Development and Field Experience of Performance-Based Low Permeability Asphalt Mixture Used to Overlay Bridge Decks

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ABSTRACT

Asphalt mixtures on bridge decks often do not last as intended. Raveling, delamination, and potholing are more frequently observed on bridge decks as compared to their adjacent asphalt surfaces. The main cause of such differences in performance could be simply due to inability to achieve proper in-place density by being restricted to static only compaction mode and reduced temperature. Compaction temperature is limited to a certain range to avoid melting any underlying waterproofing membranes that could cause so called “slippage planes.” Compaction mode and temperature restrictions could further complicate the projects when the distance between the job site and production plant is far away.

This paper provides information on the development of a performance-based low permeability overlay mix to protect bridge decks against the penetration of water and de-icing chemicals. This paper also provides steps employed to develop a performance-based requirement focused on permeability and long-term fatigue behaviour under extreme repetitive stresses that would be expected from heavily loaded traffic coupled with extreme temperatures. Production and paving experience with the low permeability mix is also included, as well as more field performance of a trial section in Southern Ontario.

RÉSUMÉ

Les mélanges d’asphalte sur les tabliers de pont ne durent souvent pas comme prévu. On observe plus fréquemment de l’effilochage, du délaminage et des nids de poule sur les tabliers de ponts comparés aux surfaces en asphalte adjacentes. La cause principale de telles différences de performances pourrait être simplement due à l’incapacité d’atteindre une densité en place appropriée, car elle est limitée au mode de compactage uniquement statique et à une température réduite. La température de compactage est limitée à une certaine plage pour éviter de faire fondre les membranes d'étanchéité sous-jacentes susceptibles de provoquer des "plans de glissement". Le mode de compactage et les restrictions de température pourraient compliquer davantage les projets lorsque la distance entre le site de travail et l'usine de production est très éloignée.

Ce document fournit des informations sur le développement d'un mélange de revêtement à faible perméabilité basé sur les performances, destiné à protéger les tabliers de pont contre la pénétration d'eau et de produits chimiques de dégivrage. Ce document fournit également les étapes utilisées pour développer une exigence basée sur les performances, axée sur la perméabilité et le comportement à la fatigue à long terme sous des contraintes répétitives extrêmes attendues d'un trafic très chargé couplé à des températures extrêmes. Les expériences de production et de pavage avec le mélange à faible perméabilité sont également incluses, ainsi que les performances sur le terrain d'une section d'essai dans le sud de l'Ontario.

1.0 INTRODUCTION

Bridge deck deterioration is one of the major problems affecting the longevity of bridges. Although a number of factors could contribute to bridge deck distresses, moisture and chloride intrusion certainly accelerate the deterioration. In Canada, the practice of bridge design and protection against reinforcement corrosion has evolved over the last 50 years to address the ingress of moisture and ensure a minimum level of protection against corrosion by including a waterproofing system. This system may vary in complexity depending on the provincial specification, but generally includes a thin impermeable membrane placed between the bridge deck and a protective riding surface. Other components such as primer and tack coat are required to promote bonding of membrane to bridge deck and riding surface, respectively. All these components together create a robust waterproofing system whose integrity depends on adequate performance of each component.

In Canada, asphalt mixtures have been predominantly used as the protective riding surface over the waterproofing membrane. But it is observed that asphalt overlays on bridge decks often do not last as intended. Raveling, delamination, and potholing are more frequently observed on bridge decks as compared to their adjacent asphalt surfaces. Factors such as lack of bonding due to improper application of tack coat or overall strength of the mix could be contributing factors. However, the main cause of such difference in performance could be simply due to the inability to achieve proper in-place density by being restricted to the use of static compaction and reduced temperatures. Compaction temperature is limited to avoid melting any underlying waterproofing membranes that could cause so called "slippage planes." Compaction mode and temperature restrictions could further complicate the projects when the distance between the job site and production plant is great. This could cause the mix to not achieve proper in-place density, which could lead to a permeable mix with less effective waterproofing characteristics.

The waterproofing characteristic of an asphalt mix is related to permeability, which is significantly controlled by the aggregate size, shape and gradation, but most significantly air voids in the mix and lift thickness [1]. The lower the air voids, the lower the permeability of the mix. The effect of lift thickness on permeability is also important, as it could affect in-place voids and interconnectivity of the voids. In contrast, higher in-place air voids could allow water and air penetrate the mix leading to increased potential for moisture damage and oxidative hardening. Moisture damage occurs when the asphalt binder is stripped from the aggregate; resulting in raveling, delamination and potholes. Oxidative hardening occurs when the asphalt binder coated the aggregate particles becomes excessively brittle after being exposed to air.

The objective of this research work was to develop a mix that can be easily compacted to low in-place air voids under compaction method and temperature restrictions. This paper provides information on the development of such an overlay mix and provides further steps in developing performance-based requirements focused on permeability and long-term fatigue behaviour. Production and paving experience with the low permeability mix is also included in this paper, as well as more field performance of a trial section in Southern Ontario.

2.0 MIXTURE DEVELOPMENT

2.1 Overview

As previously mentioned, the waterproofing characteristic of an asphalt mix is related to permeability. Lowering the air voids reduces both interconnected and isolated voids, and further reduces water flow through the mix. This could translate into hydraulic conductivity of less that $1x10^{-7}$ cm per seconds, which classifies the mix as a low to very low permeability type of material based on permeability ranges provided in Table 1.

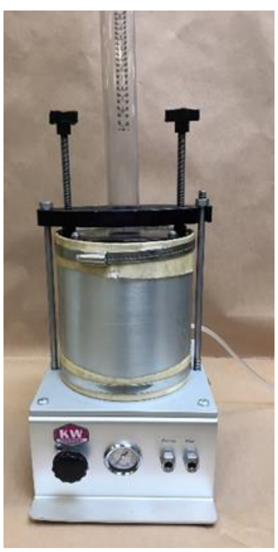
A study completed by the National Center for Asphalt Technology (NCAT) in 2003 [2] confirmed the critical impact of in-place air voids on mixture permeability. This study further showed that permeability can be decreased at a given void level by using finer-graded mixtures. For instance, at 6 percent in-place air voids, a mix with 12.5 mm Nominal Maximum Aggregate Size (NMAS) was observed to be nearly 7 times more permeable than a 9.5 mm NMAS mix.

Table 1. Category of Asphalt Mixtures Based on Permeability [3]

Permeability (µm/s)	Description
0.01 – 0.1	Very low permeability
0.1 – 1	Low permeability
1 – 10	Moderate permeability: some water infiltrating under traffic
10 – 100	Permeable: substantial water entering under traffic
100 – 1000	Moderately free-draining: permeates freely under traffic or raindrop impact. Pumping of fines
1000 – 10,000	Free draining

To develop a Low Permeability (LP) mix, three aggregate sources were used to prepare a design blend: (1) 9.5 mm crushed stone, and (2) washed screenings, and (3) unwashed screenings. A modified Asphalt Cement (AC) suitable for the climate and traffic conditions in Southern Ontario was used in combination with a special additive. The design trials were prepared using 50 Marshall blows (approximatively equivalent to 50 Superpave gyrations) at varying asphalt contents. It should be mentioned that the design compactive effort was dropped to 50 blows to create a mix that is easier to compact. Furthermore, aggregate gradation control points recommended by the Ministry of Transportation Ontario's [4] were used to develop initial aggregate blends. For this process, three design blends were prepared and tested at three AC contents varying from 5.5 to 7.5 percent in 1.0 increments. This was to find the optimum design blend with the highest Marshall Stability at 60°C. Then, the optimum blend was selected to further optimize the air voids to achieve lowest permeability.

Permeability was assessed with a falling head permeameter shown in Figure 1. This apparatus measures one-dimensional coefficient of permeability, similar to the ASTM D5084 [5] test method by using a procedure outlined by the Florida Department of Transportation [6]. To test the permeability, a compacted specimen was placed inside a metal cylinder, where it was held in place by a latex membrane. The cylinder was then pressurized to 68.9 kPa (10 psi) to expand the latex membrane against the outer edge of the specimen, filling in voids and preventing the flow of water down the side of the specimen. Then a certain amount of water was allowed to flow through the specimen while being timed for permeability. Then the coefficient of permeability was calculated by using Equation 1. Figure 1 shows the permeability results versus air voids which was compared to the categories of permeability listed in Table 1. Based on these results, it was decided to proceed with the targeted design of 1.50 percent air voids.



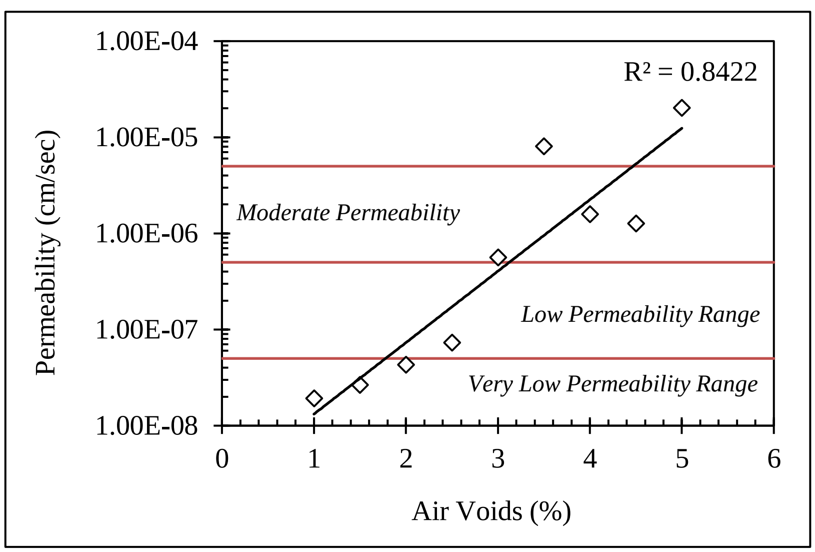


Figure 1. Karol-Warner Asphalt Permeameter (Left) and Laboratory Permeability versus Air Voids Measured For Low Permeability Asphalt Mixture (Right).

$$k = \frac{aL}{At}\ln(\frac{h_1}{h_2})t_c \qquad (1)$$

Where: k is coefficient of permeability in cm/sec;
a is inside cross-sectional area of the burette in cm^2;
L is average thickness of the test specimen in cm;
A is average cross-sectional area of the test specimen in cm^2;
t is elapsed time between h_1 and h_2;
h_1 and h_2 are initial and final head across the test specimen in cm, respectively; and
t_c is temperature correction for viscosity of water if different than standard temperature of 20°C

After optimization of the design trial based on Marshall volumetric properties and permeability, the selected design trial was further assessed for rutting and overall flexibility. During this phase, fine adjustments to the binder's Useful Temperature Interval (UTI) were applied. But for the purpose of this paper, only one trial is presented which was compared with a typical SP 12.5 FC2 mixture used in Ontario as a heavy-duty surface mixture for major arterials and highways as shown in Table 2.

Table 2. Selected Physical Properties of Control Superpave 12.5 FC2 and Low Permeability Asphalt Mix

Property	**Sieve Size (mm)**	**SP 12.5 FC2 Control Mix**	**Low Permeability Mix**
Gradation (% Passing)	12.5	98.2	100
	9.5	83.4	96.0
	4.75	56.2	84.0
	2.36	48.0	55.0
	0.075	5.80	7.0
Air Voids (%) at N_{design}		4.00	1.50
Voids in Mineral Aggregate, VMA (% Minimum)		14.1	18.9
Asphalt Cement Content (%)		4.90	7.0
Asphalt Binder Performance Grade		70-28J	LP PMA
Asphalt Binder Physical Properties			
Non-recoverable Creep Compliance at 3.2 kPa, J_{nr} (1/kPa)		0.103	0.04
Percent Recovery at 3.2 kPa, R (%)		89.62	94.82
Multiple Stress Creep Recovery Test Temperature (°C)		58	58

2.2 Permanent Deformation

Rutting was a concern when the design compaction was decreased to 50 Marshall blows in conjunction with an increase asphalt binder content. The resistance to rutting and moisture damage was evaluated by using a Hamburg Wheel Tracking Device (HWTD) in accordance with AASHTO T324-04 [7]. For this test, a hard-rubber wheel was tracked across the surface of gyratory compacted specimens submerged in a hot water bath at 50°C for 20,000-wheel passes. During the test, the deformation of specimens under the wheel path was recorded as a function of the number of passes by using Linear Variable Differential Transducers (LVDTs). Table 3 provides average rut results for low permeability mix and the typical SP 12.5 mm mix considered as the control. It was observed that, in general, increased asphalt binder and using a finer gradation for the low permeability mix did not increase rutting susceptibility significantly. In fact, the low permeability mix exhibited very good rutting resistance as compared to the upper limit of 12 mm as per MTO's criterion for surface rut depth.

Table 3. Rutting Depth Results for SP 12.5 mm Control Mix and Low Permeability Mix

Mixture Type	Average Rut Depth (mm)	Standard Deviation (mm)
SP 12.5 mm (Control Mix)	4.92	0.46
Low Permeability Mix	8.21	0.37

2.3 Fatigue Cracking Evaluation

The fatigue cracking properties of the mixtures were evaluated using two test procedures: (1) Semi-Circular Bend (SCB) Flexibility Index (AASHTO TP124), and (2) Flexural Beam Fatigue (AASHTO T321). Fatigue cracking tests were conducted on long-term conditioned asphalt mixtures. The long-term conditioning was completed after conditioning loose mixtures for 24 hours at 135°C to simulate the late life (greater than 10 years) aged condition of the asphalt mixture. Figure 2 displays the laboratory apparatus for the SCB tests and four-point bending beam.

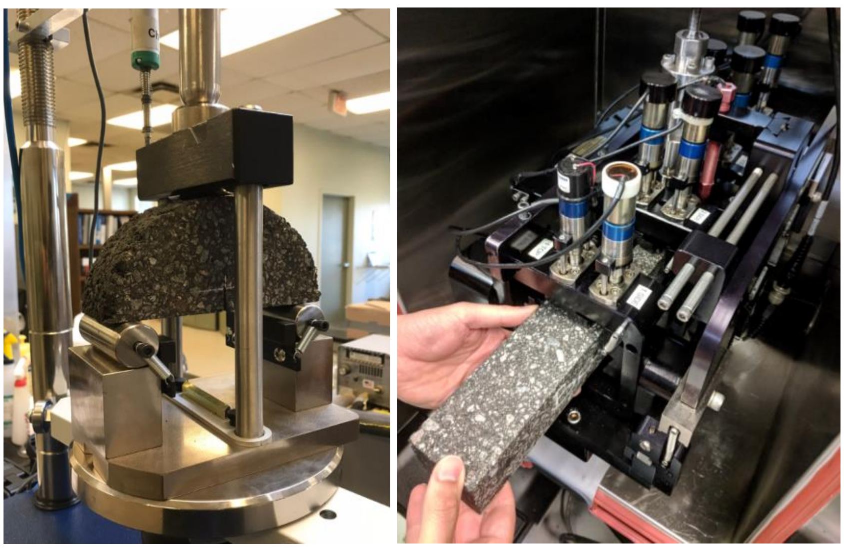


Figure 2. Semi-Circular Bend Test Setup (left) and Four-Point Flexural Beam Fatigue Test (right)

2.3.1 Semi-Circular Bend (SCB) Test

The Illinois SCB test was used to determine Illinois Flexibility Index (I-FI) in accordance with AASHTO TP 124, "Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature" [8]. For this test, specimens were cut from the middle of a gyratory sample to a thickness of 50 mm. Strength and displacement were recorded during a 50 mm/min deformation rate. Testing was performed at 25°C and each SCB sample also has 15.0 mm notch depth to initiate the location of the crack. The FI was then calculated by dividing the fracture energy by the slope of the post-peak load-displacement curve at the inflection point shown in Figure 3 by using Equation 2. In general, as the SCB FI value increases, the asphalt mixture's fatigue cracking resistance increases.

The SCB FI fatigue cracking test results are shown in Figure 4, while the error bars represent one standard deviation from the average value of four replicates tested. The test results show that at the low permeability asphalt mixture had almost seven times more flexibility than a conventional SP 12.5 mm mixture. Fracture energy also indicated that the low permeability asphalt mixture exhibited almost twice the resistance to fracture compared to the conventional SP 12.5 mm mixture.

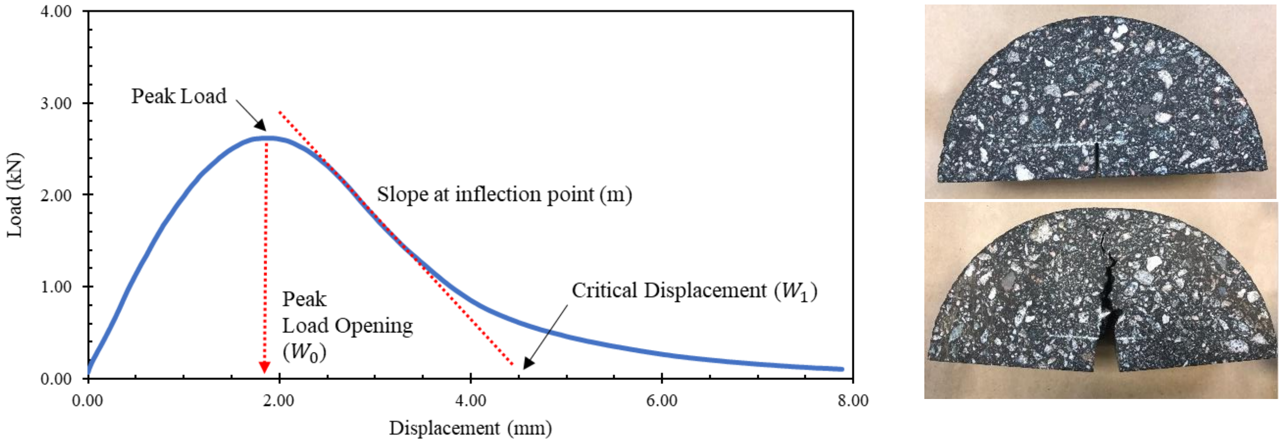


Figure 3. Typical graph used after Illinois Semi-Circular Bend (SCB) test to calculate Flexibility Index (FI) and a specimen of Low Permeability Mix before and after SCB test.

$$\text{Flexibility Index (FI)} = A \times G_F \times \frac{1}{|m|} \tag{2}$$

Where: A is ligament area in cm^2;
G_F is fracture energy which is the work of fracture; and
m is the slope of the post-peak load-displacement curve at the inflection point

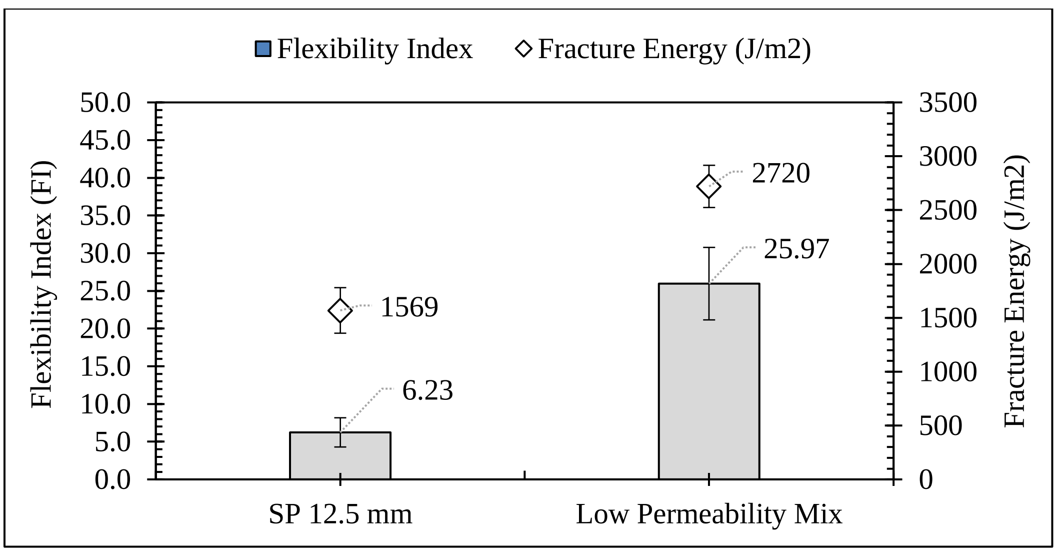


Figure 4. Semi-Circular Bend (SCB) test results for SP 12.5 mm Control Mix and Low Permeability Mix.

2.3.2 Flexural Beam Fatigue Beam Test

The flexural beam fatigue test was performed in accordance with AASHTO T 321-07 [9]. For this test, beams measuring 380 mm long by 63 mm wide by 50 mm thick were saw-cut from asphalt slabs and compacted using an Asphalt Vibratory Compactor (AVC). The testing procedure involved subjecting an asphalt beam to flexural loading applied in a sinusoidal waveform with loading frequency of 10 Hz at a micro-strain level. Fatigue failure was then defined as the number of load cycles until initial stiffness is reduced by 50 percent. The applied strain levels were 650, 750, and 850 micro-strains. Samples were tested after being subjected to long-term aging. Testing was conducted at 21°C.

The flexural beam fatigue results are shown in Figure 5. At a micro-strain level of 750, the LP mix endured 1.8 million cycles to failure, which was five times more than the heavy-duty SP 12.5 mm mixture used for major arterials and highways in Ontario.

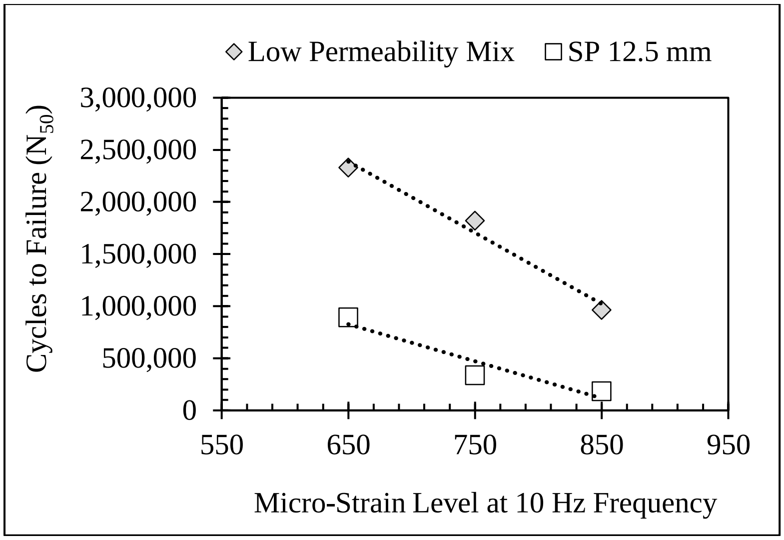


Figure 5. Fatigue Results for SP 12.5 mm Control Mix and Low Permeability Mix.

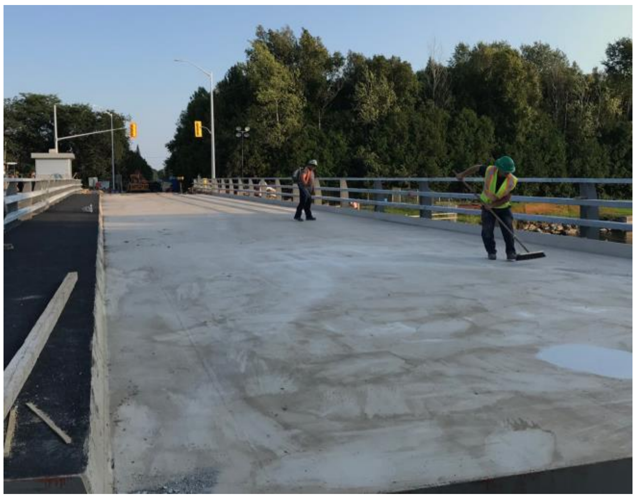
3.0 PLANT PRODUCTION AND PAVING EXPERIENCE

A field trial was conducted in August 2018. The job site was in the vicinity of the Prince Edward County in Southern Ontario. The LP mix was used to surface the entire deck of a new orthotropic bridge shown in Figure 6.

Figure 6. An Orthotropic Steel Swing Bridge located in Southern Ontario prior to placement of Low Permeability Surface Mix (August 2018).

This new bridge replaced a 1947 era steel truss bridge which had restrictions for emergency and service vehicles only. The new bridge replacement was an upgrade to a two-lane structure with pedestrian walkaway. The new bridge has a full highway load rating with no loading restrictions.

The bridge was fabricated off-site and assembled at the site. Prior to paving, the deck was treated with two layers of waterproofing system, which consisted of a primer and spray-applied membrane. The primer was a two-component acrylic metal primer was used to promote a cohesive bond between the steel deck and the spray-applied acrylic resin membrane as shown in Figure 7(a). Then, a rubberized tack coat was used to promote the bonding between the low permeability asphalt mix and the membrane system as shown in Figure 7(b).



(a) Steel deck after being treated by an acrylic metal primer followed by an application of sprayed-applied acrylic resin membrane.

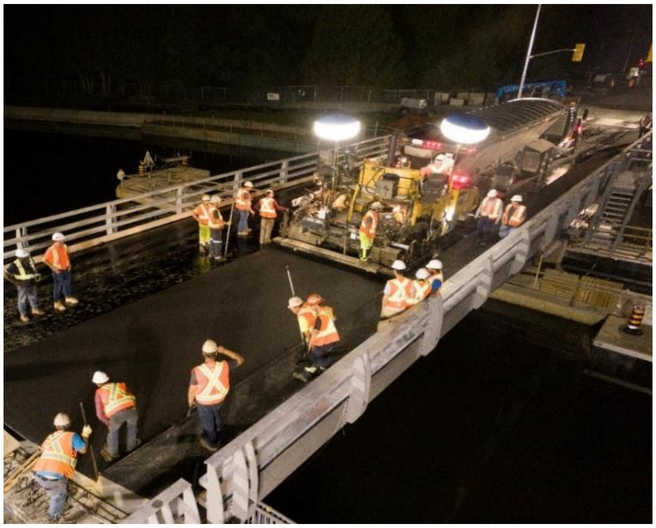
(b) Hand application of rubberized tack coat by using an oil-jacketed melter

Figure 7. Membrane and Tack Coat Application Prior to Placement of Low Permeability Mix

The mix was produced at a conventional HMA batch plant which was located 120 kilometres from the job site. The mix was produced at 150°C without any issues pumping the binder through the plant, nor any issues mixing the binder with aggregate blend to achieve proper coating. The LP mix was delivered to the job site with conventional haulage equipment and placed with conventional paving equipment shown in Figure 8(a). A Material Transfer Vehicle (MTV) was not used in this trial. An infrared imaging station was used to monitor thermal variation and overall uniformity of mat temperature behind the paver as shown in Figure 9, which indicated no signs of segregation.

Laydown temperature was observed between 145 to 135˚C throughout the job. No visible fumes were observed during the placement, as shown in Figure 8. The paving crew did not have any problem in terms workability and placement; especially for hard-to-reach areas for the compactor that required hand-roll compaction as shown in Figure 8(c) and (d). Targeted density was achieved after only three passes of 12-ton steel roller in static mode. The low permeability characteristics of the mix caused the release agent liquid used for compaction to stay on the surface as shown in Figure 8(b) and (e).

Permeability test was performed in the field by following the method prescribed by NCAT [10]. For this test, a falling-head type of permeameter consisting of four tiers was used to measure the time it takes for the water permeate the surface. Results of this test indicated average permeability of much less than 1x10-8 cm per second for different locations on the deck, as well as the longitudinal joint between the two lanes.



(a) Paving a low permeability asphalt mixture on an orthotopic steel bridge deck by using conventional paving equipment

(b) Achieving targeted density after only three passes of 12-ton steel roller in static mode. The low permeability characteristics of the mix caused the release agent liquid used for compaction to stay on the surface

(c) No issues with using hand-roller to compact around the hard-to-reach areas

(d) Ease of handwork with sign of mix segregation

(e) Final texture of low permeability mix

Figure 8. Placement of Low Permeability (LP) Mix on and Orthotropic Steel Bridge, August 2018

Figure 9. Infrared camera image showing consistent mat temperature behind the paver prior to compaction.

4.0 FIELD PERFORMANCE

A number of field follow-ups were conducted since placement, but in this paper provides only observations from the latest manual distress survey conducted on June 6, 2019. The weather during the survey was a mix of sun and cloud, air temperature of 15°C, and light wind (>20 km/hr). During this survey, the LP mix exhibited excellent performance in waterproofing the deck as shown in Figures 10 and 11. No signs of cracking or distresses were observed.

Figure 10. A Steel Swing-Bridge located in Southern Ontario after placement of Low Permeability Surface Mix (June 2018)

Figure 11. A Steel Swing-Bridge located in Southern Ontario after placement of Low Permeability Surface Mix (June 2018)

5.0 SUMMARY AND CONCLUSIONS

In summary, the main goal of designing a high-performance premium bridge deck overlay was to minimize permeability while keeping the stiffness in balance with volumetric properties in such a way that the mix is stiff enough at higher service temperatures to resist rutting, and yet has enough flexibility at intermediate and colder temperatures to resist fatigue and thermal cracking.

The research work presented in this paper demonstrated development process of a mix that can be easily compacted to low in-place air voids under static compaction effort and temperature restrictions related to bridge-deck paving. This paper further provided steps employed to develop a performance-based requirement focused on permeability and long-term fatigue behaviour.

This balanced method of design is not limited to low permeability asphalt mixtures and can be used for any other type of mixture such as those designed for airport and highway applications. This concept is not limited to design stage only, it also provides insight into relative long-term performance that could be used in developing deterioration models. Such models can be used to better manage maintenance and rehabilitation activities.

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