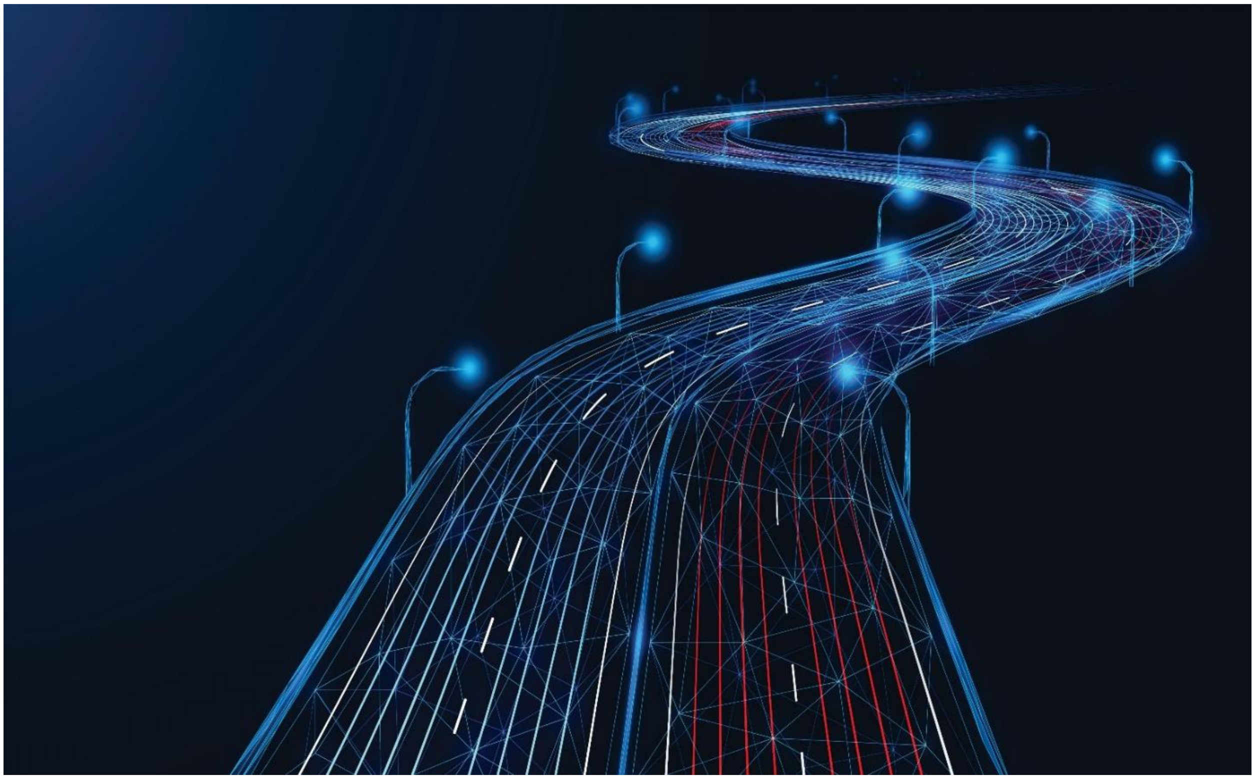

International Experiences with High RAP Content Mixtures

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Introduction

As producing more sustainable pavements becomes a necessity, the use of recycled materials must gain traction in Ontario again. Efforts must be taken by all industry partners to ensure the successful use of recycled materials such as reclaimed asphalt pavements (RAP). Hot Mix Asphalt including more than 25% RAP are typically considered as high RAP mixtures. In many states, performance testing requirements are included for such specialty mixtures with these amounts of recycled material [1]. The stage where these tests are implemented in the construction process varies by state. For example, some states only require performance tests in mix design submittals while others verify the field produced material through construction of a test strip and subsequent monitoring of mixture performance during production. To this end, it is crucial to be cognizant of the dominant distress mode in the jurisdiction of interest and hence include proper sets of performance testing in the process. International experiences with high RAP mixtures also exhibit some use of performance testing. Many of the jurisdictions which will be discussed in this report also make use of different RAP management and characterization practices. Increasing RAP usage and developing mixtures that perform well for Ontario's climate and traffic needs will require changes to the current design process, specifications, and handling of RAP at the production level. To progress, Ontario must reconsider its approach in each of these areas. This report will outline examples from many different international experiences ranging from similar climate and traffic to vastly different conditions. The goal of this report is to present the commonalities in their approaches and suggest a route forward for Ontario to achieve similar outcomes.

Effect of RAP on Mix Properties and Performance

To understand the role RAP plays in impacting pavement performance, we must first consider the general behaviour of asphalt mixtures. Asphalt cement and mixtures are viscoelastic materials in nature. This means that under certain temperatures and loading conditions the material will exhibit either a viscous-dominated or elastic-dominated behaviour. Therefore, balancing these contradicting properties is necessary for ensuring good pavement performance throughout the entire service life. Rutting resistance mainly comes from the resistance to flow and plastic deformation at higher temperatures and heavier loading conditions. On the other hand, cracking resistance can be influenced and altered in several ways. Among the several possible approaches, increasing the stiffness of the pavement and improving the material response to loading at different temperature ranges (elastic versus viscous) can be named as two common approaches. There is sometime a misconception that higher stiffness means more brittle, which results in overlooking valuable opportunities to improve the durability of our pavements. If properly designed, increasing the stiffness of a pavement structure can potentially reduce fatigue cracking through reducing the critical tensile strain in asphalt concrete layers, however, introducing a stiff material with a brittle behaviour can cause an issue. Asphalt concrete mixtures with higher stiffness and yet maintaining the required resilience under loading can be effectively designed nowadays.

Binder related mix properties can be used to control how the material responds to loading. Increasing the asphalt cement content or using a softer binder both promote a more “viscous-like” behaviour that can help with low temperature properties while SBS polymer modification adds a “rubbery” behaviour which can make the pavement more strain tolerant. Looking at the way a material functions in the pavement structure, it can be realized that a material that is too soft may experience larger strains and become more prone to fatigue cracking. Figure 1 we can visualize all these different behaviours in a simplified manner. In other words, on the plus side a stiffer material can resist deflection and reduce the level of maximum strain that the material experiences in the pavement where an equivalent softer material will have the opposite behaviour. This larger strain level can accelerate cracking and premature failure of the material.

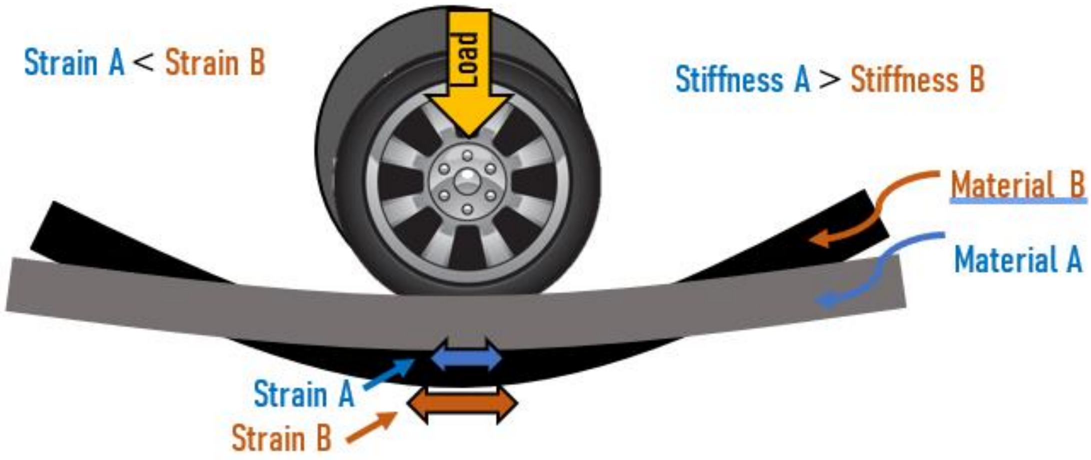

Figure 1. Diagram of load imparted by vehicle during regular pavement use

This brings us back to RAP. Properties of RAP will vary depending on the source and age of the material, but one major characteristic is hardening due to oxidation. Pavement materials will oxidize at different rates. The nominal maximum aggregate size, binder source, presence of additives and permeability introduced by construction issues can impact the rate of oxidation. RAP is a hardened material and introducing this into new mixtures must be accommodated properly to ensure performance is maintained. Generally, introducing RAP will relatively increase the stiffness of the mix, which, when designed for can improve the pavement performance. One of the biggest issues is ensuring that the mix does not react poorly under repeated traffic loading. Increasing stiffness alone without considering the impact on the material response to loading can prove to be detrimental to performance. Different mixture variables can be adjusted to account for RAP. Different techniques have been successfully employed by the paving industry across the world to account for this aspect proportional to the amount of RAP used in new mix production. Examples include, but are not limited to, base binder grade adjustment, use of rejuvenators, increasing the total binder content while still saving on virgin asphalt usage, and utilizing different types of polymers and additives.

Adjusting mix properties to accommodate RAP in higher concentrations have been evaluated by many researchers internationally. Zaumanis et al. [2] analyzed 200 different studies to determine which factors are most likely to impact the performance of mixtures. This analysis formed the basis of their research for creating a 100% RAP surface course (to be discussed in the section regarding Research Performed at Swiss Federal Laboratories for Materials Science and Technology). All the variables identified in Table 1 can be evaluated when developing high RAP mixtures. They determined gradation and binder content as the two more prominent mixture variables for controlling performance. The numbers in parentheses indicate the approximate degree to which the parameter impacts performance (1 meaning smaller impact, while 2 meaning larger impact).

The review illustrates how increasing the stiffness of pavement materials can generally lead to improved rutting and cracking resistance. The only parameter identified as largely detrimental to performance is high air voids. The performance of higher RAP content mixtures depends on other parameters such as binder content and gradation. The addition of RAP should not be feared in the context of performance. These observations may differ slightly with Ontario mixtures because of the relatively low asphalt cement contents used, but the principles can still be applied to properly engineered mixtures.

Table 1. Analysis of primary factors impacting asphalt mixture performance [2]

Parameter	**Rutting Resistance**	**Stiffness**	**Load-related Cracking Resistance**
Higher Binder Content	Usually Decreases (2)[a]	Dependent on Other Parameters (2)[b]	Usually Increases (2)
Harder Binder	Usually Increases (1)	Usually Increases (2)	Strain Mode: May Decrease (2) Stress Mode: Usually Increases (2)[c,d]
Higher Filler Content	Dependent on Other Parameters (1)	May Increase (1)	Dependent on Other Parameters (1)
Coarser Gradation	Dependent on Other Parameters (1)	May Decrease (1)	May Decrease (2)
High Air Voids	Usually Decreases (2)	Usually Decreases (2)	Usually Decrease (2)
Higher RAP Content (No treatment)	Usually Increases (2)	May Increase (2)	Dependent on Other Parameters (2)
Poor Blending between RAP and Virgin Binder	Usually Decreases (2)	May Increase (1)	May Increase (1)

Notes:

a. Resistance to studded tire wear may increase
b. Increase to specific binder content then decrease follows
c. Mode of stress application impacts observations
d. Top-down cracking resistance usually decreases with stiffer binder

Japanese High RAP Mixtures (NAPA IS139)

In Japan, on average, 47% RAP is used in asphalt pavements [3]. The Japanese attribute their successful use of high levels of RAP in HMA to three key points:

1. A focus on quality (reducing variability), including processing RAP (i.e., fractionating) and covering stockpiles.
2. Heating the RAP to drive out moisture and soften the RAP binder.
3. Using a softening agent (and other mixing best practices) to achieve desired mix characteristics.

Japanese mix producers take great care in minimizing moisture in the raw materials by utilizing as little water as possible in crushing operations and keeping the stockpiles and bins covered. Most Japanese plants use a separate drum for drying and heating RAP, the so-called parallel heating method. Afterburner technology is used to eliminate hydrocarbon odor. The hot gases are ducted to the virgin aggregate dryer to recover some of the heat energy. The use of rejuvenators (also referred to as softening agents) is common for high RAP content mixtures in Japan. The rejuvenators are used to restore some physical characteristics of the RAP binder. Rejuvenators are mixed directly with the heated RAP in a small pugmill. The merit of this approach is that it allows the rejuvenator to quickly diffuse into the
softened aged RAP binder [].

Collection and Processing of RAP

RAP is processed from multiple sources. No restrictions are made as to the origin of the RAP. RAP processing operations generally include multiple stages of crushing and screening. RAP is typically fractionated into two sizes: −13 to 5 mm, and −5 mm. RAP stockpiles were maintained in large, covered bins. Fractionation of RAP is a contractor’s choice, not a requirement. Most contractors choose to fractionate the RAP. Some best practices for RAP management followed by contractors:

1. Stockpiles are covered and on a paved surface
2. Moisture and dust contents of the RAP are minimized during crushing, processing, and storage
3. RAP binders are recovered and tested to evaluate their stiffness
4. RAP is fractionated, and the plants are equipped with multiple RAP feed bins

RAP Testing and Specifications

RAP quality is judged by three criteria:

1. It must have a minimum asphalt content of 3.8%.
2. The recovered RAP binder must have a penetration greater than 20 or samples of the compacted RAP must have an IDT coefficient of less than 1.70 MPa/mm.
3. The processed RAP material may not contain more than 5% P200 fines.

Although the amount of RAP that fails to meet these requirements is typically very low, failing material may still be recycled for other purposes, such as in unbound base layers. Recently, an alternative to the minimum penetration grade of the RAP binder was developed to address concerns about an increasing quantity of RAP binders failing to meet the specification limit due to the increased use of polymer-modified asphalt, as well as repeated recycling of pavements. Much of the asphalt pavement being recycled now in Japan contains polymer-modified asphalts [4]. In lieu of the penetration test on recovered RAP asphalt, specimens of 100% RAP are compacted and tested using an indirect tensile strength test at 20°C. From this test, an indirect tensile coefficient (Referred to as the "IDT modulus" in Japan) is determined. If the IDT coefficient of the compacted RAP samples exceeds 1.70 MPa/mm, it may not be used in new asphalt mixtures [5].

Mix Design and Production

Mix designs use the Marshall Method and criteria with a simple supplemental performance test, the indirect tensile coefficient which limits mixtures with very high stiffness (and low cracking resistance). Asphalt binders are penetration graded with additional requirements on softening point, ductility, flash point, mass loss and penetration ratio after the thin film oven test. The most common grades used for virgin asphalt are 40/60 and 60/80 pen grades. Polymer-modified asphalt binders are typically used in porous friction course mixtures and dense-graded mixtures used on trunk roads and often on other heavy traffic roadways. Crude oil imported primarily from the Middle East is refined in Japan and is the primary source for asphalt binders. Blending charts are used to determine the appropriate blending ratio of virgin to recycled binders. In Japan, the blending charts are based on penetration grade values. These charts follow the same concept as the PG blending charts and viscosity-based blending charts used in North

America. Japanese production processes also have some major differences compared to typical North American practices. The major differences are listed below:

1) Stockpile moisture content of the RAP and virgin aggregates is minimized
2) Use of batch plants instead of continuous mix plants
3) Use of a separate drum for drying and heating RAP (parallel heating method)
4) Use of the afterburner technology to burn off any hydrocarbons in RAP dryer exhaust
5) Rejuvenators mixed directly with heated RAP in a small pugmill

Paving Operations

Unique aspects of the paving operation include:

- a slow speed of paving
- no signs of segregation
- vertical longitudinal joint construction
- slow compaction process

One of the most unique aspects of the paving operation was how the contractor built the longitudinal joints. The longitudinal joints are vertical butt-joints. Edges of the first lane are essentially “formed” using wooden boards (similar in size to 2×4 lumber) held in place below the stringline with heavy weights. This results in a vertical face against which the second lane is butted against. Prior to placing the second lane, a light tack coat is manually applied to the vertical edge of the first lane. To avoid destruction of the vertical edge by haul trucks traversing across the lanes, a few lumber forms were moved along ahead of the paver to protect the joint.

Swedish High RAP Mixtures

The general requirements of manufacturing hot recycled asphalt in Sweden are similar to the quality control process for new asphalt mixtures. As for an introduction, Swedish road authorities are mainly following the Marshall mix design and are using a Penetration grading system for Asphalt Cement quality control and grading procedures.

Using modified central plants is a common practice in Sweden to reuse and recycle asphalt pavements, and using these plants, 10 to 50 percent RAP has been successfully incorporated into asphalt mixtures. However, other factors are determining the proper amount of RAP allowed in the mix besides central plant mixing capabilities and technical procedures. As expected, traffic volume and the quality of existing RAP are the most important. By adjusting the heating temperature for virgin aggregates, the plants could mix up to 40 percent RAP in a modified drum mix plant [6].

One primary precaution that has been performed in reported case studies by the Swedish Transport Administration to control the variability in the properties of the RAP was to use RAP collected from one specific project. This has mainly been performed to avoid the inherent variability of using large stockpiles that usually combine RAP from various locations.

The Swedish approach to characterizing the available RAP material combines three aspects of RAP.

- Wet sieving to obtain the particle size distribution
- Asphalt cement content and characterization,
- Petrographic analysis of aggregates (between 8 and 16 mm)

The recovered asphalt cement from the target RAP material is then tested for penetration, softening point, ductility, and Fraass breaking point (representative of the flexibility of the asphalt cement at low temperatures). However, the decision-making on the appropriate recycling tactic mainly relies on the results of penetration and softening point as a representative of the aging degree of existing asphalt cement in the RAP material. As a rule, having lower penetration and higher softening point (stiffer RAC) would result in incorporating lower RAP and/or using softer virgin asphalt to compensate for stiffer RAP binder.

The short-term aging throughout the asphalt mix production, transportation, and the paving process is controlled by the Swedish Transport Administration by limiting the increase in softening point of RAC from the final product (compared to the tank sample) to a maximum 8°C.

In addition to conventional Marshall mix design criteria, high RAP-containing mixtures must satisfy a few performance-based testing. These tests are stiffness modulus measurement (as per EN12697-26 on Marshall compacted samples), dynamic creep test (according to EN12697-25 on gyratory compacted samples), and indirect tensile strength (as per EN12697-23 on Marshall compacted samples). For heavy-duty roads designed to carry high traffic volume, the Swedish transport administration recommends a stiffness modulus of a minimum of 5,500 MPa at 10°C. Implementing this criterion on stiffness modulus of asphalt mix will harness the consistency of virgin binder, meaning one cannot use an excessively soft binder to compensate for the use of excessively aged RAP material at high concentration (to satisfy the requirement on softening point increase on final product) unless one makes sure that the asphalt in RAP material has properly interacted with virgin asphalt throughout the production process.

The Swedish transport administration tested the application of a medium to high percentage of RAP in the mixtures on various pavements with various environmental and traffic loading conditions, followed by a 10-year follow-up study and field investigation [7].

In a case study on Road 40, Delen Rya-Grandalen, the upper binder layer of the existing pavement (aged between 10 to 20 years) was excavated and used as RAP to pave the same road. Recovered asphalt cement showed a low penetration of 32 dmm and a considerably high softening point of 59°C. However, results of ductility and Fraass breaking point showed the asphalt cement still shows elastic and flexible properties. Using the Marshall method, mix designs for 0, 20, and 40 percent RAP material with two different grades of virgin asphalt cement (B85 with a penetration of 85 dmm and B180 with a penetration of 180 dmm) were utilized. Regarding the softening point criteria on the RAC from the final product, except for one sample (40% RAP with B180), the increase in softening point was within tolerable limits.

Performing stiffness modulus tests didn't show any significant change due to incorporating RAP in the mix, although a denser mix structure was observed for mixtures with RAP (in terms of voids filled with asphalt and air voids). Interestingly, mixtures with RAP exhibited higher durability (lower water susceptibilities) in the indirect tensile ratio, which was attributed to better asphalt cement coverage of aggregates. RAP-containing mixtures also performed better in the dynamic creep test as a measure of the rutting resistance of mixtures.

In another case, the same RAP contents were incorporated into mixtures in Road 42 – Fristad. In this case, RAP from intermediate storage was used. Analyzing the RAC showed a much stiffer RAP binder with a penetration of 20 dmm and softening point of 69°C. A similar asphalt mix evaluation procedure was performed on prepared samples. Generally, a similar observation was made for durability and dynamic creep stiffness, but unlike case 1 (Road 40), introducing RAP with stiffer asphalt cement resulted in a higher stiffness modulus.

The results of a ten-year follow-up study on both cases, which were made by visual inspection, macrotexture measurement (using Laser-RST Road surface test), IRI, and rut depths measurement, showed no mechanical damage to any of the test sections. RAP-containing mixtures also outperformed reference sections in terms of average rut depth.

Another case study was performed on the road between Kaunisvaara and Svappavaara, which is expected to be loaded mainly with very heavy mining trucks (90 tonnes) in the north of Sweden. This study's test sections were paved using 0 (control), 10, 20, and 30 percent RAP. A similar testing scheme for two earlier mentioned cases was made, and no significant drawback was observed by using up to 30 percent RAP.

High RAP Research Performed at Swiss Federal Laboratories for Materials Science and Technology (EMPA)

Swiss Federal Laboratories for Materials Science and Technology (EMPA) [8] have undertaken research efforts to create High RAP surface mixtures designed to replicate the High Modulus Asphalt Concrete (HMAC) concept developed by French pavement authorities. HMAC is designed to be a very stiff mixture and has been shown to exhibit excellent rutting and cracking resistance [9]. EMPA researchers identified the fact that RAP properties are well suited to making a high-modulus asphalt and attempted to do so using 100% RAP. Researchers used a reference mixture as the benchmark for their performance criteria. They then produced 100% RAP mixtures and modified the appropriate parameters to match the performance of their benchmark mixture. Researchers looked at changing the binder content, binder stiffness, different combinations of binder types and RAP particle size to alter the performance of the 100% RAP mix. After running the reference mix and modified recycled mix through their accelerated loading tester, they found the recycled mixture was less resistant to cracking.

Despite the reduced performance, the mixture showed promise and the concepts used in the design process can still be applied elsewhere. The researchers noted their existing mixture design procedure was insufficient for evaluating cracking resistance and suggested the use of a cracking propagation test to improve their design process. Figure 2 outlines the general methodology the researchers followed. The process began with a reference mixture, performance testing and then validation of the mixture. This general procedure can be followed when developing High RAP mixtures. The researchers noted that improving the fatigue resistance of the 100% RAP mixture required higher binder content than normally used in HMAC. Fractionation of the RAP into three sizes gave the researchers more flexibility to improve the performance. RAP particle size impacts the diffusion of aged RAP binder into the mixture. HMAC is typically used in high traffic applications and as such, the reduced performance exhibited in the 100% RAP mixture indicated it was not suitable for high traffic levels, however, researchers noted the possibility of using a 100% RAP mixture in lower traffic applications.

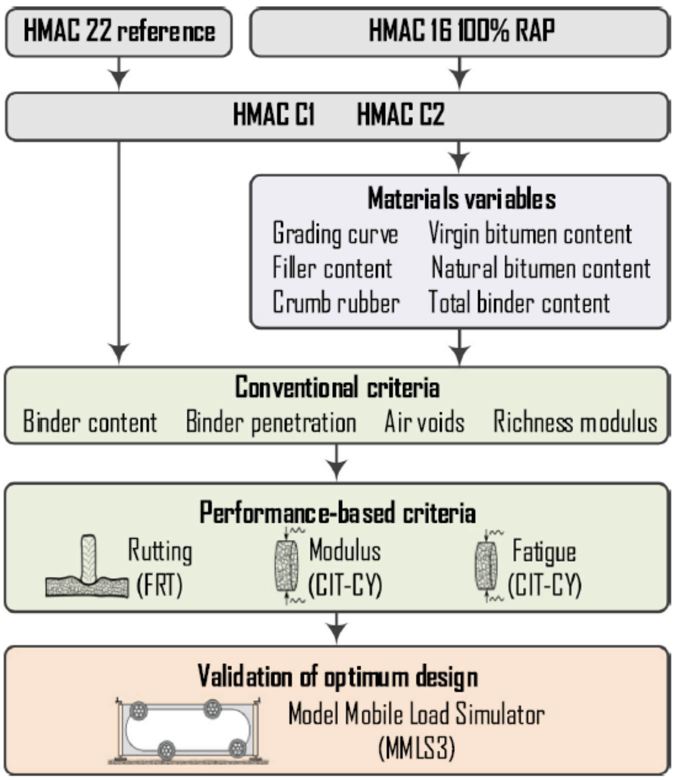

Figure 2. Outline of EMPA plan for evaluation of HMAC 100% RAP mixture [9]

Despite the failures to replicate a HMAC using 100% RAP, the same research group was successful in producing 100% RAP surface mixtures using a similar design approach. Researchers were able to produce a 100% RAP mixture which could sustain 2.5 times more load applications before cracking when compared to their standard mixture design. This project used two different RAP gradations in addition to a rejuvenating agent. Researchers produced three mixtures: a reference, 100% Fine RAP and 100% Coarse RAP. The virgin reference mixture (AC8N) used a 70/100 virgin binder with an asphalt cement content of 6.2%. The two RAP mixtures made use of a rejuvenating agent. The rejuvenator used was based on a distilled version of tall oil. The optimal dosage was determined by blending the rejuvenator at two dosages and extrapolating the curve to their target penetration. The target penetration was 60 x 0.1mm, which is comparable to the 50/70 virgin binders used in the area. Two Fine RAP mixtures were created with 6.0% and 6.5% asphalt cement content, while the two Coarse RAP mixtures were produced using 5.5% and 6.0% binder content. A sixth mixture was tested where 0.5% polymer modified asphalt cement was added to the Coarse RAP mixture rather than an additional 0.5% virgin binder [9].

All these mixtures were subjected to the French Rut Test, and Semi-Circular Bend test as well as safety tests to evaluate particle abrasion and skid resistance. Once the laboratory testing was complete the researchers made use of the Model Mobile Load Simulator (MMLS3) to verify the performance of the materials. The Coarse RAP mixtures all displayed the best rutting resistance in the laboratory but did not achieve the same cracking resistance as the virgin mixture. The Coarse RAP mixtures with additional asphalt cement (6.0%) were comparable within the margin of error. The Fine RAP mixtures showed similar rutting resistance to the virgin mixture. The Fine RAP mixture required an additional 0.5% asphalt cement content to surpass the virgin mixture laboratory performance.

The researchers applied the Balanced Mix Design approach to their results to optimize the binder content of their mixtures prior to field validation. By plotting the flexibility index and rutting results on the same plot, as seen in Figure 3., the researchers were able to find the optimal binder content for the Fine RAP and Coarse RAP mixture. Increasing the asphalt cement content to 6.2% was necessary to achieve the desired performance with coarse RAP. The resulting mixture lasted 2.5 times longer before cracking in the MMLS3 when compared to the virgin reference mixture. The researchers concluded that it was possible to modify the mixtures in a way that was conducive to increasing performance of 100% RAP mixtures to the level of their virgin reference mixture. These mixtures were unable to satisfy the conventional volumetric criteria, however, the researchers noted that this would not guarantee pavement performance.

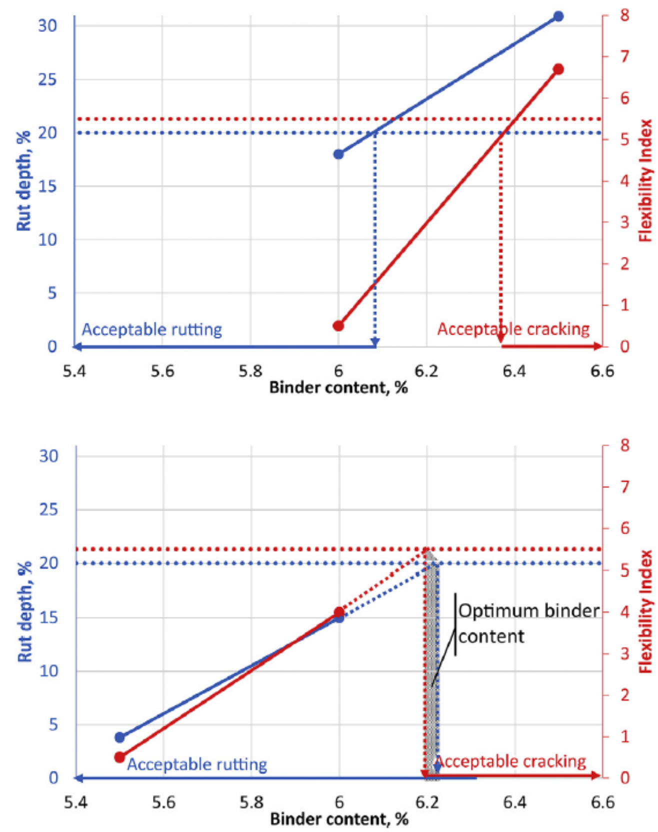

Figure 3. Determination of optimum binder content for fine and coarse graded RAP mixtures [8]

Florida High RAP Mixtures

High RAP mixtures were first explored by the Florida Department of Transportation (FDOT) in 2007 with mixed results. The mixtures in this study were limited to SP12.5 and integrated 4 different RAP contents with the highest being 45%. It should be noted that this 45% RAP mixture did not meet the minimum VMA requirement. This work established a few important concepts that are necessary for incorporating RAP effectively. The use of a linear blending equation was deemed to be appropriate. Very low RAP contents could effectively be ignored. The mixture with 45% RAP was able to achieve similar rutting performance to the control mixture, but lower RAP contents with a softer binder did show more rutting potential. The cracking performance of the high RAP mixture was not adequate, but AC content and binder type were identified as factors which may influence performance [10].

FDOT uses approximately 765,000 tons of RAP per year with several mixtures being allowed to contain an unlimited quantity of RAP. RAP content is controlled by mixture type and location. Contractors have been able to successfully produce good performing mixtures with 40% RAP and some contractors have succeeded with 50% RAP. FDOT does not allow RAP into OGFC, DGFC or High Polymer (HP) mixtures and limits the RAP content to 20% when using a PG 76-22. RAP usage is impacted by the locally available aggregate across the state. Northern Florida uses low absorption granite, while the south uses high absorption limestone. These mix types and RAP requirements can be observed in Table 2.

Contractors also have the option of using a Rap Binder Replacement Ratio of 20% rather than percent weight of the total aggregate. This is expected to allow contractors to exceed 20% by weight concentration, but it is rarely used in practice. This process uses the rap binder replacement ratio equation to determine the maximum RAP content. RAP fractionation is also something that is rarely used in Florida by contractors. This is another optional requirement and is avoided due to clumping that occurs. Stockpiles are typically generated on a project basis; however large stockpiles can be continuously added to so long as testing is performed. It must also pass a visual inspection and be approved by FDOT before use. RAP gradation is measured every 1000 tons during production and Gmm is measured every 5000 tons. Stockpiles must have a minimum AC content of 4.0% and 2.5% if it has been fractionated into coarse sizes.

FDOT follows AASHTO M 323 and R 35 for their mixture design practices, but they have deviated from the number of gyrations. Like New Jersey and Virginia, they have decreased the number of design gyrations but maintained other volumetric requirements which can be found in M 323. The FDOT design gyrations are as follows:

- Less than 3 million ESALs: Ndes = 65 gyrations
- 3 to 10 million ESALs: Ndes = 75 gyrations
- Greater than 10 million ESALs: Ndes = 100 gyrations

Blending charts have been used by FDOT for many years and the data collected helped develop their requirements for binder grade and RAP usage. With less than 15% RAP, they specify a PG 67-22, with RAP between 16-30% a PG 58-22 is specified and for RAP contents over 30% a PG 52-28 is used. This has eliminated the requirement to create blending charts for each mixture design. FDOT does evaluate extracted binders from mixtures twice per year to ensure they can make corrections if the RAP binder is softer than usual. The high temperature grade will be bumped if the RAP binder is soft to ensure they maintain their desired performance. FDOT also allows the use of Re-Refined Engine Oil Bottoms (REOB) as a softening agent for RAP mixtures. The REOB concentration is limited to 8% and is controlled by evaluating the ΔTc of the asphalt cement. Softening agents are not permitted when using a PG 76-22, but it is allowed for other grades. In addition to these requirements, FDOT also requires a 3-year warranty on pavement performance and a quality control plan. FDOT employs full-time plant inspectors which they have present during production.

Table 2. FDOT mixture types and PG binder requirements including allowable RAP percentage [10]

Region of State	Aggregate Type	Layer in Structure	Mix Type	PG Binder	Allowable Percent RAP	Notes
Northern	Granite	Surface	All	HP	0	High traffic
Northern	Granite	Surface	OGFC	PG 76-22 Modified	0	
Northern	Granite	Surface	DGFC	PG 76-22 Modified	20	
Northern	Granite	Intermediate	All	HP	0	High traffic
Northern	Granite	Intermediate	Intermediate	PG 76-22 Modified	20	High traffic
Northern	Granite	Intermediate or Base	All	Unmodified	Unlimited	Never surface mix
Southern	Limestone	Surface	All	HP	0	High traffic
Southern	Limestone	Surface	OGFC	PG 76-22 Modified	0	
Southern	Limestone	Surface	DGFC	PG 76-22 Modified	0	
Southern	Limestone	Intermediate	All	HP	0	High traffic
Southern	Limestone	Intermediate	Intermediate	PG 76-22 Modified	20	High traffic
Southern	Limestone	Intermediate or Base	All	Unmodified	Unlimited	Never surface mix

Georgia High RAP Mixtures

Georgia Department of Transportation (GDOT) began investigating general performance issues in 2012 [11]. Dense graded mixtures had poor field performance. They appeared aged, often had segregation were stiff with small windows for workability and had top-down cracking appear rapidly within the first few years of service. In response to these issues, GDOT simplified the number of gyrations to a single level, made their gradation limits finer and added performance testing to specialty mixtures. This resulted in increased asphalt cement content and improved performance [12]. GDOT also implemented their first version of the Corrected Optimum Asphalt Content (COAC) to improve the quality of their mixtures containing RAP. The first COAC was set at a 75:25 ratio meaning that 75% of the asphalt binder in the RAP was credited to the total asphalt binder. Additional virgin binder which was the equivalent of the remaining 25% was added to the mixture at the volumetrically determined optimum binder content. Following the success of this implementation, the COAC was changed to 60:40 in 2019 to further increase asphalt cement content. Currently, Georgia allows up to 40% RAP by weight in their mixtures and RAP usage varies by location due to availability [12].

In addition to COAC, GDOT also established minimum AC contents and requirements for a minimum film thickness. These changes lead to an improvement in field performance and a reduction in density-related pay reductions. The increased asphalt cement content allowed for more workable mixtures in addition to the benefits to pavement durability. GDOT uses Standard Operating Procedure 41 (SOP41) “Approval of Recycled Asphalt Pavement (RAP) for use in Asphalt Mixtures” to approve RAP on a stockpile basis [13]. SOP41 states that it is the contractor's responsibility to obtain DOT approval of RAP prior to use, monitor and preserve the quality and uniformity of the approved stockpile and comply with DOT requirement regarding replenishing the stockpile. The SOP also outlines RAP limits which are determined based on gradation and asphalt cement content as seen in Table 3 [13]. Fractionation is also an important aspect of Georgia RAP usage by allowing the contractor to have better control over the gradation.

Table 3. Georgia DOT SOP41 requirements for maximum allowable RAP by gradation and RAP asphalt cement content [13]

If ranges in asphalt content and gradation are equal to or less than:						
% asphalt cement	≤ 0.65	0.66 - 0.90	0.91 - 1.00	1.01 - 1.20	1.21 - 1.30	> 1.30
% passing No 200 Sieve	≤ 5.0	5.1 - 7.0	7.1 - 7.75	7.76 - 8.0	8.1 - 8.8	> 8.8
% passing control sieves	≤ 8.0	8.1 - 13	13.1 - 18	13.1 - 18	18.1 - 20.0	> 20.0
	the maximum % RAP allowed is:					
	Max	35%	30%	25%	20%	15%

David Vavinco Sala et al. [12] evaluated mixtures using the COAC methodology to determine if there was a noticeable increase in performance due to its adoption. GDOT currently includes Hamburg Wheel Track testing in the specification but has been exploring the use of IDEAL-CT to add a cracking test to their Balanced Mix Design approach. The first phase of this this study looked at multiple laboratory produced surface mixtures containing 30% RAP designed with different COAC ratios (100:0, 75:25 and 60:40). The study performed short-term aging in accordance with AASHTO R 30-02 to simulate field aging. The second phase of this study looked at 45 different plant mixtures which represented 7 different types ranging from 4.75mm to 25mm nominal maximum aggregate size.

IDEAL-CT testing revealed that for aged and unaged specimens, the cracking performance improved as the COAC favored lower contribution of binder from RAP. The 60:40 COAC mixtures performed the best for both the 9.5mm and 12.5mm mixtures. The addition of asphalt cement did not negatively affect the rutting performance as all mixtures still passed GDOT requirements. The second phase of the project attempted to benchmark the 45 mixtures and only noticed a statistically different performance when analyzing the SMA mixtures. All mixtures tested here exceeded the proposed minimum threshold values as determined by the NCAT Test Track Cracking Group. The benefits of COAC were clearly observed in the IDEAL-CT testing performed in phase one, but the second phase found no strong correlation between asphalt content and RAP binder ratio. This is likely due to the fact many of these mixtures contained different asphalt cement contents and other mixture volumetric properties impacted the performance.

Minnesota High RAP Mixtures

Local Road Research Board (LRRB) published a synopsis of Minnesota's RAP usage and states that MnDOT has maintained RAP usage in their specifications for over 30 years. A 2014 survey found that 97% of the agencies within the state follow the MnDOT ratios of added new asphalt binder, 64% of the respondents believed RAP mixtures perform as well as virgin mixtures and 14% of the agencies were increasing their RAP usage [14]. This contrasts with the findings of the 2009 MnDOT RAP Report where it was found that roughly 1/3 of agencies excluded RAP from the wearing course [15]. Minnesota pavement agencies were most comfortable with using 30% maximum RAP. Table 2360-8 (Figure 4) as it is referred to in the MnDOT specifications gives the requirements for virgin asphalt binder content within a RAP mixture. The mixture must have a minimum virgin binder content depending on binder grade and location of the mixture. Pavements using a PG 58X-34 under the AASHTO M 332 cannot contain more than 20% recycled content, while PG 58X-28, PG 52S-34, PG 49-34 and PG 64S-22 can contain up to 35% RAP in the non-wearing course and up to 30% in the wearing course [14].

Table 2360-8: MnDOT 2018 Edition of the Standard Specifications for Construction

Table 2360-8 Requirements for Ratio of Added New Asphalt Binder to Total Asphalt Binder[1] min%:			
Specified Asphalt Grade[2]	Recycled Material		
	RAS Only	RAS + RAP	RAP Only
PG 58X[3]-28, PG 52S-34, PG 49-34, PG 64S-22			
Wear	70	70	70
Non-Wear	70	70	65
PG 58X[3]-34			
Wear & Non-Wear	80	80	80

[1] The ratio of added new asphalt binder to total asphalt binder is calculated as (added binder/total binder) x 100

[2] The Contractor can elect to use a blending chart to verify compliance with the specified binder grade. The Department may take production samples to ensure the asphalt binder material meets the requirements. The blending chart is on the Bituminous Office Website.

[3] X=S,H,V,E

Figure 4. Table 2360-8 from MnDOT specifications [14]

The 2013 analysis of mixtures typical to Minnesota County saw 8 different designs produced with a PG 58-28 and a PG 58-34 in the laboratory containing 0, 25%, 40% and 55% RAP. Analysis of the data showed that virgin mixtures containing no RAP produced with a PG 58-28 had similar Indirect Tensile (IDT) low temperature performance as mixtures produced with 25% RAP and a PG 58-34. The report concluded that changing the low temperature PG grade resulted in improved IDT critical temperatures. IDT strength and SCB fracture energy did not see a significant improvement from grade substitution. The report found that of the variables analyzed, the percentage of new asphalt binder was most related to field performance [16]. A 2012 publication which followed high RAP pavements for 4 years found that all sections had been performing well despite concerns uncovered during the laboratory testing phase. The authors of the report suggested that the pavements should have shown signs of distress if the concerns were as great as they initially appeared. Eleven test sections were paved on the MnRoad test track. The control section contained 0% RAP while the remaining sections were produced with 20 or 30% RAP using various binder grades, warm mix, and fractionated RAP. Overall, the sections had been performing well but it was suggested that as time passes, the experimental data may be more indicative of performance [17].

Nebraska High RAP Mixtures

The Nebraska Department of Transportation began efforts to increase RAP usage in 2010 and have estimated they save approximately $30-50 million annually [18]. Between 2013 to 2019, NDOT averaged 39% RAP usage in their flexible pavements. Shoulder mixtures regularly contain upwards of 50% RAP. This was due to the introduction of a special provision in 2008 which created an incentive to use RAP. NDOT recognized that RAP piles were growing out of control and attempted to rectify the situation. This incentive splits the savings between the contractor and NDOT [10]. In conjunction with this incentive program, NDOT publishes their annual goals and usage. A yearly goal of 33% was presented in their 2019 RAP report [19]. University of Nebraska-Lincoln published a report in 2020 analyzing the performance of 254 pavement sections originally produced between 2009 and 2012. Some of these sections contained as much as 45% RAP. The pavements placed in Southern Nebraska showed good performance, with no statistical difference being observed between the mixtures containing 25, 40 or 45% RAP (within 95% confidence interval). Pavements placed in Northern Nebraska with 45% RAP, exceeded the cracking limit within 5-6 years of construction indicating the very high RAP content had some detrimental impact on performance in Northern Nebraska. Life Cycle Cost Analysis showed an expected 14% reduction in costs over the life of the pavement could be expected even though some increase in maintenance cost was observed [19]. Data collected by NDOT has indicated that since the increase in RAP usage, the condition of their overall network has improved. The Nebraska Serviceability Index (NSI) incorporates automated and visual inspection data to monitor the quality of their pavement network. The introduction of the special provision for RAP usage occurred in 2008 and Figure 5 shows the NSI since 2010. NDOT achieved their goal of having 80-85% of their highways in “Good” condition in 2015 and has generally been able to maintain that rating since [10].

NDOT deviates from SuperPave mix design and produces 5 mixture types known as SPS, SPR, SPH, SLX and SRM. These mixtures are designed specifically by NDOT with modifications to AASHTO M 323. SPH and SLX are considered premium surface course mixtures and contain up to 35% RAP. SPR is used in approximately 70% of NDOT projects and may contain up to 55% RAP. Their most common nominal maximum aggregate size for surface mixtures is 1/2” or 3/8” which is 12.5 mm and 9.5 mm respectively. Mixture designs are performed with AASHTO M 323 with some modifications, which include small changes to coarse and fine angularity consensus properties, a statewide specific gravity for virgin and RAP aggregates used on for VMA calculation during the design process, dust to binder ratio changes and design air voids depended on the mix type.

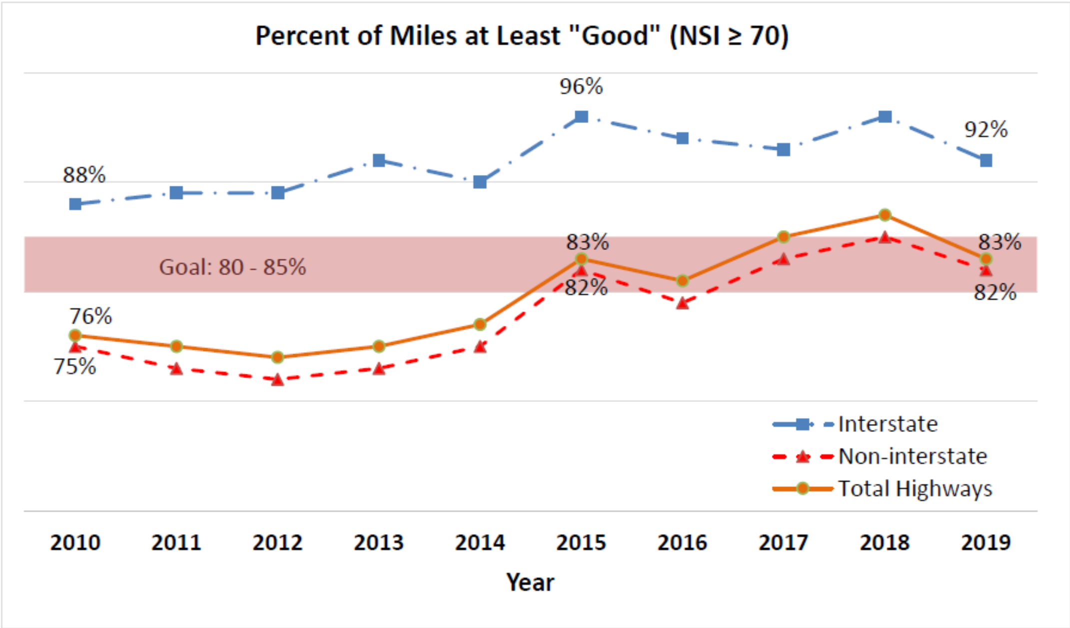

Figure 5. NDOT road performance according to Nebraska Serviceability Index (NSI) [10]

Each mixture also has a minimum binder content and gyrations have been reduced. NDOT follows AAHSTO M 332 for binder specifications and had moved to a PG XX-34 as their base grade to assist in accommodation more RAP. The binders are typically polymer modified and must meet minimum percent recoveries (MSCR) depending on the traffic grade designation. Binder content is also listed as a separate pay item to ensure the content received is sufficient. Binder requirements are listed in each contract, but all mixtures must also contain a minimum of 0.7% of an approved warm mix additive. SLX mixtures are required to be 58V-34 with 0.7% warm mix additive while SRM mixtures are 58H-34 with 0.9% warm mix additive. The design changes NDOT has made to the AASHTO M 323 are generally designed to improve durability ensuring adequate virgin binder is added to mixtures. The design air voids can be as low as 1.5% for shoulder mixtures, 2.5% for base mixtures and 3.0% for premium surface mixtures. NDOT also applies an incentive and disincentive on mainline and joint density. Pay factors with assigned acceptance schedules are unique to each mixture type. The SPR mixture acceptance schedule pays out bonus for air voids between 2.5 and 3.5%. Air voids between 2 and 4% are paid at full acceptance [10].

NDOT requires a quality control plan to be available for the project, but not for the RAP itself. The sole requirement for RAP is that it must be pre-processed either by fractionation, screening or crushing. This is done so that the product is consistent and meets the required gradation. NDOT uses a 600-ton mixture control strip, requires plant calibration, an incentive/disincentive system with encourages consistency, a material tracking system and testing of the virgin binder in 200-ton lots. These steps have been added along with plant inspectors to ensure RAP addition rate is consistent. Contractors have moved away from batch plants to accommodate the higher additions of RAP. Contractors also manage their own RAP stockpiles, and they prefer crushing to produce a more uniform material [10].

University of Nebraska-Lincoln has engaged in some research using rejuvenating agents with the goal of further increasing use of RAP. The project was divided into two phases and a report was published for each. These reports explored the impact of three types of rejuvenating agents on the mechanical and chemical properties of mixtures containing 65% RAP [20, 21]. Phase 1 included dynamic modulus, dynamic creep and SCB testing for the mechanical properties of the mixture, while the blended binder was evaluated using DSR, FTIR, AFM and SARA [20]. Phase 2 attempted to optimize dosage and treatment methods of the rejuvenating agents [21]. Both phases utilized the same three rejuvenating agents with a warm mix additive. The first rejuvenating agent was an agricultural product, the second was a petroleum product and the third was a green product. Dosages in Phase 1 were determined using manufacturer recommendations. Researchers found that all three rejuvenators softened the asphalt mixtures which is expected to negatively impact rutting performance but have a positive impact on the cracking resistance. A chemical change was observed with the addition of each rejuvenator, but each type had a different impact on the composition of the binder. Phase 2 was successfully able to optimize the addition of each rejuvenator to control the target PG grade of the binder. The optimized mixtures showed better cracking resistance than the control mixtures. The researchers also noted that chemical analysis is vital to understanding the long-term impacts of the addition of rejuvenating agents. The change in chemistry may result in changes to aging characteristics and long-term behaviour.

In a separate project, University of Nebraska-Lincoln conducted field trials using a mixture with a rejuvenating agent and 50% RAP. The report includes performance testing data from samples collected during paving, 1 year and 2 years after construction as well as pavement analysis [22]. The test section was placed on I-21 north of Lexington, Nebraska. The rejuvenator used was a bio-based additive and with the addition of RAP researchers targeted a PG grade of 64-28. The SPR mixture was produced using a binder replacement ratio of 59.5% meaning 2.1% virgin binder was added and the RAP contributed 3.1% binder by weight of the mixture. The performance of the mixtures was as expected. These mixtures were used as base layers with a control mixture used as the surface course. The control mixture (50% RAP with no rejuvenator) exhibited less rutting over the first two years but were still considered "Good" using the federal rating scale used by NDOT. International Roughness Index remained virtually unchanged after two years and was approximately half the value to be considered "Good." The section with rejuvenating agent exhibited some fatigue cracking and a small amount of thermal cracking after 1 and 2 years. The control section had no cracking after two years. The percentage of cracking was also considered "Good." The section with rejuvenating agent exhibited 1.2% fatigue cracking in year 1 and 2 while the threshold value is 5%. Researchers suggested further forensic work to determine why the rejuvenating agent increased the amount of cracking observed. As this was the base layer, the softening of the mixture with the addition of the rejuvenating agent could have resulted in higher pavement strains.

New Jersey High RAP Mixtures

New Jersey first evaluated balanced mix design (BMD) or performance testing designed mixtures in 2008. Longitudinal cracking has been cited as the primary distress of concern that necessitated the investigation of BMD. This was due to a shift towards coarser mixtures with lower asphalt cement content which were more difficult to compact. New Jersey DOT's first course of action to increase asphalt cement content was to reduce the number of gyrations while specifying polymer modified asphalt to mitigate rutting issues that may arise with the potential increase in asphalt cement content. New Jersey DOT also faced pressure from contractors with regards to using more RAP because of growing stockpiles. NJDOT began by developing a series of specialty mixtures. The process began with analyzing their current mixtures and they found that mixtures with 15% RAP were under asphalted by about 0.6%. The intention of BMD is to improve the performance of their pavements, but to also ensure that recycled materials are used in a way that does not sacrifice performance [23].

New Jersey has had very good success with their implementation of BMD and performance testing. The criteria were also able to help produce a high RAP (HRAP) mix design methodology. HRAP is defined by a minimum RAP content rather than a maximum as is traditionally done. HRAP mixtures are expected to meet the same performance criteria that was determined for virgin mixtures (Table 4). The expectation is that if the mix meets the design criteria it will perform well. The HRAP test sections are currently being monitored for performance by the New Jersey DOT. The different types of mix designs explored by New Jersey have all exhibited a positive cost-benefit ratio (CBR) when considering performance. Traditional mix designs were designated a CBR of 1.0; HRAP provided a CBR of 3.8, while overlay technologies like the High-Performance Thin Overlays (HPTO) provided a CBR of 18.0 [23]. In addition to high RAP applications, the performance testing approach was also used to evaluate High Performance Thin Overlays, Binder Rich Intermediate Course, Bridge Deck Waterproofing Surface Course, and Bottom Rich Base Course. Trial sections for each type of mixture listed above are discussed within this report. High RAP mixtures will be of interest to Ontario where RAP is currently limited in use.

Table 4. BMD Surface and Intermediate Course Specifications for New Jersey [23]

Test	Requirement			
	Surface Course		Intermediate Course	
	PG 64-22	PG 76-22	PG 64-22	PG 76-22
APA @ 8,000 loading cycles (AASHTO T 340)	< 7 mm	< 4 mm	< 7 mm	< 4 mm
Overlay Tester (NJDOT B-10)	> 150 cycles	> 175 cycles	> 100 cycles	> 125 cycles

Performance Based Acceptance Procedure

The general procedure developed by the New Jersey DOT can be listed in four steps:

1. Volumetric design using proposed materials and mixture design specifications. The contractor is expected to perform their own volumetric design which is then verified by NJDOT laboratories for approval.
2. Contractor must submit laboratory prepared mix or virgin raw materials to a NJDOT approved laboratory. This laboratory will prepare mixture test specimens for the required tests. If the current mixture meets performance criteria, the contractor may move to Step 3.
3. Asphalt mixture must be produced at the plant and a test strip will be constructed. Location of the test strip is at the discretion of the contractor subject to NJDOT approval. Loose mix used in the construction of the test strip is sampled and is supplied to a NJDOT approved

laboratory for testing. If the material fails, the contractor must repeat plant production and test strip construction until it passes. Once it passes, the material can be placed on the project site.

4. Contractors must sample material during production for continued evaluation of performance. The frequency of sampling and testing depends on the mix being produced and quantity.

NJDOT had listed the Asphalt Pavement Analyzer (Rutting), Flexural Beam Fatigue (Cracking) and Overlay Tester (Cracking) as possible test procedures required at the time of report publication. Test procedures are outlined in the report and were selected based on several factors such as experience and correlation with field results. Specification thresholds were developed by comparing laboratory data with field data. The Asphalt Pavement Analyzer was selected due to NJDOT's experience with the equipment. NJDOT used correlation with field data, ease of analysis and the ability to test field cores as well as laboratory produced specimens when evaluating cracking tests. The use of field cores is desired for potential forensic work. The Overlay Tester was also used on the early projects and NJDOT therefore had some experience with the testing and equipment as well.

The Overlay Tester had limited data initially and the first year of the project included testing loose mix from numerous paving projects and compared to field data. This produced a database of values for different types of mixtures for which they could base specification on. The conventional mix performance criteria followed the criteria developed for High RAP mixtures while SMA and OGFC criteria were based on typical mixture performance and field data.

Balanced mix designs work by making the optimal asphalt cement content a function of performance rather than air voids while taking workability into consideration. When using the appropriate laboratory evaluations, the mixture should perform as expected. NJDOT followed the initial work by Texas DOT on reintroducing this concept. This methodology involves selecting materials, volumetric evaluation at different asphalt cement contents, performance testing at those asphalt cement contents, verifying the mix meets both criteria and then adjusting the asphalt cement content to meet performance if necessary. An example of that process can be seen in Figure 6.

The NJDOT approach differs in the selection of rutting test but follows a similar process. The criteria were based on NJDOT approved materials and equipment available locally. Their experience with the projects listed in this summary also helped provide important information for the development of specifications. The report shows some examples of mixtures that were put through the evaluation process developed by Texas DOT. Mixtures were prepared at different asphalt cement contents for volumetric evaluation and then performance testing. This work led to the discovery that RAP mixtures (with 15% RAP) required an additional 0.6% asphalt cement on average. The addition of RAP increases the stiffness ensuring rutting is not an issue while the increase in asphalt cement content adds durability [23].

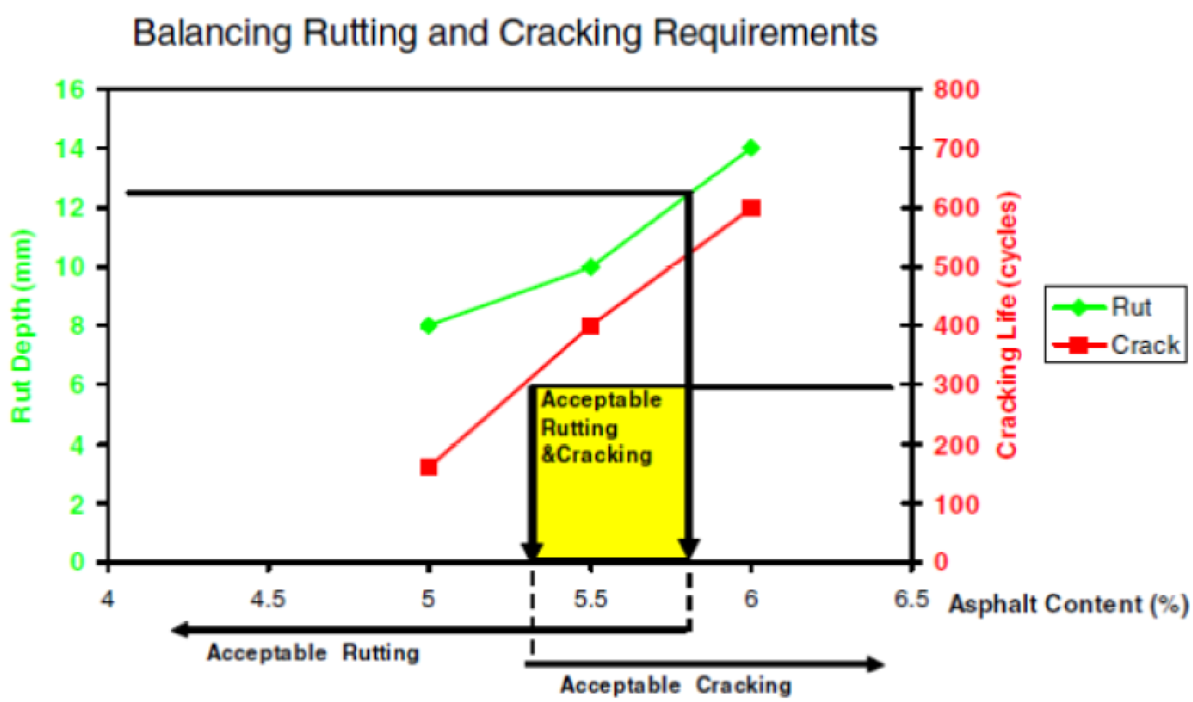

Figure 6. Balanced Mix Design Results Originally adapted from Zhou et al. [24]

Specifications and Field Evaluation

The following section will outline the five performance-based mixtures that require advanced testing and their test sections with corresponding evaluation. This summary will focus on the general lessons learned but specific information such as blend gradations and volumetric requirements are included in the final report. The data and experience collected in these test sections helped produce the performance criteria for conventional mixtures. These different mixtures may be interesting starting points for various performance testing related trials and evaluations in Ontario.

High RAP Mixtures (HRAP)

The use of performance testing allows for flexibility in mixture design especially with the introduction of RAP. High RAP mixtures would be possible with the introduction of warm mix, rejuvenators, softer asphalt binders and increased asphalt cement content [23]. These techniques would all be verifiable with performance testing. NJDOT's HRAP mixtures are specified with a minimum RAP content; 20% in the surface layer and 30% in the intermediate and base layers. The HRAP mixtures must meet a minimum cracking threshold and not exceed a maximum rut depth. The criteria for Overly Tester and Asphalt Pavement Analyzer were derived using the performance database on virgin mixtures. NJDOT specification relies on the premise that "if you can produce a high RAP mixture that performs as well as a virgin mix, then the NJDOT will accept it."

The magnitude of the acceptance values also depends on the application of the pavement. The criteria will change whether the mixture is to be used as a surface or base course. In addition to performance requirements, small adjustments were made to the volumetric design properties of HRAP. The Voids in Mineral Aggregate were increased by 1% and during production control, air voids may be between 95 and 98.5% of the maximum specific gravity. Testing is conducted during the mixture design, when the plant produces a test strip and when it is placed on the project.

NJDOT implemented a HRAP project on Interstate 295 in 2012. The project would cover approximately 3 miles and use 3700 tons. In preparation for the mixture design and production, the contractor fractionated the RAP into Coarse RAP and Fine RAP stockpiles for improved control. The Fine RAP had roughly twice the asphalt cement content as the Coarse RAP stockpile and the RAP binder had a continuous grade of PG 83.8-18.8. Five different mixtures were submitted for the surface and intermediate course before performance and volumetric requirements were met. The final designs incorporated 25% RAP into the surface and 35% into the intermediate course. Final mixture properties can be found in Table 11 of the report [23]. Binder grade selection was left to whatever would be most appropriate for performance.

Performance of the HRAP mixtures greatly exceeded the criteria and the pavement was found to be visibly very similar to the warm mix asphalt placed adjacent to it using 15% RAP. Measurements of IRI and in-place density indicated that the mixture did not introduce issues with compaction. Initial performance criteria were met, and the section continues to be evaluated.

NJDOT developed performance testing specifications through the development of a database of currently approved mixtures as well as specific field trials which relied heavily on these concepts. The use of both approaches has allowed the NJDOT to gain experience with various test methods and develop laboratory to field correlations for the selected tests. The specialty mixtures are all very interesting to analyze because they typically have smaller NMAS than are used in Ontario. The use of 9.5 mm or smaller NMAS mixtures appears on surface and base courses in New Jersey. The emphasis on these projects is placed on achieving the desired performance for the appropriate function and material selection (specifically binders) is secondary. Ensuring the design of the material meets the intended function is a common theme among performance testing specifications. These changes may be valuable parameters to modify when evaluating High RAP mixtures.

The use of High RAP mixtures is also quite interesting and offers some lessons for Ontario. Small changes to volumetric design may be necessary, but the ability of NJDOT to increase RAP usage is quite simple. If the HRAP mixture meets the same performance level as virgin mixtures, it is considered to have good performance. In Ontario, where RAP is shied away from, this concept can easily be applied. It should be noted that the trial discussed in this report had a contractor willing to ensure good control over the RAP stockpiles to meet performance. This would be required in Ontario if it is not yet something that is controlled to a high degree.

NJDOT was careful to base performance criteria on local materials rather than simply apply limits developed by Texas for the Overlay Tester. This would be highly important for performance testing specifications in Ontario. This also highlights the necessity of further mixture crack testing research as many cracking tests are still highly localized. The general approach to performance testing can be similar. The four-step approach is something that can be easily adopted in Ontario in some fashion. There may be some resistance to quality assurance testing of plant produced mixtures and without the correct criteria or test selection this may become an issue. The relationship between plant produced and laboratory produced mixtures would require research if this approach is taken.

South Carolina High RAP Mixtures

South Carolina Department of Transportation (SCDOT) has had provisions for use of up to 35% RAP dating back to 2011 [10]. Between 2008 to 2013, SCDOT estimates savings of roughly $90 million. SC-M-407 "Recycled Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS)" has been updated as of January 1, 2022, and remains largely unchanged [25]. One of the interesting features of SC-M-407 is that the RAP content is dependent on whether the stockpile has been fractionated. The requirements for RAP content are shown in Table 5. The RAP content is defined by maximum percent of aged binder which is equivalent to RAP Binder Replacement ratio. RAP fractionation is considered more consistent by SCDOT, but the practice remains optional. Most contractors in South Carolina choose to fractionate their RAP with ¼ inch being the delineation between coarse and fine RAP [10].

Table 5. Maximum aged binder percentage by type of mix according to SC-M-407 [25]

Type of Mix	Maximum % Aged Binder from RAP and RAS	
	Non Fractionated RAP	Fractionated RAP
Surface A	-	15
Surface B	15	25
Surface C**	20	30
Surface D**	20	30
Surface E	-	30*
PMTLSC	15	30*
Intermediate A	-	15
Intermediate B	20	30
Intermediate C**	25	35
Base A**	30	35
Base B**	30	35
Base C	-	35*
Base D	-	35*
Shoulder Widening**	30	45

*Fractionated Fine Rap only
** RAS permitted

SCDOT has addressed durability concerns with a wide number of changes which generally have resulted in an increase in asphalt cement content. The use of finer graded surface mixtures has expanded while changes have also come to design gyrations, design air voids, asphalt binder availability, voids in mineral aggregate, dust proportion, binder selection and contract requirements for payment of asphalt cement content. In similar fashion to other states mentioned in this report, SCDOT has lowered their design gyrations with simple criteria. All interstates and primary will be designed with 75 gyrations while secondary routes are designed with 50 gyrations. Design air voids are selected in combination with the optimum asphalt cement content and is 96 to 97% of the theoretical maximum specific gravity (Gmm). This is maintained at 96% for mixtures containing RAP but increases to 96.5% for virgin mixtures. SCDOT specifies a higher VMA than AASHTO M 323 by increasing the minimum by 0.5%. Effective specific gravity is used in the calculation and when combined with the VMA increase allows for an additional 0.3 to 0.5% asphalt cement content.

For surface and intermediate mixtures, SCDOT uses a Corrective Optimum Asphalt Content (COAC) to account for binder availability. RAP binder availability is fixed at 75% while the remaining 25% is treated as "black rock." The COAC is determined by multiplying the RAP binder content by 25% and adding it to the optimum asphalt content determined volumetrically. Air voids may not drop below 2.5% when applying the COAC correction. This ensures that rutting performance is not compromised. Mixtures are also subjected to the Asphalt Pavement Analyzer (APA) to verify rutting resistance. Additionally, asphalt cement is listed as a separate pay item which helps to ensure that the changes are adhered to during production. SCDOT commonly uses PG 64-22 in 90% of their mixtures but does not allow softening of the binder to discourage the use of REOB.

Contractors are required to implement separate RAP and project QC plans. Contractors also fractionate the RAP and store it in sheds with sloped pads to minimize moisture and clumping. They have also found that the use of an external mixer after discharge from the drum can improve coating of high RAP mixtures. The contractors find the use of COAC favorable because of the improvement in density that accompanies the higher asphalt cement content in addition to AC content being a pay item.

Virginia High RAP Mixtures

In 2007, Virginia Department of Transportation began allowing up to 30% RAP in their surface mixtures but asked the Virginia Transportation Research Council (VTRC, formerly Virginia Center for Transportation Innovation and Research) to begin exploring the possibilities of expanding RAP usage in 2013 [26]. Report VTRC 15-R6 looked at the possibility of using RAP in unbound base and subbase layers to reduce costs by up to 30%. The report noted RAP stockpiles had reached approximately 5 million tons [27].

A laboratory evaluation of high RAP mixtures was published in 2014 [28]. Report VCTIR 15-R8 noted commonly cited concerns about the potential detrimental impacts incurred using RAP. They also noted the potential environmental benefits that come with reducing use of virgin aggregates and asphalt binder. This was an early evaluation of a 40% RAP surface mix which had not been permitted by VODT at the time. The report had a simple experimental design whereby mixtures were tested at their design, design + 0.5% and design + 1.0% asphalt cement content with a Superpave gyratory compaction effort of 65 gyrations. The design asphalt cement content came from standard volumetric methods. Once these mixtures were prepared, they were subjected to Dynamic Modulus, Flow Number (rutting), Asphalt Pavement Analyzer (rutting) and Repeated Flexural Bending (fatigue) testing. These performance tests were selected after extensive literature review and used to determine the impacts of asphalt cement content on rutting and fatigue resistance.

Researchers here tested mixtures with 0, 20 and 40% RAP obtained from local contractors. The 0 and 20% RAP mixtures were designed to meet VDOT specifications while the 40% RAP mixture was obtained from a private project. Volumetric analysis showed that this 40% RAP mix also met some of the VDOT specifications. In addition to this, the researchers also tried an experimental 100% RAP mixture. It was generally observed that increasing binder content led to an improvement in fatigue life but could have a detrimental impact on rutting resistance. The 40% RAP mixture was deemed to be at an optimal AC content at the design AC and thus did not improve with the addition of asphalt cement. Bleeding and flushing were observed. The 100% RAP mixture with additional 1.5% AC performed similarly in fatigue testing to the 20% RAP at the design AC. The design changes resulted in higher VMA, higher VFA and higher asphalt cement contents were expected to improve performance.

The researchers recommended further studies on high RAP mixtures, softer binders, and the impact of different performance grades on the mixture performance. Based on the ability of performance tests to evaluate the mixtures in this study, the researchers also recommended performance testing become part of the design methodology.

VTRC placed several field trials using high RAP mixtures in 2013 and 2014. These mixtures were developed using 20, 30, 40 and 45% RAP content. The maximum RAP content was still limited to 30% by VDOT at this time. This project was set up to evaluate the performance of these mixtures and evaluate several new performance tests that were not used in the previous report. Trials consisted of multiple SP12.5 mixtures and one trial using an SP9.5 mixture. Mixtures containing 30% or more RAP were produced using a combination of natural and manufactured sands. The report also indicates that the RAP used was crushed to a consistent size for all mixtures. In addition to the tests used previously, VTRC also included Texas Overlay, Semi-Circular Bend for fatigue resistance and the Cantabro Mass Loss. Mixtures were designed with a minimum VMA of 15% and it was generally higher for high RAP mixtures.

Performance of these mixtures was very similar in flexural bending and Texas Overlay fatigue testing except for the 40% RAP mix used on SR 3. The 40% mixture using 58-28 (CR 639) was shown to have similar performance to the other mixtures produced here. These two mixtures had the lowest effective binder content, but the use of a softer binder compensated for this in the better performing mixture. It is also interesting to note that while the flexural bending and Texas Overlay showed good agreement, the Semi-Circular Bend test results suggested all these mixtures would likely have premature cracking. Evaluation of these mixtures 2-3 years after placement has shown this was not the case. Despite this inconsistency, the researchers noted the importance of using performance tests for designing high RAP mixtures and were pleased with the performance achieved.

Following these efforts, VTRC began benchmarking mixtures in 2017 for the purpose of understanding performance. These mixtures were samples in 2015 and reheated. This resulted in the development of a performance-based specification for surface mixtures in 2021. Part of the validation process for this special provision specification was field trials placed in 2019 using high RAP mixtures. The results of these field trials were published in FHWA/VTRC 21-R21 [29]. Email correspondence with one of authors of this report indicates the trials were performing very well as of February 2022 [30].

VTRC developed 9 SP9.5 mixtures using a variety of techniques including warm mix additives and recycling agents. Several of the mixtures were produced with 30 and 40% RAP using different binder types, while the remaining mixtures were produced with 26% RAP and different combinations of warm mix additives and recycling agents. One 40% RAP mixture was produced using a recycling agent. This project was designed to evaluate the different mixtures but also to evaluate the application of the special provision and balanced mix design concepts. Production variability was also determined to be an important aspect of this work. Samples were taken during the design phase and production phase. Plant samples were compacted immediately following production and further samples were taken to examine the impact of reheating. Testing was simplified to Asphalt Pavement Analyzer for rutting, Indirect Tensile Cracking Test at intermediate temperatures for fatigue resistance and the Cantabro Mass Loss test. The testing plan is demonstrated in Figure 7.

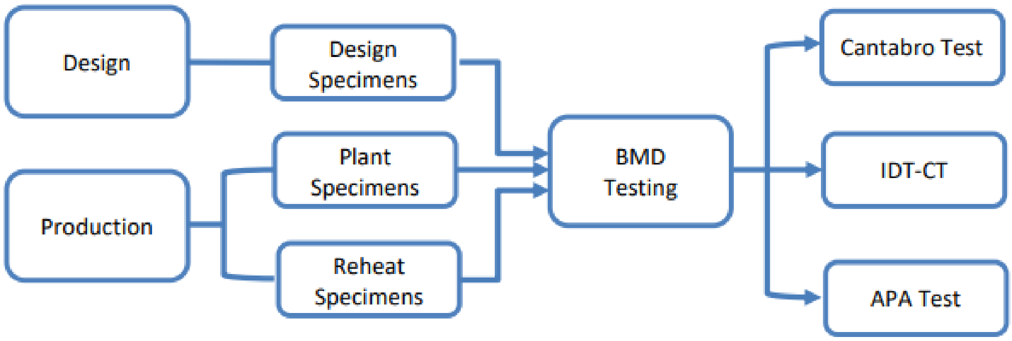

Figure 7. VRTC testing plan for development of mixtures using balanced mix design procedures [27]

Two producers were used, and all the mixtures used passed VDOT specifications including a minimum VMA of 16.0 and a VFA range of 70-85. The effective binder content was higher than 5.3% for all mixtures. Mixture A-I and A-II had job mix formula VMAs of 17.8 and 17.3, respectively. Other mixtures produced by Producer A were designed with VMAs between 16.0 and 17.0. Three of Producer A's mixtures were designed to meet standard specifications and two were designed to meet the new special provision. Producer B's job mix formula set VMA as 17.0 for the 26% RAP mixtures including warm mix additives and recycling agents.

Testing of Producer A's mixtures found that there was no statistical difference between the performance of the 5 mixtures produced in all three performance tests. The largest differences in performance were between plant compacted and reheated samples which prompted further evaluation by the researchers. They also found that the difference in binder grade had no impact on performance. Some statistically significant results were obtained through testing Producer B's mixtures. Warm mix additives and recycling agents did seem to reduce mass loss in the Cantabro Mass Loss test. Generally, fatigue resistance is expected to be the same for mixtures containing warm mix additives and recycling agents. Rutting resistance was also consistent although there were some concerns with variability. Overall, the researchers were impressed with the performance of these mixtures.

This report notes VDOT's expected implementation of 2023 for Balanced Mix Design and has the following recommendations:

- Continued work on planned implementation of Balanced Mix Design
- Development of precision estimates for the tests used
- Monitoring field performance

- Continued work to evaluated relationship between mixture properties and performance test results
- Evaluation of performance testing criteria
- Evaluation of short- and long-term laboratory aging on performance tests

Meroni et al. [31] evaluated high RAP mixtures using VDOT's mixture criteria with three levels of performance testing. This project allowed the researchers to evaluate the mixture properties impact on performance and compare tests of varying levels of complexity as VTRC look to optimize their Balanced Mix Design system. Through this work, they were able to develop a mixture with 45% RAP which had the best cracking resistance, but worst rutting resistance which contradicts expected performance for high RAP mixtures. The three different performance levels showed excellent correlation with each other, prompting ideas for simplification of the system. According to researchers here, the level of complexity for tests will decrease with lower traffic volume roads.

It should be clear through VTRC's projects on high RAP mixtures that performance testing has been highly valued. The use of tests on the mixture itself allows the user to understand the impact of RAP on a level that volumetric testing alone is incapable of doing. In addition to using these tests, it's clear that they expected higher VMA, VFA and asphalt cement contents through these designs. When compared to Ontario Provincial standards, minimum VMA is 1.0% higher for the corresponding mixture. They were careful to note that the higher asphalt cement content could lead to rutting issues, but there are ways to mitigate this issue. The Balanced Mix Design approach should ensure that the rutting and cracking resistance are balanced with respect to each other to ensure the mixture performs well. Recycling agents and warm mix additives were also shown to have positive impacts on RAP usage. Recycling agents soften the binder allowing for a higher RAP content to be used effectively.

Wisconsin High RAP Mixtures

Wisconsin Department of Transportation (WisDOT) started developing high RAP asphalt mixtures using Performance testing during both the mix design and production in 2014. They mainly utilized the Hamburg Wheel Tracking (HWT) test, the Semi-Circular Bend (SCB) test at intermediate temperature, and the Disc-Shaped Compact Tension (DCT) test at low pavement temperatures. An example of such effort is the pilot project on State Highway 77 in Ashland County of Wisconsin. The results from this pilot project indicated that a climate-based approach should be used for test temperature selection rather than using a generalized temperature (e.g., 25oC for SCB which did not yield good correlations with the performance). WisDOT also concluded that post-peak analysis should be considered to better discriminate between mix composition and ageing conditions. According to Hanz et al. [32] the high RAP mixtures in their pilot study exhibited equal or even better performance relative to the conventional reference mix across all the selected performance tests.

In Wisconsin, Recycled Asphalt Materials (RAM) mainly includes RAP, Recycled Asphalt Shingles (RAS) or a combination of RAP and RAS. The limits are based on the percent binder replacement (PBR) and varies based on the layer in which the materials will be used and the type of RAM. There is also a mandatory asphalt binder grade reduction for all high RAM and RAS surface mixtures. To achieve the goals of a sustainable high RAP mix, WisDOT developed a Special Provision (SPV) for high RAM mixtures and made changes to mix design requirements, included more frequent monitoring of recycled sources, and put requirements for performance tests into both the mix design and production processes. To this end, WisDOT allows 50% PBR in lower layers and 40% PBR in upper layers of flexible pavements. It should be noted that for PBR values greater than 25%, the high and low temperature should both be reduced by one grade.

Quality Control Requirements

In WisDOT's specifications, QC requirements for the RAP stockpiles include sampling and measuring asphalt content and gradation at frequencies of 2000 tonnes. Furthermore, daily sampling is also required during asphalt mix production, where maximum deviations allowed in asphalt content was set to be ± 0.75% in the specifications. In Wisconsin's practice at least four submittals of performance testing were required including: 1) mix design, 2) after test strip production, 3) materials sampled during the first 600 tonnes of production, and 4) after every additional 10,000 tonnes of mix production. Except for the mixture design specimens which were Laboratory Produced and Laboratory tested (LL), all three other stages used field produced and lab tested (FL) specimens. Before proceeding with each subsequent step mentioned above, the agency has to approve the performance test results through QA process. This caused about 10 days of delay from the time of test strip construction until the actual production. The high RAP mix in the discussed pilot study was classified as E-3 which is appropriate for traffic levels between 1~3 million ESALs. This included 16,000 tonnes of high RAP mixtures produced with PG 58-40 and no rejuvenating agents. Two types of mixtures, namely a 19 mm and a 12.5 mm mix, were used for the high RAP mix production. To obtain the binder formulation, they used a bio-derived softening oil (to reduce low-temperature stiffness grade) and a polymer (to increase the high temperature stiffness grade). The PBR values were 45.9% and 36.7% for the 19mm and 12.5 mm mixtures, respectively.

Table 6 provides the details of performance testing requirements developed under the SPV in Wisconsin for High RAP materials. As indicated in Table 6, the SCB test in Wisconsin is a modified version of the Louisiana method (LTRC/LSU). For the low temperature cracking, both mix testing through DCT and binder evaluation based on ΔTc were utilized. To better mimic the performance tests were done either using short term or long-term oven aging depending on the test. Later in 2017, Mandal et al. reported that after studying the effect of different mixture design parameters on the DCT measurements, concluded that there are several challenges to properly interpret the low temperature performance of mixtures based on the DCT responses when different factors are present [33].

Table 6. Performance requirements for high RAP mixtures in Wisconsin [33]

Performance characteristic	Test	Method	Limit
Short-term ageing – 4 h at 135°C loose mix (AASHTO R30)			
Moisture damage resistance and mix stability	HWT test passes @ 50°C	AASHTO T324 WisDOT modified	> 5000 to max rut depth of 12.5 mm (for PG 58-XX)
	HWT @ 50°C SIP		SIP > 5000 passes
Long-term ageing – 5 days at 85°C – compacted mix (AASHTO R30)			
Fatigue (load associated) cracking	SCB test @ 25°C	LTRC/LSU Method, WisDOT modified	Report only
Thermal cracking	Disc-shaped compact tension test @ LT PG + 10°C	ASTM D7313 WisDOT Modified	Fracture energy (G_f) > 400 J/m^2
Asphalt durability	ΔT_c (see Equation (1))	AASHTO M320	> – 5.0°C
Asphalt binder low-temperature performance	Low-temperature PG	AASHTO M320	Meets plan grade[a]

[a]PG 58-34 was the plan grade for the project studied.

This comparative analysis also provides an example of how the inclusion of performance testing can influence the material selection process and produce test results indicative of improved overall performance of the mix.

Another comprehensive study was also conducted by the Wisconsin DOT to evaluate the feasibility of performance-based specification, where developing mixtures with high recycled asphalt materials was among the four major objectives of the study. To this end, the study provided supplemental guidelines to control the properties of mixture with high RAM content. The results of the study indicated that the mortar procedure proposed by the University of Wisconsin Madison results in a solvent-free alternative to extraction and recovery method [34]. The mortar procedure could be a better alternative over blending charts and extraction because of its ability to directly characterize materials based on the amount of blending that occurs in highly recycled mixtures. According to the report published in 2016, no significant performance concerns were identified with the high RAM mix designs as compared to the control. However, at the time of publication of the report the pavement was still at a young age, and hence further monitoring should be continued in the future to capture the true performance of the high RAP mixtures relative to their control counterparts. Nevertheless, at the laboratory scale, the highly recycled mixtures performed as well or better in most performance tests in terms of the Fracture Energy. Further monitoring should also include monitoring of the materials' properties in addition to the pavement performance over time so that the initial laboratory results can be properly verified. To track the changes in the materials properties Bahia et. Al. recommended that the selected tests be performed on an annual or bi-annual basis [33]. This is believed to be the most promising approach to develop and/or establish relationships of materials properties with pavement performance.

In addition to the DOT level investigations of high RAP mixtures in Wisconsin, pertinent research by University of Wisconsin-Madison has also pointed out the importance of short-, medium-, and long-term aging of high RAP mixtures when it comes to decision making regarding their long-term performance and durability. The relative ranking of the mixtures prepared with rejuvenators and using 30% and 50% RAP was reported to change because of different aging levels in that study [35].

Summary

The experiences of other jurisdictions can be summarized as follows. It is evident that there are multiple areas which Ontario can improve when it comes to development and implementation of high RAP mixtures.

Use of Performance Testing

The use of performance testing to properly engineer high RAP mixtures or develop specifications for these mixtures should be considered a priority for Ontario. Design principles and specification changes should be based on laboratory mixture testing initially and verified in the field over time. Optimizing the usage of recycled materials has historically been one of the main drivers for balanced mix design and performance-engineered pavements. However, this concept is not by any means limited to RAP incorporated mixtures and is applicable to designing any type of mix with the goal of improved durability. Benefiting from both empiricism and scientific principles, this approach has also provided the possibility of developing specialty mixtures for certain applications where the conventional mixtures do not measure up to the requirements.

While the concept of designing for performance is somehow versatile, conducting benchmarking studies using the domestically available materials and climatic conditions is an essential step toward its success. To this end, it is crucial to study the impacts of the mix constituents when establishing thresholds for mix design and QC/QA activities. In other words, implications of using different aggregate sources or gradations, asphalt binder types and grades, recycled materials, additives, and mix production details on performance metrics should be well understood. This helps eliminate the bias effects when interpreting the performance of different mixtures and reduces the risk to the stakeholders. Evaluating the experimental conditions such as testing temperatures, passing/failing criteria, bias and precision statements, and variability of the test results is another important consideration that can be done through round-robin or interlaboratory testing. An effective information management system that can build on relevant historical data, new production data, and actual field performance would be instrumental to make the most of performance-based approach. This will facilitate establishing a relationship between the test results from lab produced and plant produced mixtures, as well as the results from testing to their corresponding field performances. Finally, relevant specifications can be developed detailing the sampling and testing plans, tolerances, and potential pay adjustment factors. Learning from experiences in other jurisdictions, this process will need to be actively monitored, especially at the beginning, and the necessary changes should be made to improve the specifications with time.

Virginia, New Jersey, Wisconsin, EMPA and many others have moved away from a purely volumetric approach in favor of performance testing to design their high RAP mixtures. It is clear from their examples and our own experience in Ontario that volumetric design is not sufficient for evaluating mixture performance and the development of high RAP mixtures. Figure 8 illustrates a conceptual summary of the steps that need to be considered for this purpose and before full implementation. While the choice of specific tests to be used in this regard is important, it has been discussed extensively elsewhere and is not the focus of this article. A promising set of tests can be picked based on past experiences, which now spans more than two decades of data. However, what mainly contributes to a successful adoption of this new approach would be a well-thought implementation plan, establishing proper thresholds that are representative of the dominant domestic conditions, and revisiting the results and fine-tuning the specifications as we progress. This requires the use of our collective knowledge and close collaboration of the different stakeholders.

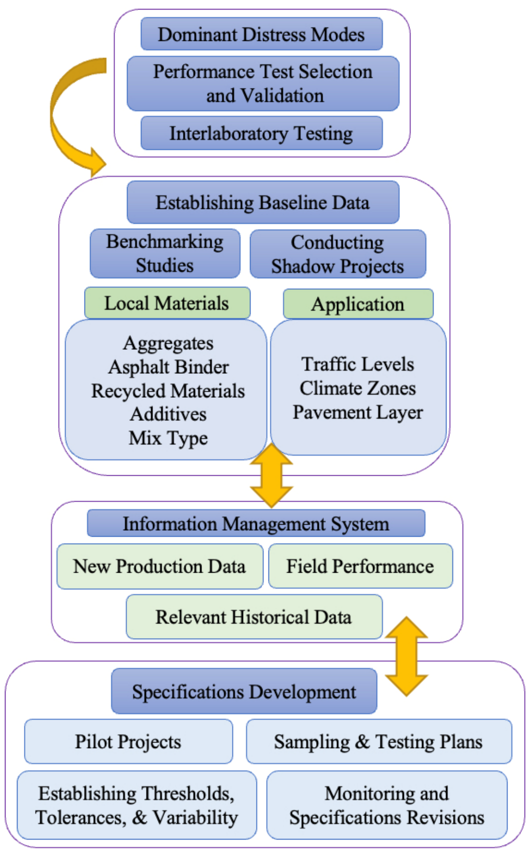

Figure 8. Overview of components of performance-based design approach

General Design Principles

The addition of RAP must be properly compensated for to balance the change in properties which can be attributed to the addition of aged asphalt binder. This is primarily done through increasing the virgin asphalt cement content of the mixture. This can be accomplished in a variety of ways, such as:

- Decreasing design gyrations
- Using finer gradations
- Decreasing the nominal maximum aggregate size
- Increasing the minimum VMA
- Decreasing the design target air voids
- Corrective Optimum Asphalt Content (COAC)
- Changing the RAP binder replacement ratio

Softening of the virgin asphalt binder can also be done in conjunction with these methods to improve the response to loading of the mixture. All these methods have been established in previous literature and are well known to increase the asphalt cement content; however, it is important to understand that these different methods may have different effectiveness in Ontario when compared to other jurisdictions. For example, some Ontario Asphalt Pavement Council (OAPC) work on lowering gyrations with virgin mixtures has led to an increase in asphalt cement content of approximately 0.2-0.3%, but this may not prove to be significant when starting at an already very low asphalt cement content [36]. Additionally, lowering gyrations alone may also not be effective for specific aggregate types. It must be made clear that multiple methods may be required, and this could necessitate changes to current specifications. Performance testing would allow industry partners to narrow down which of these may be most efficient before proceeding to field trials. Performance testing would also be important for ensuring that changes do not indirectly harm other aspects of performance. Trials to produce high RAP mixtures should follow these design principles and base decisions on data collected from performance testing.

Changes to design principles could be enshrined in specification and this has been done quite frequently by the jurisdictions mentioned in this report. The most common method appears to be lowering gyrations and decreasing the nominal maximum aggregate size, but this can be applicable to all mixtures. RAP specific items such as COAC and different RAP binder replacement ratios are also quite common.

Additionally, some jurisdictions specify RAP content by mixture use (e.g., surface, or base course). When compared to many of these other jurisdictions, Ontario has a much wider range of climates to consider. Due to this, any attempts to create a high RAP specification must also take this into consideration. It is very likely that RAP usage would need to be limited in northern climates, while Ontario could easily have some base course applications with unlimited RAP content in the southern most regions.

Requirements for RAP Quality and Handling

The quality of asphalt mixtures will be influenced by the consistency of the material supply and RAP requires equal treatment in terms of monitoring and testing to be considered usable as a construction material. This is an area where the jurisdictions presented in this report do a significantly better job than the specifications and best practices in Ontario. Common methods of controlling the RAP quality include evaluating the gradation, asphalt cement content and in some cases the penetration or recovered binder grade of the RAP. States such as Florida and Wisconsin have requirements for determining the gradation of the RAP on a per tonne basis, while Florida also includes a requirement for testing of maximum specific gravity. Wisconsin also requires daily sampling and imposes a maximum allowable tolerance on asphalt cement content of the RAP. The predominant focus on evaluating RAP quality comes in the form of monitoring the asphalt cement content and the gradation.

In addition to this, many jurisdictions reward good RAP management practices such as fractionation. This process allows the contractor to control the quality of RAP to a much higher degree and in cases such as South Carolina, allows the contractor to use more RAP by weight. Fractionation may be an approach Ontario needs to consider because of the large and inconsistent stockpiles that are currently available. Without any prior RAP management, the stockpiles in Ontario could fluctuate wildly in terms of asphalt cement content and gradation. Fractionation would allow contractors to gain control of the material properties. Georgia goes one step further than South Carolina by requiring approval for stockpile usage based on gradation and asphalt cement content. Florida DOT must also visually inspect and approve stockpiles for usage. Sweden and other jurisdictions work to separate stockpiles from different projects, where this is not possible, fractionation may prove to be a better way of improving RAP consistency.

Recommendations

The primary recommendation that this report can give is that significant work is required to produce mixtures that can contain high RAP content. All the principles discussed here can be applied to standard RAP contents as well, but moving towards high RAP mixtures is a necessity based on the increasing importance of building more sustainable pavements. The work must be completed to ensure that the methods discussed here are applicable to Ontario and that they are adapted appropriately to local variables and materials. Based on the findings in this report, the development of successful high RAP mixtures can be summarized in the following way:

- Follow well known design principles to increase asphalt cement content
- Verifying performance of these mixtures with performance tests when necessary
- Proper RAP characterization and management practices

The development of these mixtures is a relatively simple process that is only made more complicated by the relationship between contractors and owners. To overcome this, it is suggested that transparent, shared funding research projects are developed and centered around performance testing at the laboratory level, followed by trials that assess the effectiveness of different RAP management practices in addition to evaluating the mixture design changes. The assessment of mixtures at the laboratory level will allow contractors and owners to better understand which design changes are most appropriate. This will give both sides meaningful insight into the Balance Mix Design process as well as how to improve the performance of high RAP mixtures. The lessons learned here can also be applied to virgin mixture performance and performance testing specifications.

To simplify the discussion, the report suggests lowering gyrations, finer gradations, increasing the minimum VMA and using a Corrective Optimum Asphalt Content as the design principles of interest to begin with for high RAP mixtures. These factors need to be assessed separately and together to maximize the understanding of each property and their interactions to prevent unintended deficiencies in other areas of performance. If improvements to performance are not sufficient, other variables should also be explored. It is also important to understand that different requirements may be necessary for the environmental requirements posed by different regions of the province. A “one size fits all” approach will not necessarily create longer lasting, more sustainable pavements. Additionally, it is recommended that industry partners who take part in these shared funding studies commit to a regular review cycle to ensure that the desired improvements to performance are being observed and RAP usage targets are being met.

Owners and contractors should also work together towards improving RAP management practices and this could take the form of an official plant certification process. OAPC has begun taking steps towards converting the Trillium Award into a third-party verified certification, but this process should also look to include RAP management practices. These practices would need to be developed based on the data collected during the production of high RAP pavement trials but could become an effective way to control RAP quality. Practices such as fractionation may also have an impact on mixture design, and this must be taken into consideration. Monitoring and controlling asphalt cement content and RAP gradation should be the priority of these practices. Once the program gains acceptance and is implemented effectively, RAP management practices can be introduced for approval as a “second phase” of the program. The availability of RAP will also vary by region, and this should be taken into consideration when developing RAP management practices.

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