #1 silicious aggregate content) and 28.0 mg/g (Mix #2 with plastic clay issue). These aggregates were characterized as “excellent” and “failed” performance expectations, respectively. Mix #1 had untreated dry ITS of 737 KPa; with the addition of a LAS agent, it reduced to 529 KPa, a significant and unexpected reduction. The wet ITS of this AC mix increased from 371 KPa to 379 KPa, a negligible improvement. Untreated AC Mix # 2 had a dry ITS of 374 KPa and wet ITS of 257 KPa. After treatment with a LAS agent,

both of dry and wet strengths have noticeably or significantly improved. Another case study is presented later in this paper.

Table 7. Comparison MBV and ITS values

Mix No.	MBV, mg/g	Untreated			LAS treated		
		Dry strength, KPa	Wet strength, KPa	TSR,%	Dry strength, KPa	Wet strength, KPa	TSR,%
1	4.4	737	371	50.3	529	379	71.6
2	28.0	374	257	68.7	404	371	91.8

Static-Immersion Test Results

Static-Immersion tests were carried out on five AC mixes from different projects. Two different LAS products at two different dosages were applied to four AC mixes to determine what products and dosages meet the required 95% retained coating. PG 58-34 asphalt binders were used in this projects. The results of immersion testing on these four mixes are presented in Table 8. The aggregates for 5th AC mix could not provide the required TSR or wet strength with any available LAS. The trial results for the 5th project are included in Case Study Project # 2, which is presented later in this paper. The test results suggest that the available LAS agents may not always provide the required resistance to stripping.

Table 8. Summary of static immersion test results

LAS No.	LAS Dosage, %	Project #1	Project #2	Project #3	Project #4
		Retained Coating, %			
N/A (Virgin)	N/A	50	25	60	50
LAS #1	0.5	95	85	90	95
LAS #2	0.5	95	90	90	95

Case Studies

Case studies of two projects are presented in this section to demonstrate issues with some aggregates for which no LAS agents could provide the target TSR values. These case studies included several anti-stripping agents in different dosages and combinations. The names of the LAS agents were removed to maintain confidentially of those products and suppliers. It should be noted that numbering sequence and/or additive types used in Project #2 are not the same as that were used for Project #1.

Case Study Project #1

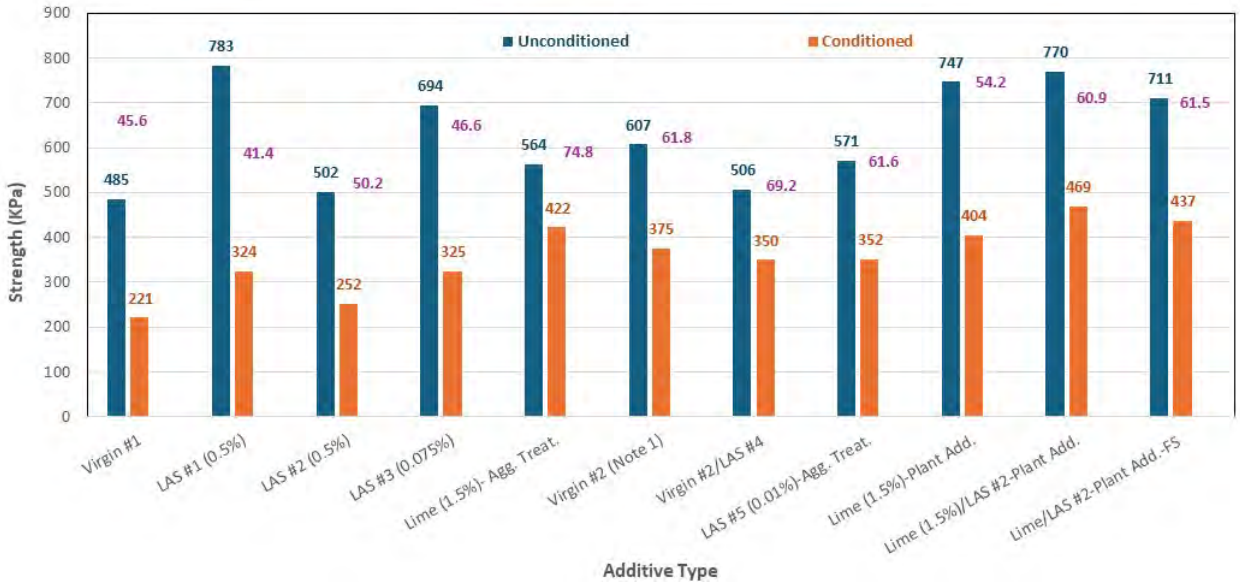
Table 9 shows the composition of different aggregates that were used in the trial AC mixes for this case study. The natural fine aggregate, VMA (voids in mineral aggregate) additive and crushed fine aggregate were 38%, 18% and 12%, respectively. The MBV of these aggregates were 41.7 mg/g, 64 mg/g and 11.5 mg/g, respectively, resulting in combined aggregate MBV of 23 mg/g. According to AASHTO T330, these aggregate combination will cause failure of asphalt mix due to moisture-related stripping.

Table 9. Properties of aggregates used in AC mixes and MBV (Project #1)

Aggregate Composition	Aggregate Type	Proportion, %	Specific Gravity	Water Absorption	Passing 0.075mm Sieve, %	MBV (mg/g)
Crushed coarse aggregate	Gravel	32	2.636	1.30	1.3	N/A
Natural fine aggregate	Gravel	38	2.540	1.90	7.6	41.7
VMA additive aggregate	Gravel	18	2.503	2.20	3.6	64.0
Crushed fine aggregate	Gravel	12	2.610	1.80	5.4	11.5
Combined aggregate	Gravel	100				23

Ten combinations of five different LAS agents, hydrated lime and anti-stripping agent addition process were used in this case study project. Figure 6 graphically shows the results of these trial combinations. The virgin (Virgin #1) aggregate AC mix exhibited a dry ITS of 485 KPa, wet ITS of 221 KPa and TSR of 45.6%. The wet strength and TSR of this AC mix are considered to be very low. The LAS #1, #2 and #3 increased the dry ITS values from 485 KPa to 783 KPa, 502 KPa and 694 KPa, respectively. However, the wet ITS remained at as low as 252 KPa with a maximum value of 325 KPa. The TSR values also remained low (41.4 to 50.2%). Both of the wet ITS and TSR values were below the desired targets. When the aggregates were pretreated with 1.5% hydrated lime, the wet ITS increased from 221 KPa to 422 KPa and the TSR increased from 45.6% to 74.8%. These prove the superiority of hydrated lime as an anti-stripping agent and the availability of an option to improve the stripping resistance of AC mixes with marginal aggregates.

Figure 6. Variation of ITS and TSR for different anti-stripping agents: Case study Project #1



Virgin #2 was a new combination (proportions) of aggregates that are listed in Table 9. The proportions of natural fine aggregate (that had a high MBV) and VMA additive aggregate (that had a very high MBV) were reduced, while the proportion of clean crushed fine aggregate (that had a low MBV) was increased. This new combination (i.e., Virgin #2) significantly improved both wet and dry strengths (375 KPa and 607 KPa, respectively) as well as the TSR, as compared to Virgin #1. These results suggest that an improved resistance to stripping can be achieved by reducing the amount of natural fines and/or other marginal aggregate(s). When the LAS #4 was added to the Virgin #2 aggregate combination, both of dry and wet

strengths dropped, which are undesirable. The addition of LAS #5 to Virgin #1 also resulted in increase of wet strength and TSR from virgin AC mix, but not from Virgin #2 AC mix.

The plant addition of 1.5% hydrated lime to Virgin #1 increased both dry and wet strengths; however, the TSR was still low. When a combination of 1.5% lime and LAS #2 was used in the plant, the wet strength further increased to 469 KPa and TSR increased to 60.9%. A field sample (FS) of this last combination also confirmed the result from the plant AC mix. These indicate that even with a high wet ITS, the TSR may not always meet the currently specified minimum (70%) requirement and Manitoba requires setting a lower target for AC mixes treated with anti-stripping agent(s). Most importantly, these trial results indicate that a wet strength of ≥400 KPa is achievable with an appropriate anti-stripping additive, even though the virgin aggregate AC mix exhibits a very low wet strength.

Figure 6 shows two pictures that were taken in winter following the construction in the proceeding summer. The project used 0.5% LAS #2 and showed poor performance within a short period, suggesting that a wet ITS well exceeding the 250 KPa mark is required to ensure adequate resistance to stripping.

Figure 6. Performance of case study Project #1 after few months



Case Study Project #2

Table 10 shows the composition of different aggregates that were used in the trial AC mixes for the Case Study Project #2. The MBV of VMA additive, natural fine and crushed fine aggregates were >16.3, 16.3 and 6.7 mg/g, respectively. Four different LAS in varying dosages were used in the trial AC mixes. Figure 7 graphically shows the results of these trials.

As shown in Figure 7, the virgin aggregate AC mix without a LAS agent had a very good wet (520 KPa) and dry (959 KPa) strengths. However, the TSR was 54.2%, indicating a substantial drop in strength when the mix was exposed to moisture. With the addition of 0.30% LAS #1, both wet and dry strength dropped, which are not desirable. With 0.50% LAS #1, wet strength increased, but the dry strength decreased from

the virgin aggregate AC mix, which resulted in an increased TSR (63.8%). With further increase in the dosage of LAS #1, dry strength increased, but the wet strength dropped. Overall, the increase in wet strength using LAS #1 was not large enough when compared to the virgin aggregate AC mix.

Table 10. Properties of aggregates used in AC mixes and MVB (Project #2)

Aggregate composition	Aggregate type	Proportion, %	Specific gravity	Water absorption, %	Passing 0.075 mm sieve, %	MBV (mg/g)
Crushed coarse aggregate	Gravel	33	2.635	1.57	1.0	
VMA additive aggregate	Gravel	20	2.397	3.72	4.5	>16.3 (Note 1)
Natural fine aggregate	Gravel	20	2.422	2.42	11.5	16.3
Crushed fine aggregate	Gravel	27	2.609	2.08	4.5	6.7

Note 1: Test stopped when the used methylene blue was close to 50 ml

LAS #2 showed a progressive increase of wet strength with 0.30% and 0.50% dosages as compared to the Virgin, but it decreased with 0.75% dosage. The TSR met the 70% target at 0.50% dosage and the wet strength increased to as high as 705 KPa. LAS #3 progressively dropped the dry strength at 0.5% and 0.75% dosages as compared to the Virgin. Both of the wet ITS and TSR improved at 0.5% dosage, but they dropped at 0.75% dosage. LAS #4 dropped dry strength, but increased the wet strength as compared to the Virgin, making a TSR of 65%. These data indicate the challenge of selecting an appropriate LAS agent and its dosage to ensure adequate resistance to stripping.

Figure 7. Variation of ITS and TSR for different anti-stripping agents: Case study Project #2

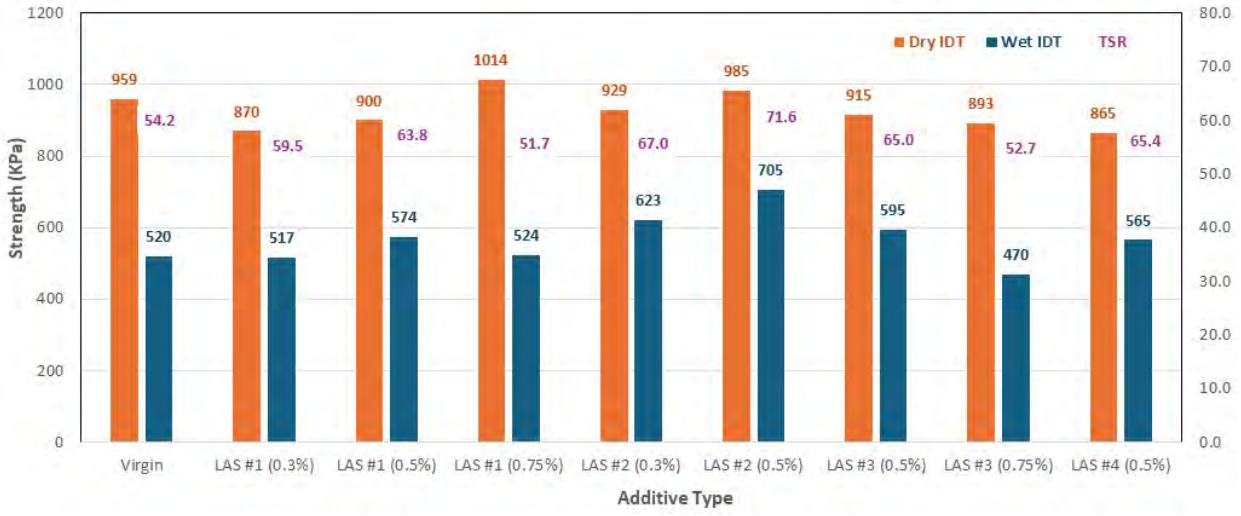


Table 11 shows the results of static-immersion test for a number of LAS agents at varying dosages. No LAS agent and dosage met the required 95% retained coating after the immersion process. The project used 0.50% LAS #1 and no performance issue has been observed so far. This may imply that static-immersion is not a reliable test for assessing the stripping potential of aggregates. The field performance of the AC mix also indicates that a TSR of as low as 60% is acceptable when an anti-stripping agent is used, as long the wet ITS meet certain minimum requirements.

Table 11. Static-immersion test results (Case Study Project #2)

Additive Type	Dosage %	Retained Coating, %
Virgin	0	20
LAS #5	0.3	55
LAS #5	0.5	75
LAS #5	0.7	75
LAS #6	0.8	65
LAS #1	0.5	45
LAS #3	0.5	75
LAS #7	0.5	75
LAS #8	0.1	45

Conclusions and Recommendations

This study analyzed the data of moisture-related stripping tests including the data from two case study projects to: i) benchmark aggregates from different areas of Manitoba; ii) recommend the desired minimum TSR and wet ITS values as the acceptance thresholds for AC mixes without using any anti-stripping agent; iii) set the threshold of wet ITS and TSR values at which any anti-stripping agent can be used; and iv) set the threshold or condition for using hydrated lime. Based on the assessment and analysis of test/trial data, the following conclusions and recommendations are made:

1. None of dry and wet ITS correlated well with specific gravity and water absorption of aggregates. However, these two properties of aggregates showed some correlations with the TSR. The MBV and static-immersion test results did not correlate well with the field performance of AC mixes.
2. To achieve a high degree of confidence on stripping resistance, an AC mix should exhibit a minimum wet ITS of 400 KPa. A wet ITS of ≥375 KPa may also provide good degree of confidence on the adequacy resistance to stripping.
3. Mixed results were obtained from the HWTT tests with the rut depths to SIP exceeding the 6.0 mm mark (at very high number of wheel passes) for some AC mixes and wet ITS in the range of 350 KPa to 375 KPa, while not exceeding the 6.0 mm mark for other AC mixes. All these AC mixes may also provide adequate resistance to stripping in the field. Accordingly, a minimum wet ITS of 350 KPa is recommended to be specified in the revised specification as a phased approach. The field performance of those AC mixes should be monitored. Should stripping still remain a considerable issue, the threshold of wet ITS should be further increased. The required minimum TSR should remain at 70% for AC mixes with no anti-stripping agent.
4. Suitable anti-stripping (LAS and/or hydrated lime) agent(s) should be used whenever the wet ITS and/or the TSR fall below the above specified minimum thresholds and those minimum requirements could not be met with a feasible alternative AC mix design.
5. The addition of an anti-stripping agent should not cause reduction of the wet ITS from the value obtained without using any anti-stripping agent, rather it should result in a minimum of 10% increase in wet ITS. A small reduction (e.g., maximum 10%) of dry ITS after the addition of a LAS agent could be acceptable.

6. It is difficult or not possible to always achieve a TSR of ≥70% using the available anti-stripping agents. A TSR of as low as 60% could be acceptable when an anti-stripping agent is added to an AC mix provided that the wet ITS meet the threshold (≥350 KPa) as specified in Item #3 and the conditions as specified in Item #5 above.
7. Hydrated lime, alone or together with a LAS agent, should be used whenever the required minimum TSR of 60% and the wet ITS of ≥350 KPa could not be achieved through any other alternative treatments. To allow time for curing and effective use of hydrated lime, it should be used to pre-treat the combined aggregates or through a pugmill.
8. Using the HWTT test, the rut depth to SIP should not exceed 6.0 mm and the number of wheel passes to SIP should not be less than 8,000 for Bit. B mixes containing PG 58-XXP or lower grade asphalt binder (refer to a different paper of the authors for other mixes and asphalt binder).
9. Consideration should be given to reduce the amount of natural fine aggregates and to the use of harmful dust/clay free aggregate to improve the stripping resistance of AC mixes.

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Appendix: Regional map of Manitoba Infrastructure and Transportation

