# Characterizing Asphalt Concrete Mixes for Balanced Mix Design (BMD) and Sustainable Pavement Structures in Manitoba

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## Abstract

An asphalt concrete (AC) mixture design is typically carried out to select a desired combination of aggregates and asphalt binder to meet some specified volumetric and stability requirements using either Marshall or SuperPave (SP) methods. However, none of these methods, explicitly set the limiting criteria and their targets for AC mix field performance in terms of rutting, fatigue cracking, thermal cracking and moisture related stripping resistance. The balanced mix design (BMD) approach attempts to make a good balance between the above specified field performance requirements with an appropriate combinations of mix constituents and their properties. The available performance tests include: i) Hamburg Wheel Track Test (HWTT) for rutting and moisture stripping; ii) Illinois Flexibility Index Test (I-FIT) or Indirect Tensile Cracking Test ($CT_{Index}$) for fatigue cracking potential; and iii) Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB) for fatigue and thermal cracking resistance. A study is being undertaken by Manitoba Transportation and Infrastructure (MTI) to characterize Manitoba's local AC mixes and establish the acceptable thresholds for the above specified BMD parameters.

Twenty two AC mix samples have been collected as of March 2026 from different project sites. Hamburg Wheel Track (HWT), I-FIT, Ideal-CT, SCB Fracture energy and resilient modulus testing on these samples have been completed or are in progress. These mixes include Bit. B (Marshall Mix), SP12.5 and SP19.0 with different types of aggregate, design traffic loads, asphalt binder grades and RAP contents. The results showed that tested AC mixes met rutting performance requirements with SP mixes showing superiority over Bit. B mixes. Few AC mixes showed potential for stripping. Mixes with polymer modified asphalt binders showed better fatigue cracking performance than mixes with standard PG XX-34 binders. The results of Ideal-CT test seemed to be inconsistent. Mixes that were tested so far for fracture energy met the thermal cracking criteria. This paper presents the details of the various tests, their results, analysis, findings and the resulting recommendations.

## Introduction

Several methods are in use in North America and elsewhere to prepare asphalt mix designs. Marshall and SuperPave are the two most commonly used mix design methods in Canada and USA. In the Marshall mix design method, agency specific requirements for aggregate gradation and physical properties such as percentages of particles with fractured faces, fine aggregate angularity, flat and elongated particles, sand equivalent values, Los Angeles abrasion loss, micro-deval abrasion loss, clay lumps and friable particles, etc. are specified. For AC mixes, required volumetric properties such as percentage of air voids (AV), voids in mineral aggregates (VMA), voids filled with asphalt (VFA) and/or effective asphalt binder contents, compaction efforts in terms of number of blows of a standard hammer, Marshall stability and flow are generally specified. Some agencies also specify the minimum tensile strength ratio (TSR) values. The required grades for asphalt binder are also specified. These requirements indirectly and generically reflect the expected performance of AC mixes in different traffic loads and climatic exposures. However, no direct correlation was developed with the actual field performance of these mixes in terms of resistance to rutting and cracking. One example of Marshall mixes is Manitoba's Bituminous B (Bit. B) mix with relatively finer grading of aggregate and lower stiffness as compared to some coarser mixes used elsewhere.

Alternatively, SuperPave (SP) mix design method has established new standard requirements for: 1) aggregate gradations and properties to withstand rutting due to different levels of traffic loads; 2) AC mix laboratory compaction method that fairly resembles vibratory compaction in the field; 3) AC mix

compaction efforts (number of gyrations and relative densities) and volumetric properties to withstand different levels of traffic loads, ensure that the AC mix can be easily compacted to the target density and maintain adequate flexibility at the end of design service life; 4) asphalt binder grade requirements to withstand rutting from different types (fast, slow and standing) and levels (low to extremely high) of design traffic loads and thermal cracking under different climatic exposures. Although, the SP mix design system aimed to establish test methods and set some field performance criteria and their limiting values, they have not yet materialized because of complexity and cost associated with those tests.

To date none of the Marshall and SuperPave methods explicitly set limiting criteria and their targets for AC mixes field performance in terms of rutting, fatigue cracking, thermal cracking and moisture related stripping resistance. The BMD approach attempts to make a good balance between field performance parameters and mix constituents. This is an important step as highway agencies and asphalt mix producers are making continued efforts to improve sustainability, particularly with the use of recycled asphalt pavement (RAP) materials, polymer modified asphalt binder and antistripping agents. The BMD uses several performance tests to simulate the mechanisms that produce several key distresses in pavements. The currently used test methods include HWT for rutting and moisture stripping, I-FIT or CT index tests for fatigue cracking and SCB test for fatigue and thermal cracking potential or resistance.

Based on the rationales and principles of development of BMD approach including the associated test methods, the BMD approach seems to be promising, which may provide optimum performance of pavement structures and contribute to sustainable infrastructure development. However, the laboratory test methods and measured performance parameters still do not directly reflect the actual environmental and traffic loadings exposure and mechanism. They are still indirect indicators of potential field performance in terms of stripping, rutting and cracking. Such laboratory measured performance will require field verification with the actual field performance before setting any hard targets for any of these laboratory measured parameters. However, highway agencies are under pressure for implementing relatively easy and rapid test methods that can go beyond the simple volumetric properties. The BMD could be considered as a new promising approach to gain some degree of comfort towards optimum performance and improved sustainability.

Manitoba has been using the Marshall mix design specifications/method for several decades. The province fully implemented the SuperPave asphalt binder grading system in 2015 and started to implement the SuperPave AC mix specifications and design method in 2018. The study has been initiated to determine the performance status of AC mixes that are currently being used on Manitoba provincial highways/roads and recommend the requirements for these AC mixes to achieve certain performance targets for durable and sustainable pavement structures.

## Background and Significance

Manitoba specifications include AC mixes based on both Marshall and Superpave methodologies. Among the Marshall mixes, only Bit. B is currently being used for pavement construction and rehabilitation. Other mixes have been postponed (e.g., Bit. C mix) or are being used for other purposes such as for asphalt pavement maintenance and localized repairs. Three SuperPave mixes, namely SP19.0, SP12.5 and SP4.75, are currently being used on highways. Of these SP mixes, SP19.0 is being used as AC base layer while SP12.5 is typically being used for AC surface layer. Manitoba also has specification for SP9.5, which is to be used for thin overlay (not yet used in any project), and thin mill and inlay, while the SP4.75 AC mix is

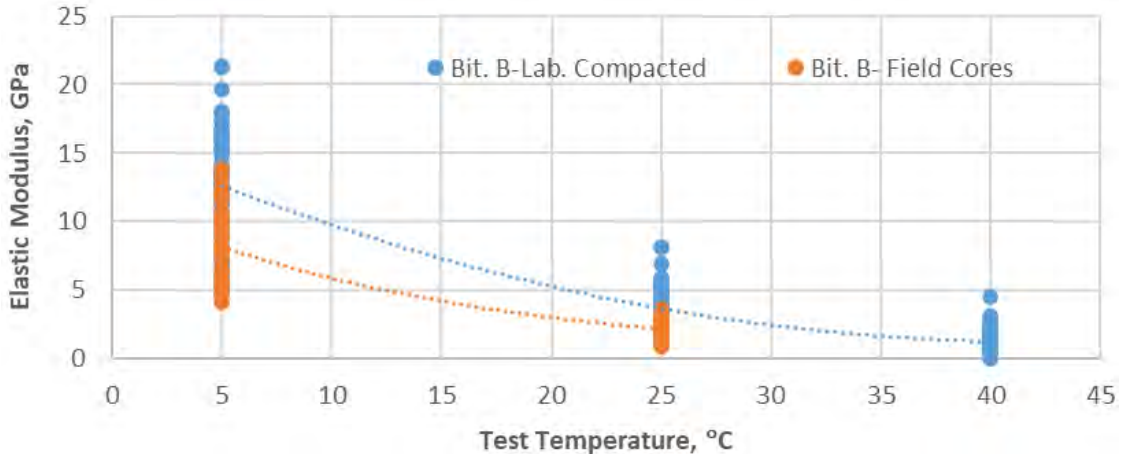
being used for ultra-thin overlay, and micro-milling and ultra-thin inlay, which are considered pavement preservation treatments.

During 2005-2017, Manitoba conducted an extensive testing on Bit. B and Bit. C mixes to characterize them for resilient modulus, poisson's ratio, dynamic modulus, creep compliance and indirect tensile (IDT) strength. A study at the University of Manitoba[1] indicated that Bit. C is an AC mix with very fine graded (sandy) aggregates which possesses very low stiffness and poor stability properties. Bit. B is also a mix with finer graded aggregates and exhibit low stiffness as well as stability properties than the AC mixes used elsewhere across Canada and USA for same purposes. The study results led to postponing the use of Bit. C mix and further improvement of Bit. B aggregate grading. Additional research was conducted at the University of Manitoba[2,3] to continue the characterization of Bit. B mixes including the effect of RAP on the mechanical properties as listed above. Table 1 presents a summary of resilient modulus (Mr) values of laboratory compacted Bit. B mixes with varying RAP contents. Figure 1 presents the Mr test results on laboratory compacted and field core test specimens. The resilient (elastic) modulus values of Bit. B mixes varied based on aggregate types and sources, and AC mix sample/specimen sources (laboratory compacted vs field core specimens). Poor performance was noted for mixes from south-western Manitoba where the available aggregates from gravel pits contains some shale, ironstone, lightweight particles and plastic dust/clay. Limestone, granite and gravel from other areas generally provided higher resilient modulus values. Laboratory compacted AC mixes provided higher stiffness than asphalt cores taken from the project sites, probably due to variation of compaction effort: Marshall hammer on confined specimens vs unconfined roller compaction in the field. Increased RAP contents resulted in an increase in resilient modulus of AC mixes.

Table 1. Elastic (resilient) modulus of Bit. B mixes with varied RAP content

| RAP % | Avg. Mr at 5 °C, GPa | Avg. Mr at 25 °C, GPa | Avg. Mr at 40 °C, GPa |
|---|---|---|---|
| 0 | 10.11 | 2.76 | 0.84 |
| 10 | 11.97 | 4.45 | 1.28 |
| 15 | 12.05 | 3.84 | 1.04 |
| 20 | 12.88 | 3.54 | 0.91 |
| 40 | 15.58 | 5.09 | 1.61 |
| 50 | 18.66 | 4.47 | 1.95 |

Figure 1. Elastic (resilient) modulus of Bit. B mixes: laboratory compacted vs field core specimens



Based on the resilient modulus test results from field core specimens, as shown in Figure 1, Manitoba revised the structural layer coefficient ($a_i$) values of Bit. B mixes from 0.42 to 0.40 for aggregate sources with no soft, lightweight or highly absorptive particles and to 0.36 for aggregate sources containing soft, lightweight or highly absorptive particles within the allowable limits. The selected $a_i$ values represent values at standard temperature of 20 °C (68 °F) based on AASHTO 1993[4] pavement design guide.

Figure 2 shows the extent of AC layer rutting, within a year of construction, of a pavement constructed with a Bit. B mix and PG 58-34 asphalt binder on a highway section with very high traffic loads. Mixes with a polymer modified stiffer asphalt binder (PG 64-34P), a 60 mm lift of SP19.0 and a 40 mm lift of SP12.5 were used to address the rutting issue. The good field performance experience with SP mixes resulted in increased focus on the implementation of SuperPave asphalt binder and mix design specifications for highways with high truck traffic volume and major intersections.

Figure 2. Rutting of a pavement constructed with Bit. B mix



Manitoba undertook a study in 2008 to evaluate the field performance of Bit. B mixes containing 0%, 15% and 50% RAP and two different asphalt binders. The 0%, 15% and one of 50% RAP mixes had 150-200 penetration graded virgin asphalt binder and the other 50% RAP mix had 200-300 penetration graded binders. The blended binder grades were PG 61-32, PG 63-30, PG 69-21 and PG 65-25, respectively. After 10 years (in 2018), these test sections experienced thermal cracking of 45 m/km, 106 m/km, 804 m/km and 213 m/km, respectively i.e., 50% RAP mixes experienced significantly higher amount of cracking as compared to mixes containing 0% and 15% RAP. The outcome of this study and difficulty in the production of homogeneous mix with higher amount of RAP discouraged Manitoba to use RAP exceeding 25%.

In 2021-2022, Manitoba tested AC mixes from three projects for rutting, stripping and cracking performance on a pilot basis: Project 1- Granite aggregate Class C SP12.5 with PG 58-37P and SP19.0 with PG 58-34 binders; Project 2- Limestone aggregate Class D SP19.0 and SP12.5 mixes, both having PG 58-34P binder; and Project 3- Limestone aggregate Class Bit. B mixes containing 10% RAP and 10% RAP+3% RAS (recycled asphalt shingles) and PG 58-34 asphalt binder for the surface lift. Laboratory tests were conducted at the University of Manitoba for rutting resistance at 45 °C using HWT and fatigue cracking resistance using I-FIT at 25 °C. Project 1 mixes passed the rutting (maximum 12.5 mm at ≥10,000 passes), moisture stripping (ratio of stripping to creep slopes of greater than 2.0 with less than 6.0 mm rut depth to stripping inflection point) and fatigue cracking resistance (FI ≥8) criteria. Project 2 mixes passed the rutting and moisture stripping resistance criteria, but failed to meet fatigue cracking resistance criteria.

For Project 3, 10% RAP mix passed all these three criteria; however, the 10% RAP+3% RAS mix did not meet the fatigue cracking resistance requirement although it showed superior rutting resistance.
The above study examples demonstrate Manitoba's efforts to characterize Bit. B AC mixes for stiffness in terms of elastic (resilient) modulus and other mechanical properties. Only a few tests were conducted to characterize mixes for potential field performance in terms of resistance to rutting, fatigue cracking, thermal cracking and stripping. Some field performance of local AC mixes also emphasizes the importance of going beyond the traditional tests for AC mix resilient modulus and other mechanical properties (dynamic modulus, creep compliance, IDT strength, etc.) that are considered to be indirect indicators of field performance. The SP mixes are relatively new in Manitoba and requires an in-depth characterization for elastic modulus, mechanical properties and performance parameters to update the pavement design/assessment inputs. Performance characteristics are also required for BMD to ensure an acceptable balance between rutting, fatigue cracking, thermal cracking and anti-stripping performance. Accordingly, this new study has been initiated in 2023-2024. This paper presents the details of various tests completed thus far, and their results and recommendations.

## Findings from Literature Review

BMD uses performance tests on conditioned specimens to assess the potential for distresses such as rutting, moisture susceptibility and cracking, taking into consideration the mix aging, expected traffic loads, exposed climate and location within the pavement structure[5]. AASHTO PP 105 specified four approaches to BMD: volumetric mix design with performance verification, volumetric mix design with performance optimization, performance modified volumetric design, and performance design[6].

As stated by Feener et al.[7], HWTT is a suitable method for evaluating the rutting and stripping resistance of AC mixes. The stripping inflection point (SIP) indicates how quickly the asphalt mix begins to strip due to moisture-induced damage, while the strip slope indicates the rate at which the mix deteriorates once moisture damage has occurred. As suggested by Iowa DOT[8], if the ratio between the stripping and creep slopes is less than 2.0, the SIP is invalid and the mix is considered to have adequate moisture resistance. Asphalt mixes with higher SIP values with low rut depths are also considered to have good performance.

The HWT testing temperature is related to the critical stripping temperature (CST) of AC mixes. Temperature above the CST demonstrates visco-plastic rutting and stripping due to moisture damage, while temperature below the CST only exhibit visco-plastic rutting. The most used testing temperature by state and federal agencies is 50°C, but several agencies have specified test temperatures based on asphalt binder grades (higher temperature for stiffer binder). For example, Colorado DOT uses a testing temperature of 45°C for PG 58-XX, 50°C for PG 64-XX, and 55°C for PG 70-XX binder[7]. Maine DOT uses a testing temperature of 45°C for PG 64-28, 48°C for PG 64E-28, and 50°C for PG 70E-28.

Several highway agencies have specified different acceptance criteria for SIP and rut depths based on their needs. For example, Maine and Massachusetts DOTs specify a maximum rut depth of 12.5 mm at 20,000 wheel passes combined with no SIP before 15,000 passes. LaDOTD specifies a maximum rut depths of 10.0 mm for mixtures with unmodified asphalt binders and 6.0 mm for polymer-modified binders after 20,000 wheel passes[7,9]. Oklahoma DOT requires a minimum of 10,000, 15,000 and 20,000 passes to 12.5 mm rut depth for PG 64-XX, PG 70-XX and PG 76-XX binders, respectively, at a testing temperature of 50°C[10]. Texas DOT requires a minimum of 15,000 and 20,000 passes to 12.5 mm rut depth for PG 70-XX and PG 76-XX or higher grade binders at a testing temperature of 50°C with no SIP before 9,000 passes[11].

Wisconsin DOT requires a minimum of 10,000, 12,500 and 15,000 passes to a maximum of 10.0 mm rut depth with no SIP, for <0.3 mil ESALs, 0.3 to <3.0 mil ESALs and ≥3.0 mil ESALs, respectively[12]. Illinois DOT requires a minimum of 5,000, 7,500, 15,000 and 20,000 passes to 12.5 mm rut depth for PG 58-XX (or lower), PG 64-XX, PG 70-XX and PG 76-XX (or higher), respectively[13].

Batioja-Alvarez et al.[14] compared the rutting and moisture susceptibility of laboratory compacted specimen to field compacted specimen for three PG binder grades (PG 64-XX, PG 70-XX and PG 76-XX) with three different Superpave mixes (19.0 mm, 12.5 mm and 9.5 mm). It was found that the moisture susceptibility is higher for softer binder.

The I-FIT[15] is a common performance test for fatigue cracking. It uses a notched semi-circular specimen to measure load and displacement over time at 25°C by applying a load line rate of 50 mm per minute. The flexibility index (FI) is calculated by dividing the fracture energy by the post-peak slope. The authors suggested a minimum FI of 8.0 for unaged specimens, and 5.0 for aged (five days at 85°C as per AASHTO R 30) specimens that are prepared in the laboratory as part of AC mix design. For plant produced AC mixes, a minimum FI of 8.0 for unaged specimens and 4.0 for aged specimens were suggested. The suggested length of long-term oven aging was reported to simulate up to 10 years of field aging. A few agencies adopted a much lower FI values for AC mix acceptance. For example, Missouri DOT requires a minimum FI of 2.0 while Caltrans requires a minimum FI of 3.0 for surface mixes and 0.5 for intermediate and bottom layers AC mixes[12].

IDEAL-CT is another performance test for fatigue cracking. It is a form of indirect tension test that involves applying a load on a 62 mm thick specimen at 25°C to failure[16]. Newcomb and Zhou[17] suggested a minimum $CT_{Index}$ of 80 as an acceptable performance criteria, but several agencies have specified different numbers based on binder type or traffic volume. Texas DOT requires a minimum indirect tensile strength of 85 to 200 Psi, and $CT_{Index}$ of 80 and 95 for PG XX-22 or higher and PG XX-28 or lower grade binders, respectively[11]. Alabama DOT requires a mix design $CT_{Index}$ of 55, 83 and 110 (50, 75 and 100 for production acceptance) for mixes designed for less than 1.0 million, between 1.0 to 10 million and 10 to 30 million ESALs, respectively[12]. Missouri DOT requires a minimum $CT_{Index}$ of 32 for their Superpave 19.0 mm mix[12].

The semi-circular bending test (SCB) is a common performance test for fatigue or thermal cracking depending on testing temperature. Similar to the I-FIT test, the SCB test uses semi-circular notched specimen to determine fatigue cracking resistance, represented by critical strain energy release rate ($J_c$ of $G_f$) at 25°C by applying a load line rate of 0.5 mm per minute. Mohammad et al.[18] suggested a minimum $J_c$ value of 0.5 KJ/m$^2$ for less than 3.0 million ESALs and 0.6 KJ/m$^2$ for more than 3.0 million ESALs. For thermal cracking performance, SCB test is conducted at a temperature 10°C higher than the PG low temperature[16]. Marasteanu et al.[19] correlated the observed transverse cracking in field test sections in Illinois, Minnesota and Wisconsin with fracture energy, and found that a minimum $J_c$ of 350 J/m$^2$ is required to prevent thermal cracking. This value was adjusted to 400 J/m$^2$ to account for aging effects.

## Objectives and Scope

As mentioned in preceding sections, although many improvements have been made to Manitoba AC mixes, the province is still facing some challenges with the current mix design approaches, which may not always provide expected field performance. It is also difficult to screen out any marginal aggregates, set the maximum limit of RAP and specify the appropriate asphalt binder under the changing climate to

ensure optimal or desired performance and improved sustainability. This research study has been undertaken to go beyond the status-quo.

The objectives of this study are to: i) characterize Manitoba's AC mixes for rutting, stripping and cracking performance in-terms of relevant indicators; ii) set the minimum requirements for rutting, stripping and cracking indicators to achieve durable and sustainable pavement structures; and iii) characterize current AC mixes for earlier listed mechanical properties to update the pavement design inputs.

Twenty two AC mix samples have been collected from highway project sites covering different types of aggregates, mix types and binder grades. Various tests have been conducted or are in process at department's Central Laboratory in Winnipeg. The objective of this paper is to present the details of various tests, results of completed tests, analysis, summary of findings and recommendations for performance indicators. Some test results for Mr have been presented in a preceding section.

## Research Methodology and Test Methods

This study was designed to characterize both SuperPave (SP19.0 and SP12.5) and Marshall (Bit. B) mixes containing aggregates from different sources across the province and different asphalt binder grades to understand the current status of mixes in terms of expected field performance. The aggregate types included pit run gravel, bedrock limestone and bedrock granite that are commonly available and used for AC mix production. The gravel aggregates from south-western Manitoba are of particular concern because of their inferior quality and the resulting in poor field performance of the AC mixes. This study is expected to clearly identify aggregate sources that have been and are potentially troublesome, and may need elimination or additional processing to meet certain minimum requirements. The study design also included typical asphalt binders (PG 64-34P, PG 58-37P, PG 58-34P and PG 58-34) that are in use on provincial highways to assess their adequacy. Overall, this study is expected to help the province in establishing the test requirements and desired targets for selected performance indicators. The following sections briefly discuss the BMD approach and used test methods that are relevant to this paper.

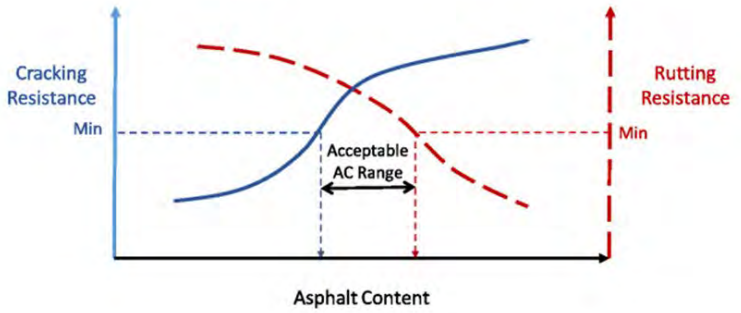
### *BMD Approach*

The BMD approach considers a balance between fatigue cracking, thermal cracking, stripping and rutting performance parameters with key focus on balancing the fatigue cracking and rutting performance parameters. The thermal cracking performance can be managed through the selection of climate specific appropriate minus grade of the asphalt binder and certain minimum AC thickness. A mix design that balances the fatigue cracking and rutting resistance through optimal air voids or density, optimal binder content and binder grade, and strong skeleton of aggregates also contribute to thermal cracking resistance. If moisture-related stripping is an issue, anti-stripping agent can be added where marginal aggregates can not be avoided. So, broadly speaking, the BMD approach combines both volumetric properties and performance indicators to optimize the design for a better long term performance.

Figure 3 graphically shows the concept of BMD for a given AC mix type and aggregate source in which a small range of asphalt binder content is selected to meet the targets of both fatigue cracking and rutting indicators. However, the most important factors are AC mix constituents, their proportions and properties including the hardness, angularity and surface roughness of aggregate particles and stiffness of asphalt binder to achieve a high stiffness and rutting resistance of an AC mix exceeding the nominal requirements.

This will provide some flexibility to increase asphalt binder content and thereby, to enhance the fatigue as well as thermal cracking resistance.

Figure 3. Graphical illustration of BMD approach




***Test Methods and Specimen Preparation***

For all testing, AC mix samples were collected from the project sites on Manitoba highways. HWTT equipment was used for the assessment of rutting and moisture-related stripping potential of AC mixes in accordance with AASHTO T324 *"Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures"*. All AC mixes were compacted to 7±0.1 percent air voids, and triplicate 150 mm diameter and ~62 mm thick cylindrical specimens were prepared. Two duplicate specimens were placed under each wheel. Most of the specimens were tested at 45 °C temperature. Specimens for few AC mixes were tested also at 50 °C to check the potential impact of increased temperature and/or high traffic loads. The equipment was set to stop at 20,000 wheel passes or 12.5 mm rut depth, whichever occurs first. The results from the HWTT included post-compaction consolidation, creep and stripping slopes, SIP, rut depth as well as the number of wheel passes to SIP, and final rut depth and/or number of wheel passes. A higher number of wheel passes for a given maximum rut depth and low amount of rutting at higher number of wheel passes reflected better resistance to rutting. A higher number of wheel passes to SIP with small rut depth and/or a smaller ratio of stripping to creep slopes (e.g., less than 2.0) indicated better resistance to moisture-related stripping.

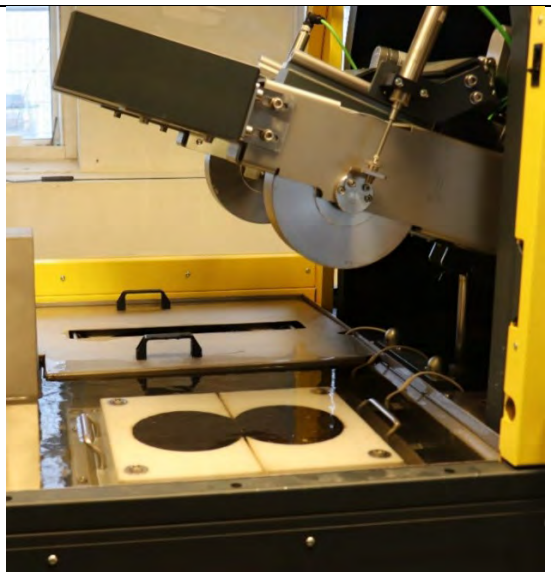
The AC mix flexibility to resist the fatigue cracking was assessed with I-FIT for FI and Ideal CT test for $CT_{Index}$ values. Both tests were conducted at 25°C on short term aged samples. The I-FIT was conducted in accordance with AASHTO T393 "*Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test (I-FIT)*". The I-FIT consisted of two semi-circular specimens with a 15 +/- 1 mm deep and 1.5 mm wide notch cut in the centre of base portion of the semi-circular specimen. The test data analysis takes into consideration two elements: fracture energy and post-peak slope at the inflection point. The calculated FI informs the degree to which an AC mix, and thereby the pavement, can resist premature cracking. In general, the larger the FI number, the more resistant the AC mix is to premature cracking-related damage. However, an excessively large FI number indicates that the AC mix is soft and has potential for flow and rutting.

The IDEAL-CT test was conducted in accordance with ASTM D8825 "*Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature"*. IDEAL-CT test is similar to traditional IDT strength test that determines the cracking potential of asphalt mixtures with a fracture mechanics-based parameter, called Cracking Tolerance Index ($CT_{Index}$). 150 mm diameter and 62 mm high AC mix specimens with 7.0±0.5% air voids were prepared. No notching/cutting is necessary for this test, making it a simpler test than other relevant

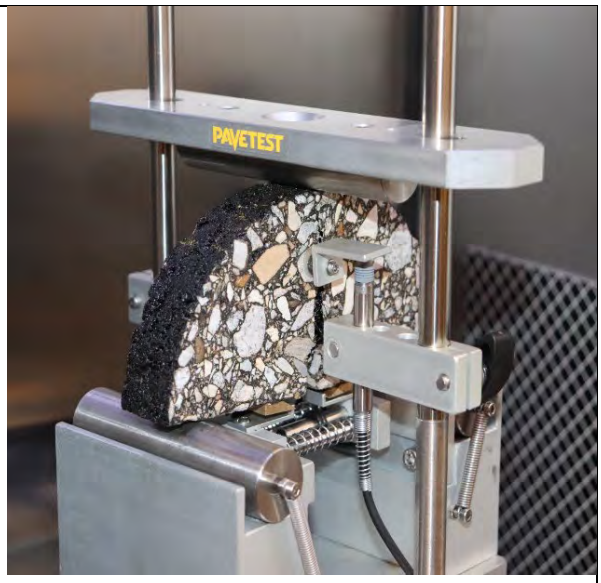
tests. The test data analysis was conducted based on the load versus displacement curve. The $CT_{Index}$ was calculated as a function of total fracture energy and the slope of the post-peak curve at 25% reduction from the peak load. The larger the $CT_{Index}$, the better the cracking resistance.

The resistance to thermal cracking of AC mixtures was measured in terms of low-temperature fracture energy and fracture toughness in accordance with AASHTO T394 *"Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)"*. The conditioned specimens were tested at temperatures which are 10°C above the asphalt binder low temperature grades. The load vs load line displacement curve was used to calculate fracture energy, toughness and stiffness. Figure 4 shows the set-up of all four testing discussed in this section.

Figure 4: Rutting and cracking testing set-up



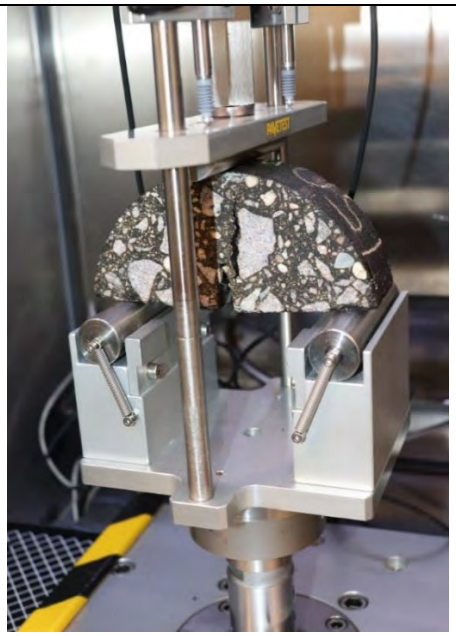
HWT Testing




SCB testing




IDEAL- CT testing



I-FIT testing

## Summary of Aggregate Properties

As mentioned earlier, AC mixes with gravel, granite and limestone aggregates from different sources were used in this study. The gradations of aggregates for Bit. B, SP12.5 and SP19.0 AC mixes are presented in Figures 5, 6 and 7, respectively. A summary of aggregate types and properties are presented in Tables 2, 3 and 4, respectively.

Figure 5. Marshall (Bit. B) mixes aggregate gradations

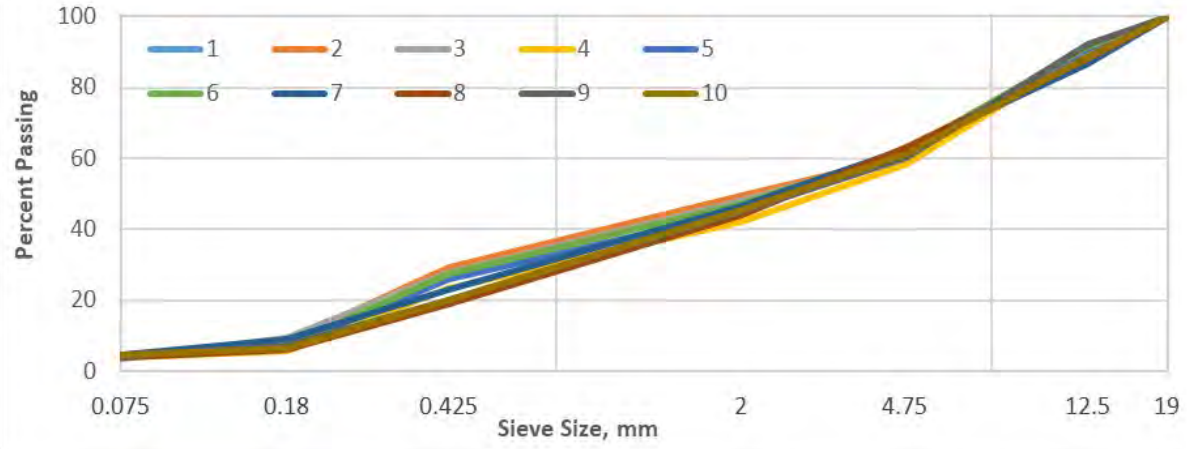



Table 2. Summary of Marshall (Bit. B) mixes aggregate physical properties

| Project # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Aggregate Type | Gravel | Gravel | Gravel | Gravel | Gravel | Gravel | Gravel | LSB | Gravel | Gravel |
| RAP, % | 10 | 20 | 0 | 0 | 15 | 25 | 0 | 0 | 0 | 0 |
| Gsb | 2.588 | 2.592 | 2.592 | 2.595 | 2.590 | 2.591 | 2.619 | 2.735 | 2.588 | 2.572 |
| Water Abs., % | 1.62 | 1.60 | 2.04 | 1.81 | 1.84 | 1.88 | 1.83 | 0.58 | 1.5 | 2.25 |
| FF, % | 70.5 | 73.2 | 91.1 | 59.1 | 62.1 | 63.5 | 84.1 | 96.1 | 66.6 | 87 |
| LWP, % | 1.0 | 1.0 | 1.2 | 1.7 | 1.3 | 1.7 | 0 | 0 | 1.4 | 1.8 |
| Ironstone, % | 3.3 | 3.5 | 0.1 | 3.7 | 3.3 | 3.7 | 0.8 | 0 | 1.5 | 4.1 |
| LAA , % | 19.9 | 19.9 | 22.6 | 19 | 19 | 19 | 30.7 | 20.9 | 18.9 | 24.7 |
| CL & FP, % | 0 | 0.8 | 0.4 | 0.47 | 0.53 | 0.52 | 0.5 | 0.1 | 0.4 | 0.2 |

*LSB = Limestone bedrock; RAP= reclaimed asphalt pavement; Gsb= bulk specific gravity; Abs.= absorption; FF= fractured faces; LWP= light weight particles; LA= Loss Angeles abrasion; CL & FP= clay lumps and friable particles.*

As shown in Figure 5 and Table 2, aggregate gradations differ narrowly among the selected ten Bit. B projects. However, there were some variation among aggregate properties. Projects (Mix ID) #1 and #2 AC mixes consisted of aggregates from the same sources; however, these AC mixes had 10% and 20% RAP, respectively. Similarly, Projects #4, #5 and #6 consisted of aggregates from same sources; however, these AC mixes had 0%, 10% and 20% RAP, respectively.

Figure 6 and Table 3 show that both of aggregate gradations and physical properties of SP12.5 AC mixes varied among the projects. Figure 7 and Table 4 also show that both of aggregate gradations and physical properties varied among the projects for SP19.0 mixes. However, SP mixes had coarser gradations and improved physical properties than the Marshall Bit. B mixes. In addition, SP mixes contained no RAP.

Figure 6. SP12.5 AC mixes aggregate gradations

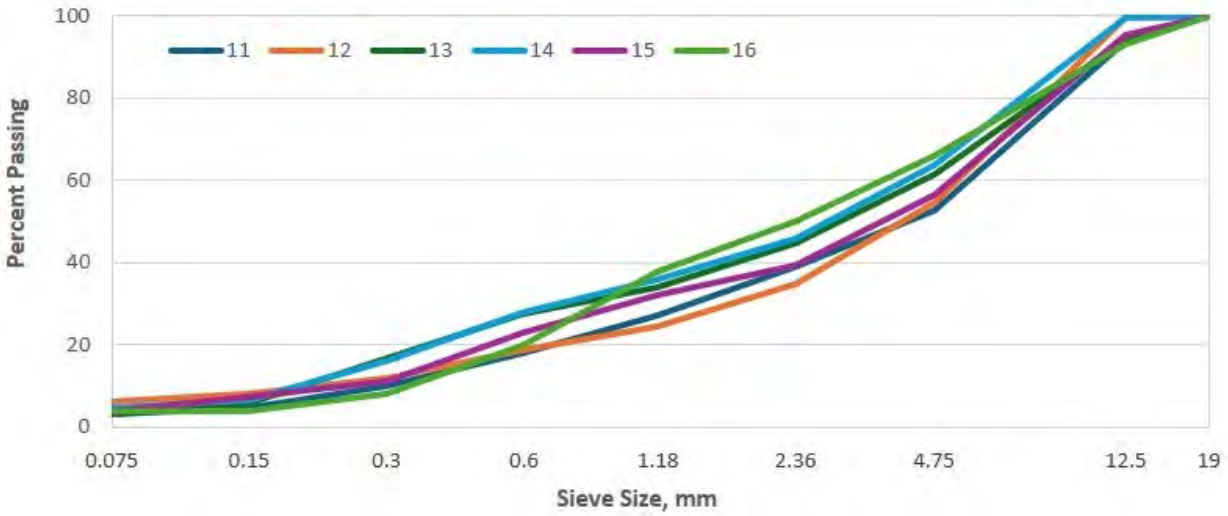



Table 3. Summary of SP12.5 AC mixes aggregate physical properties

| Project No. | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|
| Aggregate Type | Granite Bedrock | Gravel | Gravel | Gravel | Granite Bedrock | Limestone Bedrock |
| Traffic Category | SP12.5 "C" | SP12.5 “D” | SP 12.5 "D" | SP12.5 "C" | SP12.5 "D" | SP12.5 "D" |
| RAP Content, % | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Gsb | 2.614 | 2.653 | 2.62 | 2.621 | 2.669 | 2.639 |
| Water Abs., % | 0.55 | 0.99 | 1.13 | 1.384 | 0.66 | 1.72 |
| FF, % | 98.4 | 99.4 | 98.6 | 95.7 | 97.3 | 97.3 |
| LWP, % | 0 | 0.3 | 0 | 0 | 0 | 0 |
| Ironstone, % | 0 | 0.3 | 0 | 0 | 0 | 0 |
| LA, % | 29.6 | 25.9 | 24.8 | 31.9 | 23 | 23 |
| CL & FP, % | 0 | 0.5 | 0.3 | 0 | 0 | 0 |
| SE, % | | 79.6 | 73 | | 94 | |
| FAA, % | 43.2 | 45.6 | 44.7 | 46.4 | 45 | 43 |
| F & E, % | 7 | 0 | 5 | 2.4 | 4 | 4 |

*SE= sand equivalent; FAA = fine aggregate angularity; F & A= flat and elongated particles; blank cell= no testing was done.*

Figure 7. SP19.0 AC mixes aggregate gradations

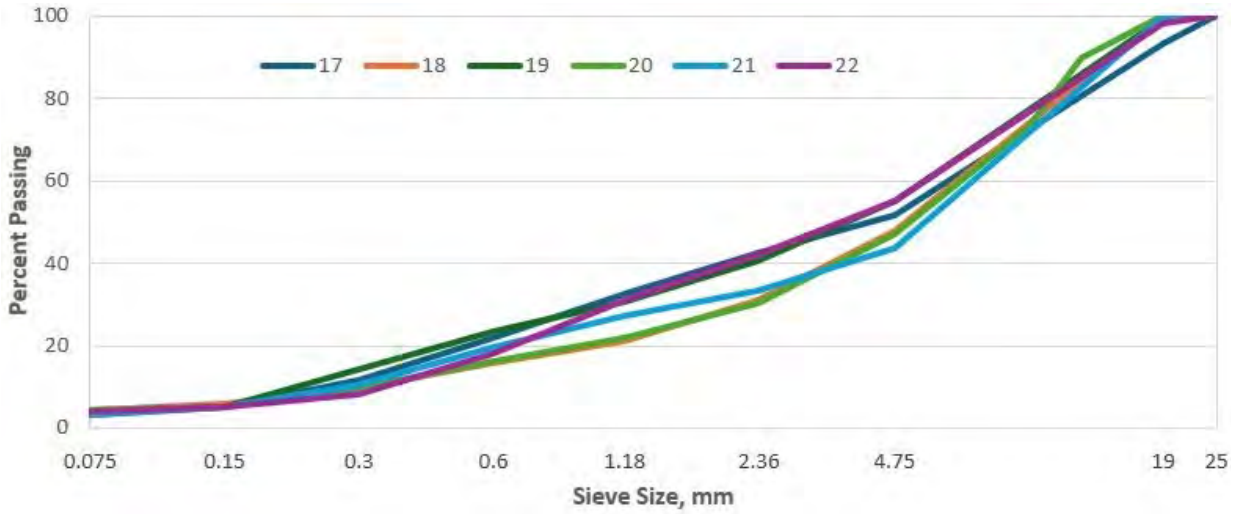



Table 4. Summary of SP19.0 AC mixes aggregate physical properties

| Project No. | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|
| Aggregate Type | Granite Bedrock | Gravel | Gravel | Gravel | Granite Bedrock | Limestone Bedrock |
| Traffic Category | SP19.0 "C" | SP19.0 “D” | SP19.0 "D" | SP19.0 "C" | SP19.0 "D" | SP19.0 "D" |
| RAP Content, % | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Gsb | 2.618 | 2.658 | 2.620 | 2.616 | 2.665 | 2.649 |
| Water Abs., % | 0.7 | 0.88 | 1.15 | 1.503 | 0.6 | 1.74 |
| FF, % | 93.9 | 100 | 98.6 | 98.7 | 99.4 | 99 |
| LWP, % | 0 | 0 | 0 | 0 | 0 | 0 |
| Ironstone, % | 0 | 0 | 0 | 0 | 0 | 0 |
| LA, % | 29.6 | 21.1 | 26.3 | 31.9 | 29 | 24.5 |
| CL & FP, % | 0 | 0 | 0.1 | 0 | 0 | 0.2 |
| SE, % | | 83 | 59 | | 84 | 92 |
| FAA, % | 43 | 48.1 | 45.3 | 45.3 | 45 | 43 |
| F & E, % | 6 | 5 | 5 | 1.1 | 6 | 3 |

## Summary of AC Mix Properties

Tables 5, 6 and 7 shows the properties of selected Bit. B (Marshall), SP 12.5 and SP19.0 AC mixes, respectively. The Bit. B mixes had PG 58-37P, PG 58-34P and PG 58-34 asphalt binders. The asphalt binder contents in these mixes varied from 5.2 to 6.5%. The effective asphalt binder contents varied with total binder content and binder absorption into aggregate pores and ranged from 4.64 to 5.13%. There were also some variations of mix properties, stability and flow; however, these variations are not widespread.

Table 5. Summary of Marshall (Bit. B) mix properties

| Mix ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| AC Type | PG 58-37P | PG 58-37P | PG 58-34P | PG 58-34P | PG 58-34 | PG 58-34 | PG 58-34P | PG 58-37P | PG 58-34P | PG 58-34P |
| Marshall Blow | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| %RAP | 10 | 20 | 0 | 0 | 15 | 25 | 0 | 0 | 0 | 0 |
| %Pb | 5.64 | 5.55 | 6.0 | 5.9 | 5.8 | 5.6 | 5.6 | 5.2 | 5.4 | 6.5 |
| Gmm | 2.448 | 2.450 | 2.453 | 2.431 | 2.432 | 2.439 | 2.469 | 2.542 | 2.426 | 2.426 |
| Gmb | 2.349 | 2.352 | 2.354 | 2.336 | 2.337 | 2.343 | 2.362 | 2.434 | 2.329 | 2.330 |
| %AV | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.3 | 4.0 | 4.0 | 4.0 |
| %VMA | 15.6 | 15.4 | 15.8 | 15.6 | 15.4 | 15.0 | 14.8 | 15.4 | 15.3 | 15.3 |
| %VFA | 74.4 | 74.1 | 74.4 | 74.4 | 74.3 | 73.5 | 70.5 | 74.7 | 74.1 | 73.9 |
| %Pba | 0.55 | 0.53 | 0.89 | 0.82 | 0.79 | 0.81 | 0.96 | 0.3 | 0.48 | 1.51 |
| %Pbe | 5.09 | 5.02 | 5.20 | 5.13 | 5.06 | 4.84 | 4.64 | 4.9 | 5.0 | 5.08 |
| Stability, kN | 10.0 | 10.4 | 13.8 | 13.1 | 9.2 | 10.2 | 12.4 | 11.8 | 9.3 | 12.9 |
| Flow, 0.25 mm | 9.8 | 8.3 | 11.0 | 10.5 | 9.9 | 9.4 | 10.7 | 10.8 | 10.6 | 10.5 |

*Pb= percentage of total asphalt binder content in AC mix; Gmm= maximum theoretical specific gravity of loose AC mix; Gmb= bulk specific gravity of compacted of AC mix; AV = air voids contents in AC mix; VMA = voids in mineral aggregates; VFA = voids filled with asphalt; Pba= percentage of asphalt binder absorbed by the aggregates; Pbe= percentage of effective asphalt binder content in the mix.*

Table 6. Summary of SP12.5 AC mix properties

| **Mix ID** | **11** | **12** | **13** | **14** | **15** | **16** |
|---|---|---|---|---|---|---|
| Gyrations @ Ndesign | 75 | 100 | 100 | 75 | 100 | 100 |
| RAP Content, % | 0 | 0 | 0 | 0 | 0 | 0 |
| AC Type | PG 58-37P | PG 64-34P | PG 58-34P | PG 58-37P | PG 64-34P | PG 64-34P |
| Pb | 5.15 | 5.55 | 4.9 | 5.2 | 5 | 5.4 |
| Gmm | 2.446 | 2.464 | 2.465 | 2.471 | 2.496 | 2.456 |
| Gmb | 2.340 | 2.365 | 2.351 | 2.373 | 2.389 | 2.358 |
| %AV | 4.3 | 4.0 | 4.6 | 4.0 | 4.3 | 4.0 |
| %VMA | 15.1 | 15.8 | 14.5 | 14.3 | 14.9 | 15.0 |
| %VFA | 71.51 | 74.5 | 67.9 | 72.1 | 71.3 | 73.2 |
| Pba | 0.63 | 0.49 | 0.62 | 0.81 | 0.51 | 0.66 |
| Dust Proportion | 0.7 | 1.2 | 0.9 | 0.9 | 0.9 | 0.84 |
| Pbe | 4.52 | 5.06 | 4.28 | 4.44 | 4.49 | 4.8 |

Table 7. Summary of SP19.0 AC mix properties

| Mix ID | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|
| Gyrations @ Ndesign | 75 | 100 | 100 | 75 | 100 | 100 |
| RAP Content, % | 0 | 0 | 0 | 0 | 0 | 0 |
| AC Type | PG 58-34 | PG 64-34P | PG 58-34P | PG 58-34 | PG 64-34P | PG 64-34P |
| Pb | 4.7 | 5.4 | 5.1 | 4.55 | 4.5 | 4.9 |
| Gmm | 2.459 | 2.486 | 2.466 | 2.471 | 2.506 | 2.496 |
| Gmb | 2.357 | 2.393 | 2.366 | 2.382 | 2.417 | 2.393 |
| %AV | 4.1 | 3.7 | 4.0 | 3.6 | 3.6 | 4.2 |
| %VMA | 14.2 | 14.8 | 14.6 | 13.1 | 13.4 | 14.1 |
| %VFA | 70.79 | 74.8 | 72.2 | 72.4 | 73.3 | 70.5 |
| Pba | 0.62 | 0.70 | 0.61 | 0.51 | 0.37 | 0.63 |
| Dust Proportion | 0.7 | 0.9 | 0.8 | 1.1 | 0.9 | 0.96 |
| Pbe | 4.08 | 4.7 | 4.56 | 4.1 | 4.1 | 4.2 |

Superpave mixes had PG 64-34P, PG 58-37P, PG 58-34P and PG 58-34 asphalt binders, where PG 58-34 binder was used in SP19.0 AC base mixes only. The AC mix properties including the asphalt binder contents also varied among the SP mixes.

## Test Results, Analysis and Discussion

The available literature indicates that the number of wheel passes to SIP in HWTT should be ≥10,000 with a small rut depth if the ratio of stripping to creep slopes (S/C ratio) is ≥2.0 or this ratio should be less than 2.0 (e.g., no SIP) for a good resistance to moisture related stripping. The acceptable maximum rut depths are 6.0 mm to 10.0 or 12.5 mm. The acceptable minimum number of wheel passes are 10,000 to 20,000 for a maximum rut depth of 6.0 mm for stiffer AC mixes (to withstand higher high pavement temperatures and/or traffic loads) and 10,000 passes for less stiffer mixes, i.e., for milder climates or low traffic loads. However, it is not clear how the 10,000 wheel passes can be attained with a low rut depth and S/C of ≥2.0 when the acceptable total rut depths are 10.0 to 12.5 mm at 10,000 wheel passes. A clearer requirement should be set to address this issue. The acceptable minimum FI value appears to be 8.0, while the $CT_{Index}$ values of 80 to 100 seem to be reasonable targets for moderate to high traffic loads. For an adequate resistance to thermal cracking, a minimum fracture energy of 400 J/m$^2$ is targeted from SCB test at low temperature. These recommended values are used as a basis for assessing the status of Manitoba mixes and providing preliminary recommendations for acceptable moisture-related stripping resistance, rutting, fatigue cracking and thermal cracking performance requirements. The following sections discuss the completed test results and potentially acceptable targets.

***HWTT Results: Bit. B (Marshall) Mixes***

The results from HWTT on all 22 mixes are presented in Table 8. Mix # 1 (Bit. B) with gravel aggregates and 10% RAP exhibited a low number of wheel passes to SIP with a high S/C ratio (≥2.0), even though the mix exhibited over 10,000 wheel passes to 12.5 mm rut depth. Mix #2 with the same virgin aggregates but with 20% RAP exhibited better resistance to stripping and rutting than Mix #1 with higher number of wheel passes to SIP as well as 12.5 mm rut depth. These may indicate that aggregates in that RAP are of better quality (e.g., higher % of particles with fractured faces) than the virgin aggregates used for these

projects. These two mixes had wet ITS of 366 kPa and 367 kPa (TSR of 76.9% and 74.1%), respectively. Similar trends are observed for Mixes #4, #5 and #6 with 0%, 15% and 25% RAP, respectively, where an increased RAP content led to increased number of wheel passes to SIP, but with increasing rut depth. The rut depths to SIP also exceeded 6.0 mm target for 15% and 25% AC mixes, which may indicate that PG58-34 asphalt binder was not adequate for these two mixes containing RAP and/or aggregates are moisture susceptible (TSR values were 59.8, 64.0 to 62.2% with wet tensile strength of 365, 348 and 346 kPa, respectively). A higher number of wheel passes to 12.5 mm rut depth for Mix #4 with 100% virgin aggregates seem to be associated with stiffer virgin binder (PG58-34P, which is polymer modified) than Mix #5 that had PG58-34 asphalt binder. Increased RAP contents contributed to increased resistance to rutting, which is evident from higher number of wheel passes to 12.5 mm rut depths.

Table 8. 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 to Creep Slopes Ratio | 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 | 12.50 |
| 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 | 12.50 |
| 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 | 12.50 |
| 11a | SP12.5-C | PG58-37P | 45 | - | - | - | 20000 | 4.49 |
| 11b | SP12.5-C | PG58-37P | **50** | 7944 | **6.73** | 3.31 | 14447 | 12.50 |
| 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 |
| 15a | SP12.5-D | PG 64-34P | 45 | - | - | - | 20000 | 2.81 |
| 15b | SP12.5-D | PG 64-34P | 50 | 15569 | 5.88 | 7.99 | 20000 | 8.58 |
| 16 | SP12.5-D | PG 64-34P | 45 | - | - | - | 20000 | 2.52 |
| 17a | SP19.0-C | PG58-34 | 45 | 16915 | 4.92 | 3.85 | 20000 | 6.66 |
| 17b | SP19.0-C | PG58-34 | **50** | 8156 | **6.77** | 4.16 | 13804 | 12.50 |
| 18 | SP19.0-D | PG64-34P | 45 | - | - | - | 20000 | 3.10 |
| 19 | SP19.0-D | PG 58-34P | 45 | 16734 | **6.92** | 4.33 | 20000 | 7.22 |
| 20 | SP19.0-C | PG 58-34 | 45 | - | - | - | 20000 | 3.46 |
| 21a | SP19.0-D | PG 64-34P | 45 | - | - | - | 20000 | 2.80 |
| 21b | SP19.0-D | PG 64-34P | **50** | 15020 | 5.27 | 9.94 | 20000 | 5.59 |
| 22 | SP19.0-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.*

Mix #3 with a PG 58-37P asphalt binder exceeded 10,000 wheel passes with 3.16 mm rut depth to SIP and 8.28 mm rut depth after 20,000 wheel passes, which may indicate that this mix has very good resistance to stripping and rutting (no TSR test data is available). Mix #7 with gravel and Mix #8 with limestone aggregates provided similar results for number wheel passes to SIP and 12.5 mm rut depth, and also had low (≤6.0 mm) rut depths to SIP. Mix #7 had a wet ITS of 417 kPa and no testing for TSR was done for Mix #8. Mix #9 with a PG 58-34P asphalt binder shown similar results as Mix #3 with PG 58-37P binder in terms of number of wheel passes to SIP and rut depth after 20,000 wheel passes. However, the rut depth to SIP exceeded 6.0 mm for Mix #9 at >15,000 wheel passes (it exhibited a wet ITS of 373 kPa and TSR of 72.2%). Mix #10a with hydrated lime, a liquid anti-striping agent and PG 58-34P binder provided similar results as of Mix #3. Mix #10b, which is exactly the same as Mix #10a but contained only the liquid anti-strip agent that was used in Mix #10a, withstood a lower number of passes to SIP and maximum rut depth (12.5 mm) with lower number of wheel passes. Both mixes (#10a and 10b) seemed to have met the moisture stripping and rutting resistance requirements. However, hydrated lime has improved the rutting and moisture-related stripping resistance.

### *HWTT Results: SP12.5 Mixes*

As shown in Table 8, Mix #11, which is a Class C SP12.5 mix containing granite aggregates and PG 58-37P asphalt binder, withstood 20,000 wheel passes by exhibiting a small rut depth of 4.49 mm and no SIP when tested at 45 °C. The same mix when tested at 50 °C exhibited 6.73 mm rut depth to SIP and 12.5 mm rut depth after 14,447 wheel passes. This indicates that SuperPave mix traffic category (or class) C is not suitable for high pavement temperature and/or traffic loads, and also supports the strategic highway research program recommendation for mix requirements based on traffic load categories. Similar trends for HWTT results, at 45 °C vs 50 °C, were noted for Mix #15, which is a Class D SP12.5 mix also containing granite aggregates. However, Mix #15 had stiffer (PG 64-34P) asphalt binder, more stringent mix and aggregate properties than Mix #11. Accordingly, Mix #15 exhibited higher resistance to rutting (than Mix #11) with a total of 2.81 mm rut depth at 45 °C and 8.58 mm rut depth at 50 °C after 20,000 wheel passes. There was no SIP at 45 °C test temperature, while the rut depth to SIP was 5.88 mm at 50 °C after over 15,000 wheel passes.

Class D SP12.5 mix containing PG 64-34P binder and gravel (Mix ID #12), granite (Mix ID #15a) and limestone (Mix ID #16) aggregates provided similar performance with a total rut depth of less than 3.0 mm and no SIP at 45 °C. This indicates that aggregate type is not a factor for rutting performance and moisture-related stripping resistance if they exhibit similar physical and mechanical properties. Mixes #13 and #14 had same asphalt binder in terms of high temperature grade (PG58-34P and PG 58-37P, respectively). Both mixes experienced less than 12.5 mm rutting after 20,000 wheel passes and less than 6.0 mm rut depth to SIP. However, Mix #13, which is a Class D SP12.5 mix, exhibited significantly smaller rut depths (3.89 mm after 20,000 wheel passes and 3.09 mm to SIP) than Mix #14, which is Class C SP12.5 mix and experienced rut depths of 10.59 mm after 20,000 wheel passes and 5.31 mm to SIP. This further confirms the stringent requirements for aggregate properties and AC mixes for high traffic applications.

### *HWTT Results: SP19.0 Mixes*

Table 8 shows that the Class C SP19.0 Mix #17 containing granite aggregates exhibited similar trends as the Class C SP12.5 Mix #11 for changes in test temperatures. However, the SP19.0 mix with a PG 58-34 asphalt binder experienced larger rut depth (4.92 mm) to SIP and larger total rut depth (6.66 mm) after 20,000 wheel passes than the SP12.5 mix (no SIP and 4.49 mm rut depth after 20,000 passes at 45 °C), as expected. The Class D SP19.0 Mix #21 and Class D SP12.5 Mix #15 exhibited similar rut depths after 20,000 wheel passes (and no SIP) at 45 °C. However, when tested at 50 °C, the SP19.0 mix exhibited smaller rut depth to SIP (5.27 mm) and total rut depth after 20,000 wheel passes (5.59 mm) than the SP12.5 mix (rut depth to SIP= 5.88 mm and total rut depth after 20,000 wheel passes= 8.58 mm) due to better interlock and inter-aggregate friction with coarser aggregates in the SP19.0 mix.

At 45 °C temperature, the Class D SP19.0 Mix #18 experienced slightly larger rut depth (3.10 mm) than the Class D SP12.5 Mix #12 (2.28 mm) with no SIP for both mixes. This small difference could be related to variation in specimen preparation and/or mix combinations. The Class D SP19.0 Mix #19 with PG 58-34P asphalt binder experienced larger rut depths to SIP (6.92 mm, which is above the target value of ≤6.0 mm) and 7.22 mm total after 20,000 wheel passes than the Class D SP12.5 Mix #13 (rut depth to SIP= 3.09 mm and total after 20,000 wheel passes= 3.89 mm). Mix #19 had a wet tensile strength of 361 kPa. Higher rut depths for SP19.0 mix, as compared to the SP12.5 mix, seem to be related to the variation of aggregate and AC mix properties, particularly the clay contents in aggregates (SE= 59% for SP19.0 fine aggregates vs 73% SP12.5 fine aggregates) and the effective asphalt binder content in AC mixes (4.56% in SP19.0 vs 4.28% in SP12.5).

The Class C SP19.0 Mix #20 containing PG 58-37P asphalt binder withstood 20,000 wheel passes with a total rut depth of 3.46 mm and no SIP. This SP19.0 mix outweighed the performance of Class C SP12.5 Mix #14 containing PG 58-34 asphalt binder, which experienced 5.31 mm rut depth to SIP and total 10.59 mm rut depth after 20,000 wheel passes. The superior performance of SP19.0 mix seems to be related to coarser aggregate skeleton in this AC mix. The limestone aggregate Class D SP19.0 mix (Mix #22) exhibited similar performance (total rut depth of 2.43 mm after 20,000 wheel passes and no SIP) as the corresponding SP12.5 AC mix (Mix #16: 2.52 mm rut depth after 20,000 passes and no SIP). The smaller rut depth for SP19.0 mix seems to be associated with coarser aggregates in SP19.0 mixes than SP12.5 mix. However, the difference is not as large as expected, which is probably associated with higher fracture potential of relatively softer limestone large aggregate particles under compaction than smaller particles and/or significantly lower effective asphalt binder content in SP19.0 mix (4.2%) than in the SP12.5 (4.8%).

### *I-FIT, IDEAL-CT and Low Temperature SCB Test Results*

Table 9 shows the results of various cracking performance tests that have been completed so far. The table shows that AC mixes (Bit. B, SP12.5 and SP.19.0) containing PG 64-34P, PG 58-37P and PG 58-34P asphalt binders exhibited FI values of 8.0 to 16, which met or exceeded the recommended minimum FI value of 8.0, except for the Mix #10a. Mix #10a contained hydrated lime as an anti-stripping agent and exhibited a low FI value of 4.0, which seems to be reasonable as lime hardens the AC mixes. All AC mixes with PG 58-34 asphalt binder exhibited FI values of less than 8.0. Among the AC mixes with polymer modified asphalt binders, Mixes #3, 11 and 18 met the target minimum $CT_{Index}$ value of 80.

Mixes #1 and #2 with 10% and 20% RAP, respectively, met the FI target of 8.0. However, Mix #1 exhibited a low number of wheel passes to SIP indicating a potential for stripping issue (probably due to poor quality virgin aggregates). These two mixes exhibited wet ITS of 366 kPa and 367 kPa, respectively. An antistripping agent may improve the moisture related stripping resistance of such AC mixes. Mix #4 with a PG 58-34P asphalt binder exhibited a good FI value of 13, while the IDEAL-CT test provided a $CT_{Index}$ value of 28, which is significantly lower than the target value of 80. This AC mix also showed a fracture energy of 495 J/m$^2$, which is above the target minimum value of 400 J/m$^2$, indicating a good resistance to thermal cracking. Accordingly, the low $CT_{Index}$ value for this mix does not seem to be reasonable at all.

Mixes #5 and #6, containing 15% and 25% RAP, showed FI values of 6.0 and 7.0, respectively, flagging a potential for poor resistance to cracking. These two mixes also showed large rut depths (>6.0 mm) to SIP indicating a potential for moisture-related stripping issues (these mixes exhibited wet ITS of 348 kPa and 346 kPa, respectively). These indicate that AC mixes containing RAP should be more carefully designed considering the true contributions of RAP binder (percentage and grades) and the required virgin asphalt binder grades and percentage, and any requirement for anti-stripping agent. The $CT_{Index}$ of 86 and 48, respectively, for these two mixes seem to be unreasonable and inconsistent.

Table 9. Summary of cracking performance test results

| Mix ID | Mix Type | Binder Grade | FI (AASHTO 393) | CT Index (ASTM D8825) | Semi Circular Bend (AASHTO T394) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test Temp. (°C) | Fracture Energy ($J/m^2$) | Tensile Strength (MPa) | Fracture of Toughness $MPA*m^{05}$ |
| 1 | Bit B | PG 58-37P | 12 | 76 | | | | |
| 2 | Bit B | PG58-37P | 10 | 63 | | | | |
| 3* | Bit B | PG 58-37P | 12 | 99 | | | | |
| 4* | Bit B | PG 58-34P | 13 | **28** | -24 | 495 | 435 | 0.7 |
| 5* | Bit B | PG 58-34 | **6** | 86 | | | | |
| 6* | Bit B | PG 58-34 | **7** | 48 | | | | |
| 7 | Bit B | PG 58-34P | 16 | | | | | |
| 8 | Bit B | PG 58-37P | 14 | | | | | |
| 9 | Bit B | PG 58-34P | 12 | | | | | |
| 10a** | Bit B | PG58-34P | 4 | | | | | |
| 10b* | Bit B | PG58-34P | 10 | | | | | |
| 11 | SP12.5-C | PG58-37P | 15 | 80 | -24 | 600 | 366 | 0.6 |
| 12 | SP12.5-D | PG64-34P | 10 | 43 | | | | |
| 13 | SP12.5-D | PG 58-34P | 10 | 49 | -24 | 409 | 301 | 0.5 |
| 14 | SP12.5-C | PG 58-37P | 14 | | | | | |
| 15 | SP12.5-D | PG 64-34P | 13 | 71 | -24 | 678 | 470 | 0.8 |
| 17 | SP19.0-C | PG58-34 | **7** | 35 | | | | |
| 18 | SP19.0-D | PG64-34P | 15 | 89 | | | | |
| 19 | SP19.0-D | PG 58-34P | 8 | 45 | | | | |
| 20 | SP19.0-C | PG 58-34 | **6** | | | | | |
| 22 | SP19.0-D | PG 64-34P | 9 | | | | | |

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

*Missing Mix ID and blank cell= No test has been completed so far; white cell= gravel aggregates; yellow cell: limestone aggregates; grey cell= granite aggregates*

Bit. B Mix #9 with a PG 58-34P binder met the FI target of 8.0; however, the rut depth to SIP exceeded the 6.0 mm target at high number (>15,000) of wheel passes, indicating moisture-related stripping potential at later ages of pavement life cycle. This mix exhibited a wet ITS of 373 kPa. An anti-striping agent may be added to reduce the rut depth to SIP. Mix # 11 with a PG 58-37P asphalt binder exhibited a higher fracture energy (600 $J/m^2$) than Mix #4 and Mix #13 with PG58-34P asphalt binder, which seems to be very reasonable. Mixes #13 and #15 also met both of the FI and fracture energy targets. However, they did not meet the $CT_{Index}$ target.

The Class C SP19.0 Mix #17 containing 4.08% (PG 58-34) effective asphalt binder exhibited a FI value of 7.0. It undergone 6.66 mm rutting after 20,000 wheel passes in HWTT indicating good resistance to rutting. With a slight increase of the effective asphalt binder content and/or using a PG58-34P asphalt

binder, the FI value is expected to meet the target. Mix #19 met the minimum FI target of 8.0; however, it also experienced greater than 6.0 mm rut depth to SIP (at >15,000 wheel passes) indicating possible stripping issues (the mix had a wet ITS of 361 kPa) at later ages of pavement life cycle. Antistripping agent may be helpful to enhance resistance to moisture related stripping of this mix and extend the life cycle towards sustainability.

The Class C SP19.0 Mix #20 exhibited superior resistance to rutting and stripping with a rut depth of 2.43 mm after 20,000 wheel passes and no SIP; however, it showed a low FI value of 6.0. This mix had an effective asphalt binder content of 4.1%. With an increase of effective asphalt binder content by 0.1 or 0.2% and/or using a PG58-34P asphalt binder, the FI value is expected to easily go up to 8.0 or above.

## Summary of Findings

This study aimed to examine the currently used asphalt mixes for potential field performance in terms of resistance to moisture-related stripping, rutting, fatigue cracking and thermal cracking. Twenty two asphalt mix production samples were collected from Manitoba highway project sites. Tests have been conducted or are in progress using the HWT for resistance to stripping and rutting, I-FIT and IDEAL-CT for resistance to fatigue cracking and SCB for resistance to low temperature (thermal) cracking. Based on the results of completed tests, analysis and discussion as presented in previous sections, the key findings are summarized below:

1. At 45 °C temperature, Manitoba Bit. B mixes with no RAP experienced 3.16 to 6.89 mm rut depths to SIP at 8,796 to 15,852 wheel passes and S/C ratio of >2.0. Only one mix experienced a rut depth to SIP exceeding 6.0 mm at >15,000 wheel passes. These mixes exhibited a minimum of 16,222 wheel passes at 12.5 mm rut depth to 20,000 wheel passes at 8.28 mm rut depth. The FI values ranged from 12 to 16, indicating good resistance to fatigue cracking.
2. Bit. B mixes with 10% to 25% RAP experienced 3.54 to 6.25 mm rut depths to SIP at 4,807 to 10,466 wheel passes at 45 °C temperature, which is substantially less than Bit. B mixes containing no RAP. These RAP AC mixes experienced 12.5 mm rut depth after 13,153 to 18,691 wheel passes. Mixes containing 10% and 20% RAP and PG 58-37P asphalt binder had FI values of 12 and 10, respectively. Mixes containing 15% and 25% RAP and PG 58-34 binder had FI values of 6.0 and 7.0, respectively. This emphasizes the importance of proper characterization of RAPs for their binder contribution (in terms of true grade and percentage) to AC mixes and use of appropriate virgin binder grade and percentage to improve or meet the resistance to stripping and cracking.
3. Class C SP12.5 mixes experienced no SIP or a maximum of 5.31 mm rut depth to SIP after 15,144 wheel passes at 45 °C temperature, and 4.49 mm to 10.59 mm rutting after 20,000 wheel passes. The mix having no SIP at 45 °C, has undergone 6.73 mm deep rutting after 7,944 wheel passes and the rut depth reached to 12.5 mm after 14,447 wheel passes at 50 °C temperature. These mixes, having PG 58-37P asphalt binder, exhibited FI values of 14-15, indicating very good resistance to cracking.
4. Class D SP12.5 mixes experienced no SIP or a maximum of 3.09 mm rut depth to SIP after 16,057 wheel passes at 45 °C temperature, and 2.28 mm to 3.89 mm rutting after 20,000 passes. The mix that exhibited 2.83 mm rut depth after 20,000 passes at 45 °C, undergone a total of 8.58 mm rut depth after 20,000 wheel passes and 5.88 mm rut depth to SIP after 15,567 wheel passes at 50 °C. These indicate that the Class D SuperPave mixes can withstand high temperatures and/or high

traffic loads than Class C, as expected. These mixes, having PG 58-34P and PG 64-34P asphalt binders, exhibited FI values of 10-13 indicating good resistance to cracking.

5. Class C SP19.0 mixes with PG 58-34 asphalt binder experienced no SIP or a maximum of 4.92 mm rut depth to SIP after ≥16,915 passes at 45 °C temperature, and 3.46 mm to 6.66 mm rutting after 20,000 passes. The mix that exhibited 6.66 mm rutting after 20,000 passes and had 4.92 mm rut depth to SIP at 45 °C, experienced 12.5 mm rut depth after 13,804 wheel passes and exhibited 6.77 mm rut depth to SIP after 8,186 wheel passes when tested at 50 °C temperature. These mixes exhibited FI values of 6.0-7.0 indicating poor resistance to cracking. This probably indicates that PG 58-34 asphalt binder is inadequate to provide the required cracking resistance.
6. Class D SP19.0 mixes with PG 64-34P asphalt binder experienced 2.43 to 3.10 mm rutting after 20,000 wheel passes and no SIP at 45 °C indicating superior rutting resistance of these mixes. One of these mixes experienced 5.59 mm rut depth after 20,000 passes and 5.27 mm rut depth to SIP after 15,020 passes when tested at 50 °C. Class D SP19.0 mix with PG 58-34P asphalt binder experienced 6.92 mm rut depth to SIP after 16,734 wheel passes and 7.22 mm rutting after 20,000 wheel passes at 45 °C temperature. These observations further indicate that Class D SuperPave mixes can withstand high temperatures and/or high traffic loads than Class C, as expected. These mixes exhibited FI values of 8.0-15 indicating acceptable to very good resistance to cracking.
7. The tested AC mixes having PG 58-34P, 58-37P and PG 64-34P asphalt binders showed fracture energies of 409 to 678 J/m$^2$ indicating a good resistance to thermal cracking.
8. The variation of $CT_{Index}$ values did not follow the trends of FI and the expectation for the variation of mix type, asphalt binder content and binder grades.
9. Hydrated lime improved the resistance to stripping with significantly smaller rut depth and higher number of wheel passes to SIP and maximum rut depth as compared to liquid anti-stripping agent. However, the AC mix with hydrated lime as an anti-stripping agent exhibited a low FI of 4.0.
10. Aggregate types such as gravel, granite and limestone with similar properties did not show any flaggable impact on the rutting and cracking performance.

## Recommendations

Manitoba has been using Bit. B mixes for decades and the observed fatigue cracking over the design service life has been pretty low. The extensive thermal cracking issues have been and being addressed through the use appropriate asphalt binder grades for each project location. Rutting has been issues for highways with high traffic loads, major intersections/interchanges and urban slow traffic scenarios. These are being addressed through the use of appropriate SuperPave mixes and stiffer asphalt binder. Keeping these experience in mind and based on the results from this study, the following preliminary recommendations are made, which are considered to be achievable with some adjustments and measures, as discussed earlier, to mixes that are not meeting the recommended targets:

1. Bit. B Mix with PG 58-XXP and Lower Grades Binders: ≤6.0 mm rut depth to SIP with ≥8,000 wheel passes, and ≥14,000 wheel passes to ≤12.5 mm rut depth when tested at 45 °C temperature. The minimum target for FI value should be 12.
2. Class C SP12.5 Mix: ≤6.0 mm rut depth to SIP with ≥12,000 wheel passes, and ≥20,000 wheel passes to ≤12.5 mm rut depth at 45 °C. The minimum target for FI value should be 12.

3. Class C SP19.0 Mix: ≤6.0 mm rut depth to SIP with ≥15,000 wheel passes, and ≥20,000 wheel passes to ≤10.0 mm rut depth at 45 °C. The minimum target for FI value should be 10.
4. Class D SP12.5 Mix: ≤6.0 mm rut depth to SIP with ≥15,000 wheel passes, and ≥20,000 wheel passes to ≤10.0 mm rut depth at 50°C. The minimum target for FI value should be 10.
5. Class D SP19.0 Mix: ≤6.0 mm rut depth to SIP with ≥15,000 wheel passes, and ≤20,000 wheel passes ≤10.0 mm rut depth at 50 °C temperature. The minimum target for FI value should be 8.0.
6. Mixes containing RAP should be designed to meet above targets through the use of appropriate virgin asphalt binder percentage and grades.
7. When hydrated lime is used as an anti-stripping agent, binder grade and/or content should be adjusted to attain a minimum FI 8.0.

The above stated recommendations should be confirmed through additional testing and verified through comparison with field performance in terms of observed cracking.

## References


1. Harran, G. and Shalaby, A. “Representative Values for Resilient and Dynamic Moduli of Asphalt Mixtures in Manitoba.” Final Report Prepared for Manitoba Infrastructure and Transportation (MIT), Pavement Research Laboratory, University of Manitoba. (March 2008).
2. Esfandiarpour, S., Shalaby, A., Ahammed, M. A., Liske, T. and Kass, S. “Effects of RAP on the Mechanical Properties of Asphalt Mixes and Binder, and on the Predicted Pavement Performance”. Characterization of Soils and Materials for Mechanistic Empirical Pavement Design Session of the 2014 Conference of the Transportation Association of Canada, Montreal, Quebec. (2014).
3. Esfandiarpour, S., Shalaby, A., Ahammed, M. A., Liske, T. and Kass, S. “An evaluation of pavement ME design dynamic modulus prediction model for asphalt mixes containing RAP.” 2015 Conference of the Transportation Association of Canada, Charlottetown, PEI. (2015).
4. AASHTO 1993. “AASHTO Guide for Design of Pavement Structure.” American Association of State Highway and Transportation Officials. Washington, D.C. (1993).
5. Yin, F., Taylor, A. J., & Tran, Nam. “Performance Testing for Quality Control and Acceptance of Balanced Mix Design.” NCAT Report 20-02. National Center for Asphalt Technology (May 2020).
6. West, R., & Yin, F. “Guidance on Progressing through BMD Approaches.” Balanced Mix Design, Special Report 228. National Asphalt Pavement Association (April 2024).
7. Feener, B., Barnes, C., & Marlin, A. “Determination of Critical Stripping Temperatures for Typical Asphalt Concrete Mixtures Used in Nova Scotia.” Transportation Association of Canada (2021).
8. Iowa Department of Transportation. “Matls IM 319, Moisture Sensitivity Testing of Asphalt Mixtures.” https://www.iowadot.gov/erl/current/IM/content/319.htm. Accessed, April 29, 2026.
9. Maine Department of Transportation (2019). “HMA Hamburg Wheel Tracker Specification”. Special Provision Division 400 Section 401 – Hot Mix Asphalt Pavement.

10. Oklahoma Department of Transportation. “Special Provision for Plant Mix Bituminous Bases and Surfaces (Superpave).” Special Provision: 708-26(a-f) 09. (Accessed April 2026).
11. Texas Department of Transportation. “Superpave Mixtures – Balanced Mix Design.” Special Specification 3024. (2024)
12. Yin. F., and West. R. “Balanced Mix Design Resource Guide.” National Asphalt Pavement Association. Report No. IS-143. (Accessed April 2026).
13. Illinois Department of Transportation. “Standard Specification for Road and Bridge Construction.” (2022).
14. Batioja-Alvarez, D., Lee, J., Rahbar-Rastegar, R., & Haddock, J.E. “Asphalt Mixture Quality Acceptance using the Hamburg Wheel-Tracking Test.” Transportation Research Record. 2674 (8), 338-349. https://doi.org/10.1177/0361198120919749. Accessed April 20, 2026.
15. Al-Qadi, I. L., Ozer, H., Zhu, Z., Singhvi, P., Ali, U. N., Sawalha, M., Luque, A. F. E., Mainieri, J. J. G., & Zehr, T. G. “Development of Long-Term Aging Protocol for Implementation of the Illinois Flexibility Index Test (I-FIT).” Illinois Center for Transportation. Report No. FHWA-ICT-19-009 (August 2019).
16. Newcomb, D., Arabali, P., Al-Khayat, H., & Zhou, F. “Test Methods to Quantify Cracking Resistance of Asphalt Binders and Mixtures.” Texas A&M Transportation Institute. Report No. MN 2021-02 (January 2021).
17. Newcomb, D., & Zhou, F. “Balanced Design of Asphalt Mixtures.” Texas A&M Transportation Institute. Report No. MN/RC 2018-22 (June 2018).
18. Mohammed, L., Akentuna, M., Boateng, K. A., & Pant, S. “Assessment of Long-Term Performance of Louisiana Asphalt Pavements.” Report No. FHWA/LA.25/711. Louisiana Transportation Research Center. Report No. FHWA/LA.25/711 (June 2025).
19. Marasteanu, M., W. Buttlar, H. Bahia, & C. Williams.. “Investigation of Low Temperature Cracking in Asphalt Pavements.” National Pooled Fund Study - Phase II, Report No. MN/RC 2012-23. Minnesota Department of Transportation, St. Paul, MN. (2012).