Blending Between Aged and Virgin Asphalt Binders in Recycled Pavements: A Review Study

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Abstract. It is the intent of this work to provide a background on works on diffusion in asphalt binders and review the researches carried out at Imperial Oil and ExxonMobil Technology Centres which have investigated nature of diffusion in asphalt material. These investigations include diffusion between Reclaimed Asphalt Pavement (RAP) and virgin binders, progress of diffusion in laboratory-produced mix samples from rheology perspective, and impact of silo storage on diffusion progress between binders and its manifestation on the performance of plant-produced asphalt mix. RAP is a major component of manufacturing hot mix asphalt (HMA) in North America. RAP utilization promotes sustainability of asphalt industry with economic and environmental incentives for manufacturing process. Recent statistics in North America show that RAP content of HMA has increased from 15 to 20%. This RAP content increase further prompts development and implementation of science-based practices in manufacturing plants to achieve optimum quality of RAP containing mixes. Quality of blending between aged and virgin binders has been shown to significantly impact performance and durability of final mix in the field. It has been demonstrated that mechanical blending helps achieving effective contacts between RAP and virgin binder. However, diffusion is the dominant process to help blending between the binders. It has been demonstrated that binder diffusion follows Fick’s Law and the rate increases with temperature. Field verification indicated that around 12 hours is required to complete the diffusion at the typical hot mix production and silo storage temperatures. Mix samples with more-progressed diffusion exhibited improved rutting resistance and higher number of cycles to fatigue failure. Field work also validated that there is an optimum storage time during which diffusion is the dominant process impacting mix properties; but eventually mix hardening dominates due to oxidation, evaporation and absorption.

1. Introduction

Reclaimed Asphalt Pavement (RAP) has been part of asphalt mixture manufacturing process for several decades [1-5]. The economic and environmental incentives have been the main driving force behind increased usage of RAP [6-8]. Recent report from National Asphalt Pavement Association (NAPA) suggests that the US national average RAP content in asphalt mixture production has increased from 15% to 20% between 2009 and 2016 [9]. However, extra caution should be exercised when RAP is utilized in a new mix. This additional caution is to (1) manage the increased stiffness of the aged binder in RAP, (2) achieve the correct final mix gradation when RAP aggregates get incorporated and (3) reach proper cohesion between virgin and RAP binders as well as adhesion to aggregates [5]. Reaching the
appropriate cohesion and adhesion is impacted by the degree of blending between the new virgin and aged RAP binders [5, 10, 11]. Blending between virgin binder and aged RAP binder can be modelled to occur in two stages: mechanical mixing and diffusion. Mechanical mixing mainly occurs during manufacturing process, where mixture of virgin and RAP aggregates are combined with virgin binder and are mechanically mixed together. Mechanical mixing brings the RAP and virgin-binder-coated aggregates next to each other and produces a contact surface between the two binders to interact with each other. Plant design, operating temperature, production rate and residence time during mixing can impact the quality of mechanical mixing [7, 12-21]. Diffusion, on the other hand, starts when contact surface between the binders are established and fractions of binders migrate in the direction of concentration gradient, and eventually reach an ideally uniform distribution between the binders. Previous studies mainly on asphalt binders and laboratory mix samples have indicated that diffusion is the major process that governs the blending quality between RAP and virgin binders [12, 22-24]. It is the intent of this work to provide a brief background on diffusion studies in asphalt binders and review the research carried out at Imperial Oil and ExxonMobil Technology Centres on the nature of diffusion between RAP and virgin binders. These studies span a range of investigations starting from rheological examination of diffusion progress in binders [22] up into laboratory-produced mix samples [23].

One of the earliest works on diffusion in asphalt binder was the work by Oliver using radioactive tracers [26]. Rejuvenators/recycling agents were radioactively tagged and their concentration-time profile were utilized to estimate an average diffusion coefficient. Oliver observed an Arrhenius type dependence of average diffusion coefficient on temperature. Carpenter and Wolosick later investigated diffusion of rejuvenators into RAP binders through staged solvent washing and binder recovery of RAP-containing mixes [27]. Their work indicated that the distinction between rejuvenator-rich and aged asphalt-rich recovered layers disappeared as blending time got longer, and more uniform binder was obtained at longer blending times. Other researchers, who also utilized multistage solvent recovery have pointed to the fact that not all the RAP binder might necessarily be participating in diffusion, which results in formation of inhomogeneous binder blends around aggregates [28-31]. Rejuvenators diffusing into asphalt binders were subject of study through Attenuated Total Reflectance-Fourier Transform Infrared spectrophotometry (ATR-FTIR) [32, 33]. FTIR signals of specific chemical groups in rejuvenator markers were used to construct the concentration-time (either peak height or peak areas) profile. Results indicated that Fick’s Law of diffusion could be applied to the data and diffusion coefficient were estimated for the rejuvenators. The ATR-FTIR data also supported the fact that diffusion coefficient followed an Arrhenius-type behavior as a function of temperature. On a different approach, same authors later developed a method to verify diffusion in asphalt binders through dynamic shear rheometers (DSR) [34], which was further refined by Kriz et al. [22, 23]. Their results confirmed the observation from ATR-FTIR study, i.e. an Arrhenius type of behaviour of diffusion coefficient was also noted in examining rheological properties of binders. Recently, there has been developments in the field of fluorescent microscopy to track fluorescence-active components in asphalt binders to examine diffusion between RAP and virgin binders [35, 36]. Results suggested that diffusion coefficients estimated from DSR methods are a bit larger than those estimated from Fluorescence method, however, both are within the same order of magnitude.

Investigations on blending quality and diffusion progress in RAP-containing HMA produced in asphalt plants suggest that a majority of studies carried out have mainly focused on mechanical mixing of the binder-coated aggregates [12-15]. Given the complexities associated with conducting plant trials, controlling the thermal history of samples is not trivial, specifically post-manufacturing before examining the collected samples start. Lack of consistency in thermal treatment of samples typically has resulted in unusual trends in mechanical and performance properties. For example, it has been reported that dynamic modulus of RAP-containing mixes were less than the control virgin mixes. These studies usually did not control the required time to achieve a homogeneous blend between virgin and aged binder. The unclear thermal history of samples makes it difficult to properly track diffusion progress, and draw clear conclusion on the impact RAP on performance of the manufactured asphalt mix.
2. Objective
It is the intention of this work to provide a review specifically on diffusion process and its application to blending between virgin and aged binder in RAP. This review covers the studies where thermal history of samples were tracked, whether in the lab or in the field, to ensure the observed changes in properties of asphalt material, both binder and mix, are due to progress of diffusion [22, 23].

3. Diffusion in asphalt

3.1. Diffusion between virgin and RAP binders
Diffusion is a kinetic phenomenon that is driven by differences in concentration of material. Fick’s Law is the differential equation that connects evolution of concentration ($\phi$) in time and space with the diffusion coefficient ($D$) under appropriate boundary conditions:

$$\frac{\partial \phi}{\partial t} = D \frac{\partial^2 \phi}{\partial x^2}$$  \hspace{1cm} (1)

where $t$ and $x$ represent time and distance of diffusion, respectively, and $\phi$ can describe the asphalt binder concentration. The diffusion coefficient ($D$) is a function of temperature. Dependence of $D$ on temperature is typically formulated in the form of Arrhenius equation:

$$D = A e^{-\frac{E_a}{R T}}$$  \hspace{1cm} (2)

where $A$, $E_a$, $R$ and $T$ are pre-exponent factor, activation energy, universal gas constant and temperature (in Kelvin), respectively. Detailed investigation of diffusion in asphalt binders has not been an easy task due to complexities associated with asphalt binder, e.g. diversity of molecular composition and relatively high viscosity of the binder at ambient temperatures. Also tracking progress of diffusion requires a very accurate and stringent control over sample thermal history. In the work of Kriz et al. [22,23], $\phi$ was considered for RAP, and its evolution over time was tracked. Utilizing an expanded differential equation solution to Equation 1, and applying separation of variables and appropriate boundary conditions, the following integrated solution to Equation 1 was obtained:

$$\phi_{RAP}(x,t) = (1-\alpha)(1-\phi_{virgin}^0) - \frac{2(1-\phi_{virgin}^0)}{\pi} \sum_{n=1}^{\infty} \sin(n\pi\alpha) \cos \left( \frac{n\pi x}{L} \right) \exp \left( -\left( \frac{n\pi}{L} \right)^2 Dt \right)$$  \hspace{1cm} (3)

where $L$ is the total diffusion distance in DSR experiments, and $\alpha$ represents the fraction of RAP in a blend with virgin binder. $\phi_{RAP}(x,t)$ represents concentration of RAP at a particular location $x$ along the diffusion distance $L$, i.e. DSR gap, at a time $t$. Viscosity of the blend at a particular location $x$ is dependent on the relative concentrations of RAP and virgin binders at that location. Utilizing the blending rule [22,24,34], the instantaneous viscosity of the blend at a particular location of diffusion distance $x$ at a time $t$ can be estimated as:

$$\eta(x,t) = e^{\phi_{RAP}(x,t)} \eta_{RAP} - (1-\phi_{RAP}(x,t)) \eta_{virgin} = \frac{\eta_{RAP}(x,t)}{\eta_{virgin}^{\phi_{RAP}(x,t)-1}} \eta_{virgin}$$  \hspace{1cm} (4)

Integrating Equation 4 over the diffusion distance, i.e. DSR gap, gives the viscosity of the blend as a function of time, which is measured by DSR instrument. The rate of viscosity change is then governed
by diffusion coefficient \((D)\). Therefore, fitting the measured viscosity data from the integrated Equation 4 to Equation 3 provides an estimate of diffusion coefficient.

In their study on binder diffusion, Kriz et al. [22] examined the diffusion phenomenon in a 50:50 blend of RAP binders with Superpave grades of PG 94-10, PG 88-22 and PG 82-22 with virgin binders of PG 58-28 and PG 64-22. However, in addition to the more comprehensive mathematical model to measure diffusion coefficients, Kriz et al. [22] also looked into factors that could influence measuring diffusion coefficients, including:

- Impact of experimental setup on data acquisition, i.e. influence of evaporation and oxidation on viscosity profiles, sample thickness, impact of gravity and applied strain level
- Understanding impact of temperature on diffusion progress, i.e. applicability of Fick’s Law to RAP-virgin binder diffusion
- Estimating diffusion coefficient based on correlation with liquid viscosity according to free volume theory of diffusion

Diffusion is a kinetic process that temperature plays a significant role in its progress. According to Equation 2, higher temperatures favor diffusion progress. However, higher temperatures also favor other processes such as evaporation and oxidation. Occurrence of the latter processes can have detrimental impact on the quality of material, i.e. binders become stiffer, and can impact progress of diffusion. Therefore, as viscosity of the RAP-virgin binder blend evolves over time towards the ideal blend viscosity, corrections should be applied to distinguish the impact of diffusion from evaporation and oxidation. Such correction was applied by first measuring the complex viscosity \((\eta^*)\) of an ideal blend of RAP and virgin binder over the same duration of a diffusion experiment. The incremental increase in \(\eta^*\) towards the end of measurement time was considered as evaporation and oxidation influence on \(\eta^*\) (see Figure 1). This increase was then subtracted from raw \(\eta^*\) profile of diffusion process to obtain the sole influence of diffusion. Figure 1 provide a summary of correction procedure applied to measured \(\eta^*\) of the binder blend before fitting Equation 3 to estimate diffusion coefficient \((D)\).

Influence of sample thickness on measured diffusion coefficients was also examined. Binder blends of 100-500μm thickness, i.e. DSR gap size, were assessed. A gradual increase in diffusion coefficient was noted as the sample thickness increased. Impact of binder layer densities on the measured diffusion coefficient was investigated under two scenarios: (i) RAP sample in the top layer, (ii) RAP sample in the bottom layer. The collected data demonstrated an increase and a decrease in the measured diffusion coefficients with increased sample thickness for scenarios (i) and (ii), respectively. This impact of layer configuration on measured diffusion coefficients pointed to the potential impact of barodiffusion, meaning that the difference in density of RAP and virgin binder could have resulted in appearance of a gravitational driving force. This driving force aids diffusion when the denser RAP layer is on the top. Therefore, it was found to set the sample thickness to a minimum of 100μm to minimize dependence of diffusion coefficients to sample configuration while maintaining reasonable repeatability of results. The impact of strain level on the measured diffusion coefficient was also explored. It was demonstrated that higher strain levels in DSR dynamic testing resulted in artificially larger diffusion coefficients due to more intense mechanical mixing. Therefore, it was recommended to conduct the experiment at lower strain levels within the linear regime of viscoelastic properties, e.g. strain of 1%.
At the beginning, there are two separate binder layers. As diffusion progresses and binders blend, viscosity starts to increase (blue dots). Part of viscosity increase is due to evaporation and possible oxidation during the test. A viscosity profile of the ideal blend of the two components is collected to estimate impact of evaporation and oxidation on viscosity. The constant ideal blend viscosity is subtracted from this function to obtain the increase function due to oxidation & evaporation (orange dots). Next, this viscosity-increase function of blend is subtracted from experimentally measured $\eta^*$ data (blue dots) to separate the effects of diffusion and aging processes during DSR experiment (gray dots).

The diffusion coefficients between the listed binders were then measured, utilizing the corrected $\eta^*$ data at different temperatures using the optimized experimental setup. Corrected $\eta^*$ data were fit to the integrated Fick’s Law of diffusion in Equation 3. Fitting was performed under the assumption that the maximum achievable $\eta^*$ would be that of the ideal 50:50 blend. The collected data, presented in Figure 2, suggested that diffusion coefficients followed the Arrhenius functional form in Equation 2 for the influence of temperature.

Kriz et al. [22] also utilized a simplified version of free volume theory to estimate diffusion coefficients of straight run asphalt binders from their measured viscosity–temperature profiles. Figure 3 depicts an example of viscosity-temperature profile of a PG 52-34, a sample RAP binder and the 50:50 ideal blend of these two binders. The viscosity of a 50:50 ideal blend of the virgin and RAP binders is estimated from their corresponding viscosity-temperature data using the general form (i.e. independent of time and location) of blending rule presented in Equation 4. The slope of the viscosity-temperature data of the blend provides the activation energy of flow ($E_a$). The diffusion activation energy ($E_a$) and the pre-exponential factor ($A$) in Equation 2 can then be calculated through a set of calibration equations derived from the free volume theory. The latter numbers can then be plugged into Equation 2 and diffusion coefficients of the virgin and RAP binders can be estimated at different temperatures. It was found that the differences between the measured and the estimated diffusion coefficients were well within the uncertainties associated with experimental measurements and approximations applied to physical models.

With the developed models and estimated diffusion coefficients, an attempt was made to explore how long it might take the diffusion process between RAP and virgin binders to approach completion in a real case of hot mix asphalt (HMA). A hypothetical manufacturing and construction temperature profile was simulated for two average thicknesses of a binder blend in a HMA, 20 and 100 $\mu$m. Figure 4 summarizes the results of this simulation for the modelled hot mix asphalt (HMA) samples. It was found that thinner binders and higher temperatures facilitate diffusion to reach completion. Based on simulations, about 20% and 70% of the ideal blend viscosity might be achieved at the end of the manufacturing process for a HMA with 100 $\mu$m and 20 $\mu$m average binder thickness, respectively. Upon
storing the HMA in a silo at a typical temperature of 140°C, the viscosity of the HMAs can reach between 80-100% of that of the fully blended binders.

Figure 2. Estimated diffusion coefficients of various RAP and virgin binders estimated from fitting corrected measured $\eta^*$ data to Equation 3

Figure 3. (Left) viscosity-temperature data for a PG 52-34 virgin binder and a recovered RAP binder using blending rule (Right) estimated diffusion coefficient for PG 52-34 and RAP at different temperatures

Figure 4. Evolution of blending between RAP and virgin binders

Two different binder thicknesses were considered: 20 μm (solid black) and 100 μm (dashed black). Temperature profile is presented in solid red line. Depending on the average diffusion distance, i.e.
binder thickness, the degree of blending could be significantly different at the end of manufacturing process. However, silo storage can help further progress of blending and better blending can be achieved.

3.2. Impact of diffusion on laboratory-produced RAP-containing asphalt mix

Investigation on quality of blending between virgin and RAP binders have been mainly conducted on laboratory-produced asphalt mixes [10-12, 16, 20, 23, 30, 31]. However, utilizing DSR instrument to monitor rheological properties of an asphalt mix has been a novel approach. Kriz et al. [23] had utilized torsional bars and monitored changes in complex viscosity of RAP-containing asphalt mixes. This approach helped better understanding in situ progress of diffusion between virgin and RAP binders from rheological perspective.

A mix design for a surface course (based on Ontario Canada specifications) was considered with 30% RAP. The utilized virgin and RAP binders had a Superpave grade of PG 58-28 and PG 82-10, respectively, same materials studied in section 3.1. This study included four mix sample sets: three control sample sets and one diffusion set. Two of the control sets were produced to measure \( \eta^* \) of asphalt mix samples with individual virgin and RAP binders. These \( \eta^* \) data were fed into the fitting procedure for Equation 3, the blending rule. An additional control mix was produced to measure the \( \eta^* \) for the fully blended RAP and virgin binder with the correct asphalt mix design ratio to assess the impacts of binder evaporation and absorption into aggregates over the duration of diffusion tests. The results from the latter mix was utilized to correct the \( \eta^* \) of the diffusion sample set for evaporation and absorption (a procedure similar to the protocol applied to binders in Section 3.1). All control samples proportionally included washed RAP aggregates as part of their aggregate content to limit the changes in rheology to diffusion between RAP and virgin binders. The mix samples were prepared in small beams and were conditioned at three temperatures of 90, 120 and 150°C in a pressurized aging vessel under Nitrogen atmosphere for various time periods. The temperature profiles were closely monitored to ensure all samples were treated the same way to minimize variability in \( \eta^* \) measurements. After conditioning, samples were mounted on torsional bars to measure \( \eta^* \) of the mix. Measurements were carried out at 20°C. Figure 5 summarizes the corrected measured \( \eta^* \) values for the diffusion sample set.

![Figure 5](image-url)  
**Figure 5.** Complex viscosity of asphalt mix samples measured at three different conditioning temperatures

The measured \( \eta^* \) data were corrected for the influence of evaporation and oxidation of each mix at the conditioning temperatures. Measured \( \eta^* \) data were fitted to integrated Fick’s Law in Equation 3. The applied diffusion coefficients were from those presented in Figure 2. The best fit to Equation 3 was achieved when the average diffusion distance was set at 800 \( \mu \text{m} \).
Since the binders utilized in the examined mixes were those studied in Section 3.1, the diffusion coefficient between RAP and PG 58-28 binders at 90, 120 and 150°C were calculated from established correlations in 3.1. Similar to a binder diffusion phenomenon, it was observed that $\eta^*$ of a RAP-containing asphalt mix also evolved faster towards that of the ideal blend at higher temperatures. However, challenges were noted in fitting the measured $\eta^*$ of asphalt mix to Equation 3, compared to fitting binders’ viscosity described in Section 3.1. Heterogeneity in an asphalt mix due to aggregate gradation, air voids, distribution of binders across the sample (voids filled with asphalt), necessitated more flexibility in the range of fitted parameters such as binder fraction ($\alpha$) and average diffusion distance ($L$). The best fit of measured mix $\eta^*$ was achieved when average diffusion distance was set to 800μm (in contrast to 100μm mentioned in Section 3.1). This observation is consistent with a recent study that has measured a relatively wide range for binder thickness in an asphalt mix [38].

Simulations of HMA, conducted on binders in Section 3.1 (presented in Figure 4), were then repeated with 800 μm average diffusion distance. Results indicated that binder blending achieved about 70% of an ideal blend by the time of mix placement on the road. However, diffusion does not stop after pavement cools down to ambient temperature; instead, it will continue to progress with a much slower pace during the course of service life of the pavement. Therefore, the placed mix might experience inhomogeneous distribution of RAP and virgin binders and can become susceptible to local stress accumulation due to variability in stiffness. That potentially exposes the pavement to rutting in places with higher portions of virgin (softer) binder while other areas might be susceptible to fatigue cracking due to higher portions of RAP binder. A second round of simulation with adding silo storage, however, indicated that keeping asphalt mix at typical asphalt silo storage temperature can significantly help diffusion to approach completion. Simulated data suggested that 12 hours of silo storage for HMA at 150°C helped the final complex viscosity to achieve 95% of an ideal blend. This observation can also be noted in Figure 5 for evolution of $\eta^*$ where ideal blend viscosity was achieved around 12 hours at 150°C. Therefore, this study not only confirmed applicability of diffusion model to asphalt mix and impacts of higher temperature on facilitating progress of diffusion, but also provided an estimated timeframe required for achieving better blended binders in the type of examined asphalt mix, i.e. approximately 12 hours.

3.3. Impact of diffusion on plant-produced RAP-containing asphalt mix
Investigating blending and diffusion in plant-produced material has been a challenging task due to numerous parameters that can impact the properties of final material. As mentioned earlier, plant design and operation as well as thermal history of manufactured samples are among these parameters [4, 5, 13-15].

In both Sections 3.1 and 3.2 the applicability of diffusion model was demonstrated to asphalt binders and mixes. It was also demonstrated that higher temperatures and longer contact time help diffusion of virgin and RAP binder to further progress toward completion (see Figures 3 to 5). It was predicted through simulations that silo storage can have significant impact on progress of diffusion since the manufactured mix is kept at higher temperatures for an extended period of time. Silo storage can potentially be a stage where diffusion between virgin and RAP binders can be promoted. Given the gradual nature of diffusion, it is expected that changes in manufactured asphalt mix properties and performance should be observed over the course of silo storage, as blending between binder approaches completion. It should be noted that since no mechanical mixing occurs in a silo, changes in rheological and performance properties of the asphalt mix could mainly be attributed to the net competing impacts of diffusion, evaporation, oxidation and absorption.

Two asphalt plants (Plants 1 and 2) were asked to manufacture surface (HL-3) and base (HL-8) mix courses according to pavement specifications in the province of Ontario in Canada. These materials spanned a RAP content range from 15% up to 40%. The virgin binders included PG 52-34 and PG 58-28 for base and surface courses, respectively. Samples were collected at 0, 1, 4, 8, 12 and (when possible) 24 hours of silo storage. Mix samples were analysed for volumetric properties, dynamic modulus ($|E^*|$), rutting depths and moisture damage, as well as fatigue cracking performance. Thermal history of
samples were tightly controlled to ensure all samples are treated equally, and diffusion progress was mainly limited to silo storage duration.

An example of dynamic moduli data is presented in Figure 6 for the surface mix sample manufactured at Plant 2. It is observed that $|E^*|$ decreases over 12 hours of storage particularly at lower reduced frequencies, corresponding to higher temperatures. This is a counter-intuitive observation since it has been historically observed that silo storage usually results in an increase in mix stiffness [39-44]. This observation points to the fact that diffusion is the dominant process among all other concurrently occurring phenomena such as absorption, evaporation and oxidation up to about 12 hours. The master curve in Figure 6 at 24 hours, however, exhibited an increase in $|E^*|$ values, resembling the historical trends. This behaviour points to the fact that aging processes start to dominate after 12 hours of storage. Measured mix volumetric data also pointed to a dynamic nature of the RAP-containing mix. At a constant air void content, voids in mineral aggregates (VMA) and voids filled with asphalt (VFA) evolved over duration of silo storage. While VMA decreased over time, VFA had an increasing trend. Both properties started to plateau after 12 hours of storage. The direction of changes in VMA and VFA are indicative of diffusion.

![Figure 6. Master curve for absolute value of dynamic modulus ($|E^*|$) for surface asphalt mix from Plant 2](image)

Modulus exhibits a decrease up to 12 hours of silo storage, particularly at lower frequencies, corresponding to higher temperatures. After 12 hours, modulus starts to increase indicating dominance of aging processes during silo storage. At zero hours of storage, RAP binder is still stiff enough that its contribution to the mix is mainly as a filler. As storage time increases, stiff aged binder of RAP gets less viscous and interacts more easily with virgin binder, i.e. they diffuse into each other further. Therefore, more of RAP binder becomes available and binder content of the asphalt mix increases. Thus, part of the previously occupied space with fillers (stiff RAP) become part of the volume occupied by binder, i.e. VFA increases. These observations are in line with similar trends noted on impact of mixing temperature on improved compactability and evolution of volumetric properties of RAP-containing mixes [10,11].

Changes in mix performance parameters such as rutting depths, moisture susceptibility based on stripping inflection point (SIP) and fatigue cracking resistance with silo storage time also confirmed progress of diffusion. Figures 7 to 9 summarize rutting and fatigue cracking performance of the four mix samples as a function of silo storage duration, collected from the two plants. Plant 1 data on rutting depths for both the surface and the base courses suggest a decreasing trend within the errors of the Hamburg Wheel Tracking test. Rutting depths from Plant 2, on the other hand, demonstrate a clear decrease as a function of silo storage duration. It should be noted that the decrease in rutting depths in
Plant 2 data are due to diffusion progress up to 12 hours, as $|E^*|$ data clearly indicated dominance of diffusion process (see Figure 6). Figure 8 presents impact of diffusion progress on stripping inflection point (SIP) of asphalt mixes (this data set is limited to Plant 2 only). Data suggests that with further progress of diffusion between RAP and virgin binders, better adhesion of the binder blend to the aggregates is achieved. Fatigue cracking data, on the other hand, present an apparently different behaviour between the samples of the two plants. While both surface and base courses of Plant 2 reach an almost a plateau after 8 hours of storage, Plant 1 samples exhibit a continuous evolution in fatigue resistance properties during silo storage. Figure 9 suggests that while diffusion is still in progress between RAP and virgin binders in Plant 1 samples, it has achieved a completed stage in Plant 2 mixes after about 8 hours of storage. As mentioned earlier, parameters such as mixing temperatures, silo temperature, operation of silo (stagnant vs continuous discharge) could have been contributing factors to the behaviour observed in Plant 1 fatigue performance.

![Figure 7: Rutting performance of asphalt mixes as a function of silo storage time](image)

**Figure 7.** Rutting performance of asphalt mixes as a function of silo storage time

![Figure 8: Moisture susceptibility of asphalt mixtures collected from Plant 2](image)

**Figure 8:** Moisture susceptibility of asphalt mixtures collected from Plant 2
Susceptibility was estimated based on stripping inflection point (SIP) from measuring rutting depths. RAP content of these mixtures was 20% and 40% for the surface (HL3) and base (HL8) courses, respectively.

![Figure 9: Fatigue performance of the RAP-containing asphalt mixes as a function of silo storage time](image)

4. Concluding remarks
Managing the stiffness of the incorporated RAP, achieving proper cohesion within the binder blend and having proper adhesion to aggregates is important to optimize the quality and performance of a RAP-containing mix. After establishing surface contact between aged binder of RAP and new virgin binder through mechanical mixing, diffusion process is the dominant phenomenon driving the blending between the binders.

Studies carried out by Imperial Oil and ExxonMobil Technology Centres demonstrate that diffusion between RAP and virgin binder follows Arrhenius behaviour; therefore, temperature has a significant impact on progress of diffusion between the aged and virgin binder layers. Higher temperatures and longer contact time facilitate progress of diffusion toward completion. Proper control and tracking of thermal history of manufactured mix can significantly help maximizing the progress of diffusion, while minimizing the influence of evaporation, oxidation and absorption. A proper understanding of diffusion distance distribution, thus the required incubation time for optimal blending, in the final asphalt mix and providing enough driving force to facilitate the diffusion progress are key to optimize the quality of blending between virgin and aged RAP binders. At typical manufacturing temperatures, simulations suggested that only a 20% blending might be achieved right after manufacturing stage if the average diffusion distance is about 100μm.

Tracking evolution of complex viscosity in laboratory-produced mix samples suggested that average diffusion distance might be about 800 μm in an asphalt mix. Such average diffusion distance in asphalt mix samples suggested that approximately 12 hours is needed for diffusion to achieve its final state, i.e. full blending between RAP and virgin binders at an average manufacturing temperature of 150°C.

In both binder and laboratory-produced mix studies, the role of silo storage was emphasized as a platform to promote progress of diffusion. Simulations had indicated that silo storage can help achieving
up to 100% of ideal blend viscosity if enough time and driving force, i.e. temperature, is provided. This hypothesis was verified through a plant trial on surface and base asphalt mix samples. Mix samples containing up to 40% RAP were stored in asphalt plant silos and material were examined at different storage times. Dynamic modulus results indicated that diffusion is the dominant process up to 12 hours of storage, after which aging processes take over. This duration is consistent with the performed predictive simulations on laboratory-manufactured asphalt mixes. Progress of diffusion also had noticeable manifestation on reduction of rutting depths, improved resistance to moisture damage and fatigue cracking of the examined mix samples.

The overview of the diffusion studies spanning from laboratory-scale binders blending up to the field verification of asphalt mix samples indicates that RAP-containing asphalt mixes are dynamic systems. Evolution of diffusion between RAP and virgin binders can have significant impact on the binder contribution from RAP and volumetric properties of the mix. This dynamic nature poses a challenge to mix designers, i.e. RAP-containing mixes may not possess the expected properties right after manufacturing stage. It is also possible that unexpected changes occur in mix properties as diffusion between RAP and virgin binders progresses over the service life of a mix. On the other hand, the performance results from the conducted plant trial indicate that progress of diffusion can provide opportunities to optimize performance behaviours of an asphalt mix. Selection of Binder grade and binder content to design a rutting-resistant or a fatigue-resistant mix are directionally opposite to each other. However, utilizing RAP coupled with a maximized progress of diffusion between aged and virgin binders can help optimizing for both rutting resistance and fatigue cracking resistance at the same time.

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