

Heating and its Effect on Hot In-Place Recycling of Asphalt Pavements with Rejuvenator

Rajib B. Mallick¹⁺, Bao-Liang Chen¹, Jo Sias Daniel², and Prithvi S. Kandhal³

Abstract: The effects of artificial heating on the temperature and rejuvenation of aged asphalt during hot in-place recycling of asphalt pavements have been investigated through finite element modeling and experimental study. The major conclusions are: the temperature rise that results from heating dissipates very quickly along the depth of the pavement (1.6°C to 2.8°C per mm), a very high surface temperature does not ensure a desirable temperature of plus 100°C below the surface, and a more uniform temperature profile (along the depth) is achieved by using hot air, compared to radiation only; for the radiation levels that are desirable with respect to maximum surface temperatures of 180°C, and for conventional heating time periods, an effective increase in temperature in the pavement to plus 100°C can only be possible within the first 30 to 50 mm of the surface; the extent of rejuvenation depends on the temperature, the time of mixing, as well as the viscosity of the rejuvenator; there exists a gradient of rejuvenation across the thickness of the film of the Reclaimed Asphalt Pavement (RAP) asphalt binder. For example, for a mixing time of 90s, for a rejuvenator with a viscosity of 1/4th the viscosity of RAP binder, the extent of rejuvenation ranges from a maximum of 35 percent at the surface of the RAP binder to zero percent at 1 micrometer, for mixing at 60°C; 70 percent at the surface to zero percent at 8 micrometer, for mixing at 150°C. The percentage of rejuvenation is higher for a longer mixing time and a rejuvenator with lower viscosity. The selection of the appropriate recycling agent or rejuvenator, and for hot recycling should be made on the basis of consideration of temperature and time of mixing.

Key words: Asphalt; Hot-in-place; Recycling; Rejuvenation; Temperature.

Introduction

The temperature sensitivity of asphalt binder is utilized by its heating prior to mixing and compaction of Hot Mix Asphalt, HMA. While the heating is conducted on the individual component of the mix in a plant, heating of the mix is conducted in-place during hot in-place recycling, to facilitate recycling of the existing aged asphalt mix (or, reclaimed asphalt pavement RAP material).

Pavement temperatures fluctuate with a change in air temperatures, and natural cycles of temperature change in different types of pavements have been well researched. Such changes take place over a relatively long span of time during the course of a day and night and, and at any location, differ with a change in seasons. Artificial heating, which is conducted with one or more heaters, just prior to construction operations, is however, of relatively very short term, and hence the effect if also relatively short lived. Nevertheless, such artificial heating requires a significant amount of energy, and extra equipment and manpower.

The purpose of heating (from this point onwards the term “artificial” is dropped for the sake of brevity) for the two specific cases where it is used is different in some respect but similar in others. For both joint compaction and recycling, the raised

temperature of the mix should help in compaction and hence achieve adequate density. For recycling, however, there is one more requirement – the temperature should be high enough to facilitate the “mixing” of old and new asphalt binder such that the old asphalt binder is “rejuvenated” (and hence the term rejuvenator for recycling agents), and the quality of the existing pavement is improved significantly.

Objective

The objective of the study presented in this paper was to investigate the heating of asphalt pavements and its effect on obtaining an effectively recycled (properly blended/rejuvenated) asphalt mix.

Many researchers have looked at the concepts of heating (mostly experimental studies, [1-8]), as well as recycling – there is no dearth of data on these topics. This paper links the two concepts of heating and recycling in a thread, and answers the following questions:

1. What kind of temperature rise do we expect in the pavement?
2. How do the layers at different depth respond to the heating?
3. How much benefit is derived from such heating?
4. What can we say about the end product of construction that utilizes heating?

Scope

This study was conducted with the help of finite element (FE) modeling, analysis and simulation. FE Multiphysics modeling was conducted using heat transfer/chemical engineering modules of COMSOL software. The modeling was conducted for two mechanisms – heating with different procedures, and diffusion at different temperatures. The results were validated with an experimental study.

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Governing Equations

The modeling of the heat transfer through the pavement consisted of consideration of subdomains and boundary conditions as follows.

Sub-domain condition (asphalt pavement)

$$\rho_p C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k_p \nabla T) = Q + q_s T \quad (1)$$

where ρ_p is density of asphalt pavement, C_p is specific heat of asphalt pavement, T is temperature of pavement, t is time, ∇ is gradient, k_p is thermal conductivity of asphalt, ∇T is temperature gradient, Q is heat source, and q_s is production/absorption coefficient.

Sub-domain condition (Air layer)

$$\rho_a C_a \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q + q_s T - \rho_a \cdot C_a \cdot u \cdot \nabla T \quad (2)$$

where ρ_a is density of air, C_p is specific heat of air, T is temperature, t is time, ∇ is gradient, k_a is thermal conductivity air, u is velocity of air, ∇T is temperature gradient, Q is heat source, and q_s is production/absorption coefficient..

Boundary condition

$$(-k_p \nabla T) = q_0 + h(T_{inf} - T) + \varepsilon \sigma (T_{amb}^4 - T^4) \quad (3)$$

where k_p is thermal conductivity of asphalt pavement, ∇T is temperature gradient, q_0 is heat flux, h is heat transfer coefficient, T_{inf} is external temperature, ε is emissivity of asphalt pavement, σ is Stefan Boltzmann constant, T_{amb} is ambient temperature, and T is temperature.

Heat transfer coefficient h_{ave} was calculated as follows:

$$h_{ave} = \left(\frac{k}{L}\right) \frac{0.928 Pr^{0.33} Re^{0.5}}{\left(1 + \left(\frac{0.0207}{Pr}\right)^{0.67}\right)^{0.25}}$$

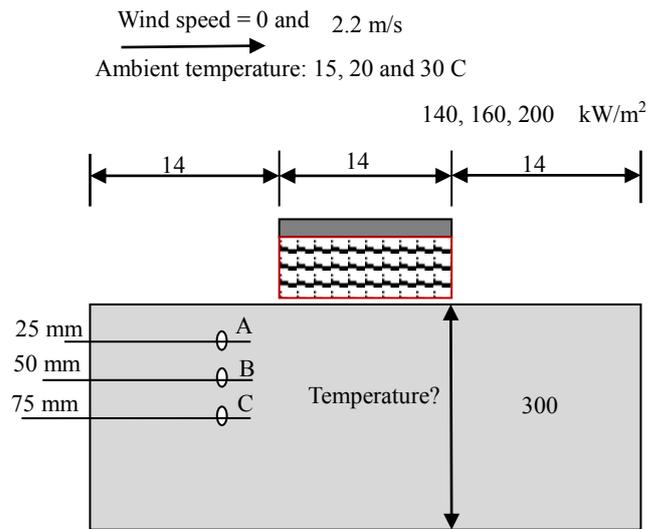
$$Pr = 2.8649 - 1.3494 \log T + 0.1949 (\log T)^2$$

where k is the thermal conductivity of air, L is the characteristic length, Pr is the Prandtl number, and Re is the Reynolds number

Fig. 1. Governing Equations.

Heating

The objective of this part of the study was to model and simulate the action of pavement heaters, and thereby evaluate the effects of the important parameters (temperature and time of heating) on the temperature of the heated pavement. Variations of heating patterns were simulated to determine the better options. Two types of currently used pavement heaters were considered: constant heat source (infrared heaters) and heat source with hot air. For both cases, the information on temperature and speed of equipment were obtained from specific equipment manufacturers. Simulations were conducted for the heating periods of time and the resulting temperatures in the different layers of the pavement, up to a depth of 100 mm were determined. The governing equations are shown in Fig. 1 (note that the equations are put all in one place, sequentially, in a figure, rather than in the main text to avoid clutter), and the two



Constant Heat Source Model

1. Model geometry: a 2-dimensional model geometry (rectangular block) was created.
2. Sub-domain condition: HMA thermal properties, density, and initial temperature were used for the analysis.
3. Boundary condition: all boundary layers were assumed to be thermally insulated except the contact surface area which received the inward radiation energy from the heater. The surface to ambient condition was used for the contact surface area, and environmental parameters used in the analysis were the heat transfer coefficient, ambient temperature, external temperature (assumed same as ambient temperature), and surface emissivity of HMA ($\varepsilon = 0.9$).

The analysis assumed that the heat was in direct contact with the HMA surface initially (time = 0), and that instant heating of HMA was occurring due to a high amount of radiation energy. (This assumption produced slightly higher than ambient temperature at the surface at zero time)

Solve: transient analysis was used for solving the model with 5 second intervals.

Fig. 2. Heating Mechanism: Constant Heat Source.

different types of heating mechanisms and their corresponding models are shown in Fig. 2 [8-10].

Parameters Used in FEM Analysis

The properties that were used in the analysis were obtained from literature [11, 12], since no construction data was actually available. Note that density and physical properties such as modulus have been shown to have no significant effect on heat transfer properties of HMA [13]. This fact also makes the results of this study applicable to a wide range of HMA.

Properties of asphalt pavement: Density, $\rho = 2,350 \text{ kg/m}^3$, Thermal conductivity, $k = 1.8 \text{ W/m}\cdot\text{K}$, Specific heat capacity, $c = 1,100 \text{ J/kg}\cdot\text{K}$, Emissivity, $\varepsilon = 0.9$.

Properties of air: Natural convective heat transfer coefficient, $h_c = 0 \text{ to } 10 \text{ W/m}^2\cdot\text{K}$, Density, $\rho = 1.18 \text{ kg/m}^3$, Thermal conductivity, $k = 0.026 \text{ W/m}\cdot\text{K}$, Specific heat capacity, $c = 1,006 \text{ J/kg}\cdot\text{K}$, Stefan-Boltzmann constant, $\sigma = 5.68 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4$

Heating Time

The heating time was determined from data received from the equipment manufacturers as follows. For the constant heat source, data from [8] indicates a total infrared heater length of 14 m traveling at a speed of 0.1143 m/s, which results in an exposure time of approximately 122 seconds. To observe the heating during the passing of the heater and afterwards, the simulation was carried out for a total of 384 seconds, 122 seconds with heat and 262 seconds without heat. Note that the paver/recycler is approximately 23 m behind the heater, and traveling at the same speed as the heater, it takes about 200 s to reach a specific spot of the heated pavement. Therefore, the amount of time it takes for the paver/recycler to reach a location after the start of heating is $(128 + 200) = 328$ s.

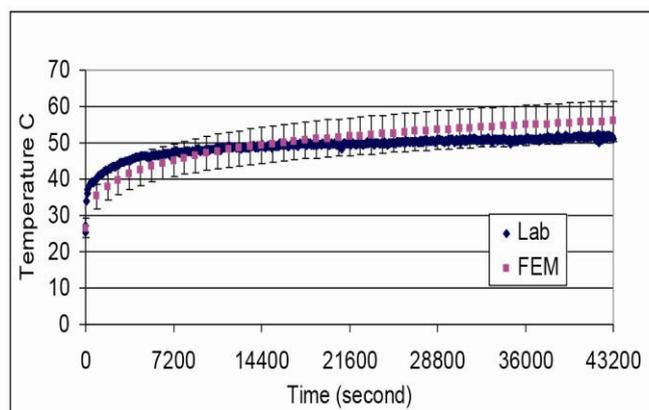
For hot air type heating, the following data was utilized [9, 10]: Typical speed of equipment during recycling: 3-5 m per minute depending on the local conditions such as traffic, mix availability etc; height of the heater from the road surface: 10 cm; temperature of the heater: 550-600°C (target surface temperature of 140°C); combined length of the two preheating units: 35 m; approximate temperature of the road surface after the 2 preheaters have passed over it: 180°C and temperature at 40 mm below the surface is 90-100°C.

Using an average speed of 4 m per minute for the 35-m long preheater(s) results in an average exposure time of $35/4 = 8.75$ minutes. The simulation and analysis for the hot air type of heaters is conducted up to 20 minutes, with 8.75 minutes of heating and remaining time without any heating. This timing was selected to consider a total time period of heating plus double the heating time period, to observe the change in temperature at the end of the heating period.

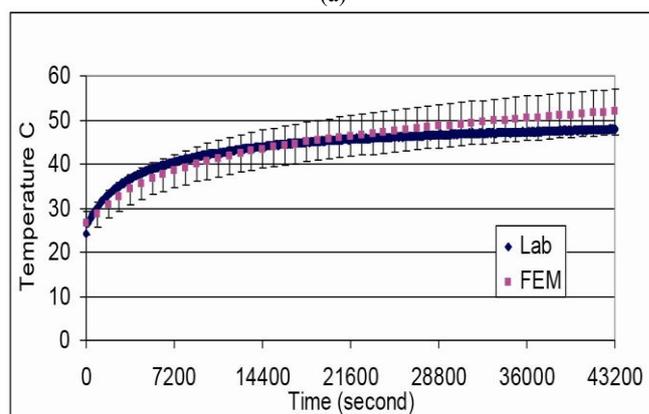
Validation of Finite Element Model

In general, it is desirable to validate the FE models by comparing the simulation results with those from field measurements. In this case, that would mean validating the FE model results with field data from an artificial heating construction (either longitudinal joint or hot in-place recycling) project. These data should include radiation, temperature at different layers, ambient temperature and wind speed. Unfortunately, such complete data were not available to the authors at this time, and hence, in this case, the FE model was validated with the use of closely controlled laboratory experiment.

In the laboratory the heating of a HMA sample was accomplished with a halogen lamp (100 W) positioned 1.1 m above the sample. The incident radiation from the lamp at this level was found to be 500 W/m^2 , as measured with a pyranometer (Model: CMP-3). Samples were also tested with wind, using a fan held close to the sample. The position of the fan was adjusted to produce a wind speed of 4.4 m/s, as measured with an anemometer. The HMA was insulated on all sides except the top. Each sample was fitted with thermocouples at different depths (surface, 25 mm and 50 mm below the surface, and two at $1/3^{\text{rd}}$ and $2/3^{\text{rd}}$ depth of the underlying base layer). The experiment thus provided the critical values that were needed for the model (such as radiation, ambient temperature and wind speed). The temperature data obtained from the experiment were compared to the temperature predicted from the FE



(a)



(b)

Fig. 3. Comparison of Experimental and FE data. (a) Sample G: Surface Temperature; (b) Sample G: Temperature at a depth of 25 mm.

model. Details of the experiment and determination of absorption and emissivity are provided in Chen, et al. [12]. Fig. 3 shows that the results compare well (the predicted temperatures were within 10% of the experimental data). Note that these data are for “Sample G”, which consisted of the following: Wearing (9.5 Nominal Maximum Aggregate Size, NMA) and two base courses (12.5 and/or 19 mm); 9.5 mm NMA mix with 6 % PG 64-28 binder; 12.5 NMA mix with 5.9 % PG 64-28 binder; 19 mm NMA mix with 5.1 % PG 64-28 binder.

Simulation of Artificial Heating with FE Model

The finite element models were used to simulate the heating for different periods of time, and the resulting temperatures at a range of locations and times were determined. An approximate radiation of 90 kW/m^2 at the source (125 mm above the pavement) was suggested by the manufacturer [8]. Considering the radiation losses, as well as a higher value the radiations that were used for simulation are 10, 20, 30, 40, 50, 90 and 140 kW/m^2 . Simulations were carried out for three ambient temperatures, 15°C, 20°C and 30°C, for a wind speed of 0 and 2.25 m/s. Note that the radiation calculated at the source is different from the “incident” radiation that is active on the surface of the pavement. The boundary conditions and assumptions used in the finite element model are as follows:

The boundary conditions in the constant heat source model

The asphalt binder and aggregate were assumed to be one entity with one overall thermal property in large-scale simulation. Only topside of the asphalt pavement was exposed to the radiative heat flux and other three sides were assumed to be thermally insulated. The constant heat flux from infrared heater was distributed uniformly on the surface of the asphalt pavement, and convective heat transfer due the presence of the air and ambient temperature was applied on the surface of the asphalt pavement. In the radiation model, the emissivity of the asphalt pavement was also taken into consideration- as the surface of the asphalt pavement emitting back-radiation to ambient.

The boundary conditions in the heat source with hot air model

The asphalt binder and aggregate were also assumed to be one entity with one overall thermal property in large-scale simulation. Only topside of the asphalt pavement was exposed to the air layer and the other three sides were assumed to be thermally insulated. The topside of the air layer was exposed to the constant temperature and the other two sides of the air layer were assumed with convective heat flux to allow for the air velocity (circulated air) in the enclosed chamber.

The constant temperature from hot air heater was uniformly applied on the top of the air layer and the constant air velocity was applied downward from hot air heater to the surface of the asphalt pavement. The interface between air layer and asphalt pavement was assumed as interior boundary condition to simplify the heat conduction from air layer to asphalt pavement.

Results of Heating Simulation

The following conclusions were made on the basis of the simulation study.

1. Peak surface temperatures (reached at the end of heating, 128 s) are significantly affected by level of radiation – and to a lesser extent by the ambient temperature. The effect of 2.25 m/s wind is lowering the temperature by about 10°C.
2. As expected, the temperatures drop off rapidly with depth, and heating results in an increase of about 5°C only near a depth of 50°C, irrespective of the level of radiation applied.
3. An incident radiation of 111 kW/m² is needed to achieve a surface temperature of 176°C.
4. For depth of 50 mm, it is obvious that the desirable temperature of 70°C is improbable, if not impossible, to achieve. In this respect, the observations from these simulations reinforce those that were made by Carmichael et al [14] regarding the dilemma between achieving very high (undesirable) surface temperature and desirable temperatures at deeper layers, versus achieving tolerable surface temperatures versus very low temperatures at deeper layers. Note that very low temperatures can lead to fracturing of aggregates during milling in the hot in-place recycling process.

Data from Modeling of Hot In-Place Recycling Equipment Pre-Heater, Using Hot Air

The modeling was conducted to match the conditions of the pre-heater. The temperature conditions were: 600°C source above 10

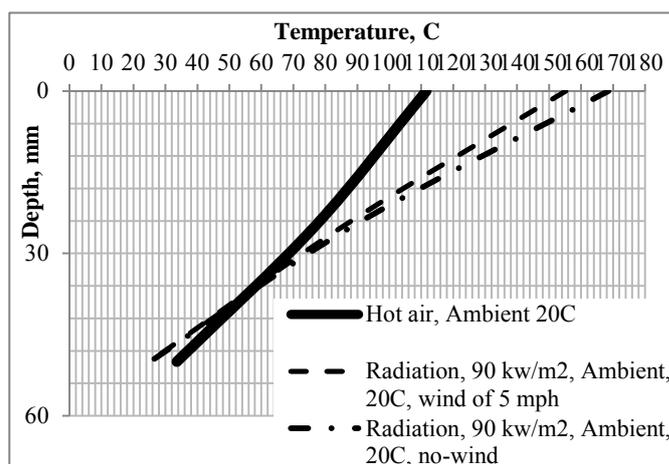


Fig. 4. Plot of Depth Versus Temperature for Two Systems of Heating – Both at the Time the Paver is Directly over the Heated Spot (328 s after Heating Started and 200 Seconds after Heating Stopped, for Radiation Heating, and 725 s after Heating Started and 200 Seconds after Heating Stopped, for Hot Air Heating).

cm of the pavement, and a 180°C temperature of the pavement after the preheater(s) passes over the pavement (8.75 minutes). These were utilized to estimate the velocity at which hot air is forced onto the pavement using FE simulation, and it was determined to be 0.03 m/s. Now, the temperature of the source and the velocity of air (as estimated) are part of standard setup and procedure that is carried out by only one company (Martec, [9, 10]) (to the authors’ knowledge). Hence, the simulations for predicting the temperature of pavements, using hot air flow, were restricted with those specific temperature and velocity of air conditions only.

As done for the radiation heating method, simulations were carried out for 15, 20 and 30°C ambient temperature. Note that in this mode of heating by hot air, the entire assembly is enclosed within a chamber, that minimizes the heat loss, and hence, there is no significant effect of wind (speed).

The following important points are noted from this simulation study:

1. The time of the maximum temperature at the surface coincides with the time of end of heating period, whereas the temperature at deeper layers continues to increase beyond the end of heating period.
2. Temperatures above 80°C are observed in depths of 20-30 mm, and at 50 mm depth the temperature ranges from 35°C to 45°C (for a range of ambient temperature of 15°C to 30°C).

Fig. 4 shows example plots of temperature versus depths for the two systems – radiation heating and hot air heating. The much steeper slope in the case of radiation heating indicates that with the hot air system, a more effective or a more uniform heating (as far as depth is concerned) is being achieved. The drop in temperature versus depth ranges from 1.6°C to 2.8°C per mm.

Plots of depth versus temperature at different times, for radiation heating, are shown in Fig. 5. The surface temperature reaches a peak, and starts dropping as the heating is stopped. The rest of the depth versus temperature profile starts becoming more and more uniform, and it would be desirable to identify the time and the specific set of conditions, at which the profile is as uniform as possible, while

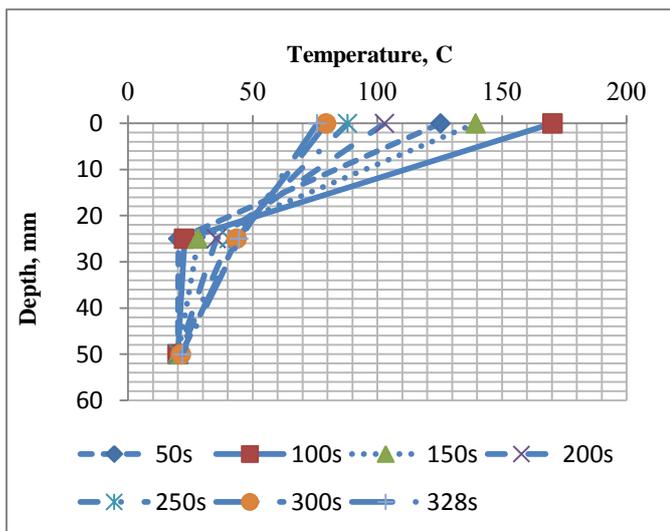


Fig. 5. Change in the Profile of Depth Versus Temperature (30 kw/m², Ambient Temperature, 20°C, no Wind) (Heating from 0-128 s, Paving at 328 s).

keeping the temperatures in their desirable range. This is because, a non uniform temperature profile means a non uniform stiffness profile, since HMA mix stiffness is very sensitive to temperature, and a non uniform stiffness profile will mean non uniform breakdown and mixing. In that sense, it seems that utilizing the hot air over a longer period of time is a better approach. However, the question of practicality, specifically regarding the extra time needed, if any, for such a method, must also be considered. Determination of the best method of heating (by considering economics also) is out of the scope of this study.

One important factor that must be kept in mind is the consequence of overheating the upper layers to reach a minimum temperature in the lower layers. The overheating will lead to aging of the binders in the upper layers. Generally a maximum temperature of 150°C is specified [15] as the maximum temperature of the scarified mix (after mixing with the rejuvenator and new mix, if used) (a minimum of 110°C is specified also) – no guidelines are available regarding the maximum temperature of the surface prior to milling or scarification. However, considering the fact that a surface temperature of 180°C has been used successfully without any indication of over heating/aging of the existing binder [9, 10], it is advisable to keep the surface temperature below 180°C.

Given the relatively low temperature at deeper layers and the non-uniformity of the depth versus temperature profile, what is the implication on the effectiveness of recycling? The next section attempts to answer this question.

Effect of Heating on Recycling/rejuvenation

Heating of the pavement during hot-in place recycling is conducted to help the recycling process. There are two important processes that dictate the HIR process – dispersion and diffusion. Dispersion is the phenomenon of distribution of the rejuvenator on the RAP and the virgin aggregates, while diffusion is the phenomenon of the intermingling of the rejuvenator with the RAP binder. The simulation study reported in this paper concerns the diffusion

process only. The diffusion process has been modeled using Stoke-Einstein's equation and Fick's Law (as indicated below), on the basis of the fact that their applicability have been proven by several researchers in the past (for example, [16, 17]).

Stoke-Einstein Equation

$$D = \frac{K_B T}{6\pi\mu(R)} \quad (4)$$

$K_B T$ is the internal heat energy, K_B is Boltzmann's constant (1.3807×10^{-23} J/K), T is absolute temperature (K). D is rate of diffusion (m²/s), R is the mean molecular radius, μ is dynamic viscosity (Pa·s).

Fick's Law

$$J = -D \frac{\partial C}{\partial x} \quad (5)$$

J is diffusion flux (mol/m²·s), D is diffusion coefficient, C is concentration (mol/m³), and x is distance (m).

It is hypothesized that the diffusion of the rejuvenator changes the viscosity of the aged binder, and as the process continues, more and more of the aged binder is "rejuvenated" – which is reflected by the change (lowering) of viscosity, until equilibrium is attained.

Note that the mixing of two materials of different viscosities to produce a mix with a specific viscosity can be modeled by the following equation:

$$\ln \mu_{mix} = c_1 \cdot \ln \mu_1 + c_2 \cdot \ln \mu_2 + c_1 \cdot c_2 \cdot G_{12} \quad (6)$$

Index 1 and 2 denote two different liquids or binder and c_1 and c_2 denote volume, mass or molar fraction of liquid/binders 1 and 2. The parameter G_{12} considers the effect of the intermolecular interaction between different sets of binders.

The above process was modeled using Finite Element (FE) method. The following are the sequence (and justification thereof) of steps (with reference to Fig. 6). Note that Fig. 6 shows all the specific values that were used.

1. Run the diffusion process for t_1 seconds; readjust the viscosity of the layers, based on the concentration of the rejuvenator in the layers at t_1 , using Eq. (6) (mixing model); run the diffusion process for another t_1 seconds; repeat for the entire time that is allowed for mixing. The selection for the t_1 seconds was made on the basis of four things – 1) how fast the diffusion is occurring; 2) what is the smallest time that can be considered without having excessive computation time, 3) what is the largest time that can be accommodated considering the stability of the numerical method/model, and 4) a realistic time interval considering the total time.
2. The concentration of the rejuvenator and the viscosity of the resultant binder at the end of different time intervals throughout the thickness of the RAP binder were determined.

The formulation of the diffusion problem with respect to HMA recycling is explained in Fig. 6. The range of rejuvenator content, viscosity and concentrations are also shown. Table 1 [18] shows the

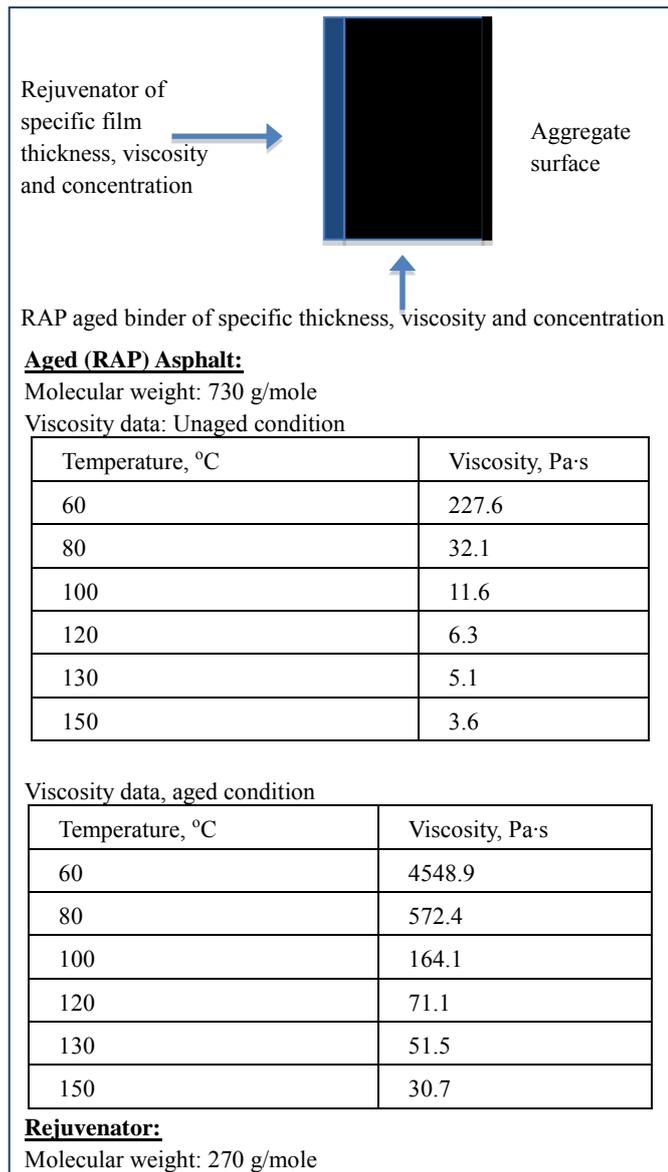


Fig. 6. Parameters Used in Formulation of the Rejuvenation Model; Note: Molecular Weights are Taken for an Asphalt and a Rejuvenator, as Mentioned in Reference [19].

Table 1. Viscosity of Binders (as Obtained from Literature, and Used for Extrapolation).

Asphalt	Temperature (°C)	Average Viscosity (Pa·s) of Original Binder
AC-30, Field Aging: 9 Years, MAAT: 62.6°F (ADOT-Kingman-1)	45	3,534
	65	191
	85	20

Source: Reference [18]

viscosity of the asphalt binders that were considered in the simulation part of this study.

Parameters Used for Modeling and Simulation

The steps in the process of selecting the specific parameters that are used for modeling are as follows.

1. *Viscosity of asphalt binder:* A log-log viscosity versus log temperature regression, with the data indicated in Table 1, was utilized to generate the viscosity of the asphalt binder at temperature ranging from 60°C to 150°C. This range was selected since it indicates a range that is commonly observed in the field, as evident from the heating simulation presented earlier and also from anecdotal field data. This data is indicated in Fig. 6. Note that a film thickness of 12 micrometer was assumed for the RAP aggregate/binder, to be on the higher side of film thickness that is recommended for dense graded mixes (9-10 micrometers, in terms of VMA [19- 21]).
2. *Viscosity of rejuvenator:* A range of viscosities were utilized for modeling although results for only two are presented in this paper – a rejuvenator that has a viscosity that is equal to ¼ of the viscosity of the RAP binder in its unaged state, and another with a viscosity that is equal to 1/1,000th of the of the viscosity of the RAP binder in its unaged state. The reason for selecting these two is that while the former represents a “bumped down” binder grade (commonly used for hot mix recycling), the latter represents more of a commonly used commercially available recycling agent or rejuvenator.
3. *Parameters for calculation of diffusion coefficient:* The molecular weight and radius were obtained from Karlsson [16], and the concentration was determined a shown in Fig. 6, considering the use of 1 percent rejuvenator. The percentage was based on commonly used percentage, and a mix design that is explained in the experimental study section. Since the simulation is conducted for the rejuvenation process in HIR, no virgin binder or aggregates is assumed to be added.
4. *Time and Temperature of diffusion:* Results of simulation with two times of diffusion are presented – 30 s and 90 s, to cover a range of expected time that will be available in the field. 90 s could also be taken as a time period (on the higher side) that is available in a hot mix recycling operation in a drum. For temperature, five temperatures were selected, on the basis of expected temperatures in the field, as mentioned earlier: 60, 80, 100, 120 and 150°C.

Discussion

There are many factors that affect the diffusion process, as is evident from Eq. (4). An example of simulation results is shown in Table 2. It can be seen that at any specific time, the concentration of the rejuvenator decreases and the viscosity increases along the thickness of the film, while for any specific section of the film, the concentration increases and the viscosity increases with an increase in the mixing time. Fig. 7 attempts to summarize the affecting factors, for two different types of rejuvenators – the upper part shows the results for a rejuvenator whose viscosity is ¼ the viscosity of the RAP asphalt binder in its unaged state and the lower part of the figure presents the results for a rejuvenator whose viscosity is 1/1,000th the viscosity of the RAP asphalt binder in its unaged state. The X axis represents distance along an assumed 12 micrometer thick asphalt binder “film”, while the Y axis shows the extent of rejuvenation as a percentage. The viscosity of the resultant recycled binder was compared to the viscosity of the RAP binder in its unaged state and RAP binder to determine the extent (%) by

Table 2. Example of Results of Simulation.

Conditions: Rejuvenator Viscosity = 1/100th of the Viscosity of the Original RAP Binder, 150 °C .

Thickness m, Along Film	Concentration (mol/m ³) of Rejuvenator in Mix			Thickness Along Film of RAP Binder	Viscosity, Pa·s		
	0 s	30 s	90 s		0 s	30 s	90 s
6 * 10 ⁻⁶	38.1	80	469.2	6 * 10 ⁻⁶	28.8	26.9	14.3
9 * 10 ⁻⁶	38.1	38.1	87	9 * 10 ⁻⁶	28.8	28.8	26.6
12 * 10 ⁻⁶	38.1	38.1	39.6	12 * 10 ⁻⁶	28.8	28.8	28.7

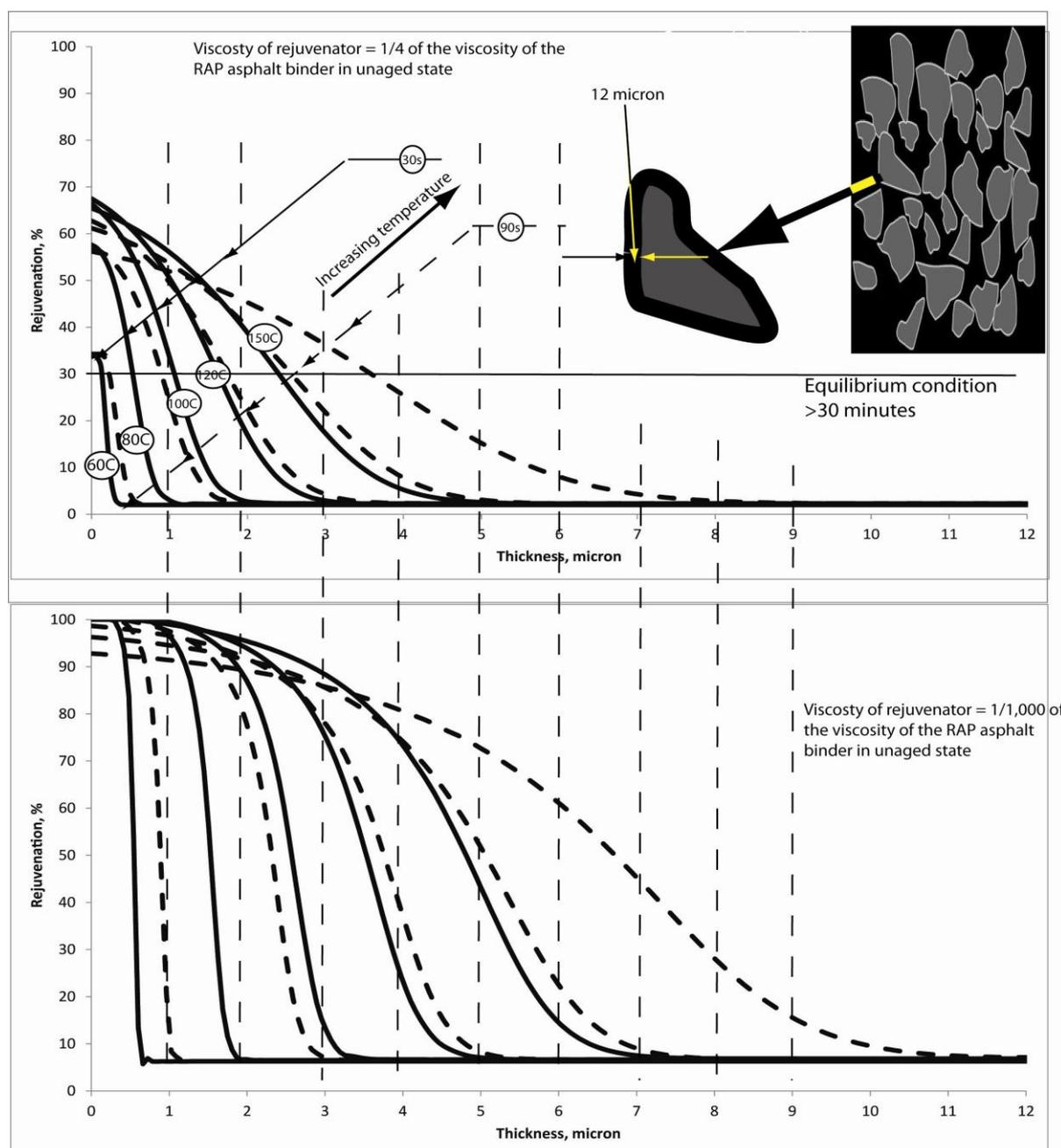


Fig. 7. Effect of Different Factors on Rejuvenation (from Results of Simulation); Figure Shows the Effects of Time, Temperature and Viscosity of Rejuvenator.

which the viscosity has been reduced as a result of diffusion. This reduction (expressed as a percentage) was then utilized as a measure of rejuvenation. For example, if the unaged viscosity is 3 Pa·s, the aged (RAP) viscosity is 30 Pa·s, 100% rejuvenation is for a change

in viscosity of $(300 - 3) = 297$ MPa. After rejuvenation, if the resultant viscosity is determined to be 90 Pa·s, then the extent of rejuvenation is expressed as $100 * (300 - 90) / (300 - 3) = 70\%$. Therefore, 100% rejuvenation indicates a lowering of viscosity from the aged

(RAP) binder state to that of unaged binder state. Data are shown for two time periods of mixing, 30s (solid curve) and 90s (dashed curve).

As expected, a higher temperature and time of mixing leads to a higher percentage of rejuvenation for any specific point along the thickness of the film; and for any specific temperature and time, the portion of film towards the part that is exposed to the rejuvenator has higher rejuvenation than the part that is away from it, or towards the aggregate surface. Obviously, there is a gradient in the extent of recycling along the thickness of the film, as discussed below.

If the curves for 150°C (with 90s mixing time) in the upper part of the figure can be taken as appropriate for hot mix recycling (as opposed to hot in-place recycling), it is evident that 40-60% rejuvenation takes place in the part that is within 3 micrometers of the aged RAP binder surface, 10-40% between 3-6 micrometers, 0-10% between 6 to 9 micrometers and virtually no rejuvenation beyond 9 micrometers. This means that about 3 micrometers of the RAP binder stays as part of the “rock”, as “black rock”. However, one can point out that since the mix is at a relatively high temperature until it is compacted rejuvenation can continue until that time. The long term effect is shown in by the straight line on the upper part of the curve (as indicated by “equilibrium condition>30minutes”). It indicates that beyond 30 minutes, the concentration of the rejuvenator (in this case, with a viscosity of ¼ the viscosity of the RAP binder in its unaged state) reaches an equilibrium condition at 30% rejuvenation, and no further rejuvenation is expected with an increase in temperature or time of mixing. However, the results do show that the entire thickness of the film is rejuvenated (to the same extent). This shows that theoretically, there exists a limit up to which the RAP binder can be rejuvenated.

Note that for the concentrations and thicknesses considered in this study, it is a coincidence that the >30 minutes (1800 seconds) equilibrium line matches with the approximately 30% rejuvenation mark on the vertical axis. The percentage at equilibrium depends on the thickness of rejuvenator film (concentration) and RAP layer; for example, when the concentration of the rejuvenator layer increases and that of the RAP layer remains at 12 micrometers, the percentage of rejuvenation at equilibrium will increase because more concentration of the rejuvenator is allowed to diffuse into RAP layer. On the other hand, when the concentration of the rejuvenator remains fixed with a layer thickness of 2 micrometers and the thickness of RAP layer decreases, the equilibrium line will shift upwards also because less volume of RAP layer is required for the rejuvenator to diffuse to reach the equilibrium condition.

Considering the curves in the lower part of the figure (with 30s mixing time) as appropriate for hot in-place recycling, it is evident that in the best case scenario (at 150°C, which is expected at the surface only, as presented earlier), only about half of the aged binder film gets rejuvenated. A higher mixing time would give a higher extent of rejuvenation. However, because of the significantly lower viscosity of this rejuvenator, it is observed that as much as 90-100% rejuvenation can be expected between 1-3 micrometers and > 50% rejuvenation is possible between 3-5 micrometers (at 150°C).

The above results from simulations match with the results of experimental studies that have been carried out in the past, of which a few are mentioned below. Noureldin and Wood (1987, [22])

carried out partial extraction technique on recycled mix to divide the asphalt film into micro layers and then tested the viscosity of each micro-film layer. They concluded that the outermost micro-layer was softer (due to rejuvenation), the middle harder (unaffected by rejuvenation) and the innermost directly coating the aggregate surface was hard (closer to viscosity at the time of construction). Similar observations have been made earlier by Carpenter and Wolosick (1980, [23]) also. Huang et al (2005, [24]) conducted a study with staged extraction of rejuvenated RAP and concluded that part of the RAP binder is blended with the new asphalt (rejuvenator) and the remaining part forms a stiff coating around the aggregate particles. Note that in this respect it must be mentioned that Karlsson [16] had conducted a comprehensive study with FTIR-ATR (Fourier Transform Infrared Spectroscopy Attenuated Total Reflectance) method to investigate and validate the concept of diffusion of rejuvenator into aged asphalt.

In both cases (of rejuvenators), it is evident that the extents of rejuvenation for 60 and 80°C are very low – almost non-existent. Hence a low temperature in that range (< 100°C) is not at all effective in rejuvenation/recycling. This effectively means, only a part of the thickness of the pavement (that is heated) undergoes some sort of rejuvenation (and that too, at different extents regarding the thickness of the asphalt binder film), depending on its location along the depth. This fact is shown schematically in Fig. 8.

Perhaps the most interesting conclusion is that the process of rejuvenation is dependent on temperature to such an extent, that the process can be assumed to be happening only during mixing or the time for which the mix is at an elevated temperature. It is highly probable that once the mix comes down below a critical temperature, the rate of diffusion falls to such a low level, that virtually no more of the rejuvenator diffuses inside the RAP binder, and instead, it oxidizes off the surface of the mix. Therefore, although proposed by many researchers, the concept of long-term rejuvenation is highly suspect. Whatever “black rock” remains at the time when the temperature falls below mixing temperature, remains as “black rock” from that time on.

Another interesting conclusion is that, for the temperature and time that are expected in conventional recycling operations (for both HIR and Hot Mix Recycling) the use of a low viscosity rejuvenating agent is more effective than one with a higher viscosity, specifically “bumped down” grade asphalts. Note that “effective” means successful in lowering the viscosity of the aged binder. This has also been observed by Shen et al [25]. However, the choice is definitely dependent on the percentage of RAP (for Hot Mix Recycling) as well as the compatibility between the RAP asphalt and the rejuvenator, and the ability to disperse the rejuvenator.

Reaching Equilibrium through Diffusion

The concentration of 3,816 mol/m³ in the rejuvenator layer (2 µm) is diffused into the aged binder layer (12 µm). The diffusion process in both layers will reach an equilibrium condition so that the concentration in the rejuvenator layer will equal the concentration in the aged binder. The concentration at equilibrium condition is similar to $(3816 + 38.16) / (7) = 550.59 \text{ mol/m}^3$, 7 being the sum of the ratio components of the thickness of the rejuvenator layer (2µm) and the aged binder layer (12µm).

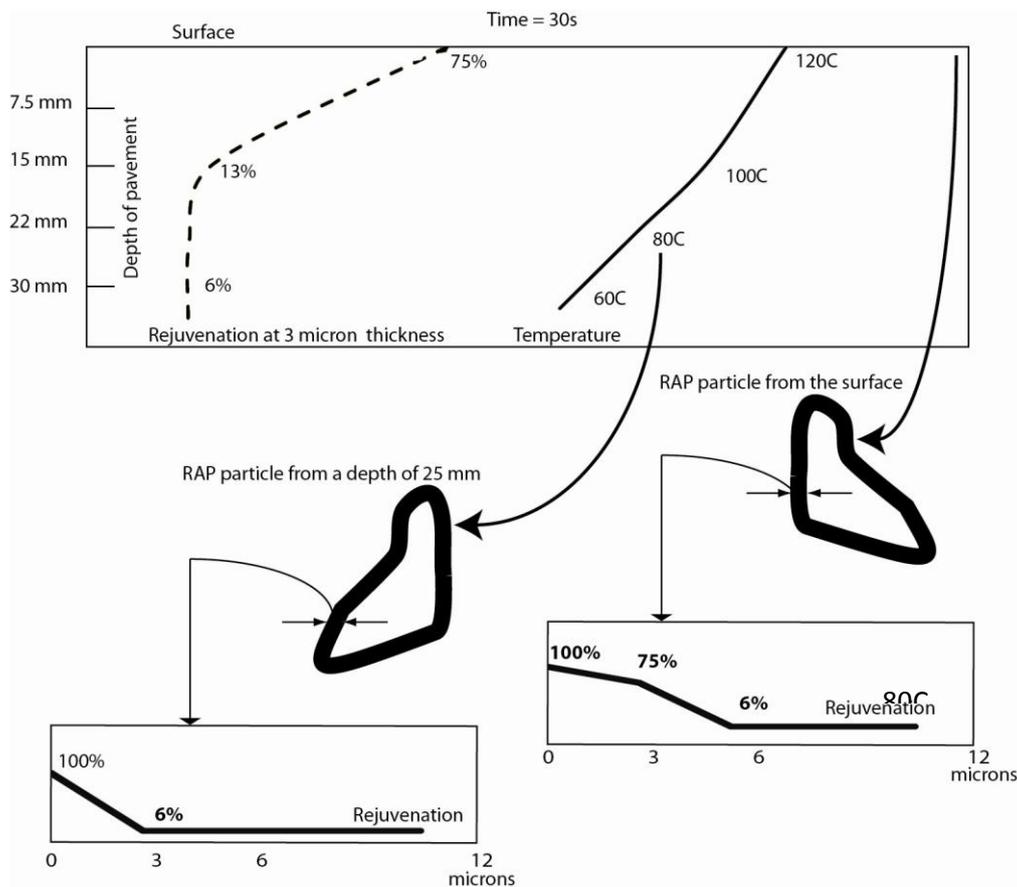


Fig.8. Schematic of Variation in Rejuvenation; Note: The Word “Micron” is Used here in Lieu of Micrometer.

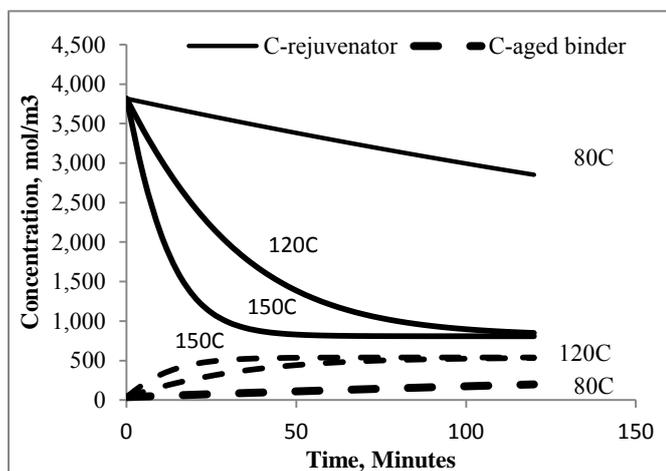


Fig. 9. Effect of Temperature on Time Required for Equilibrium Condition.

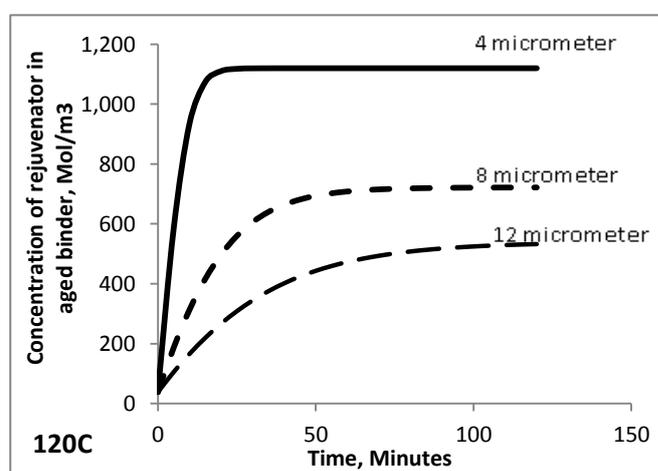
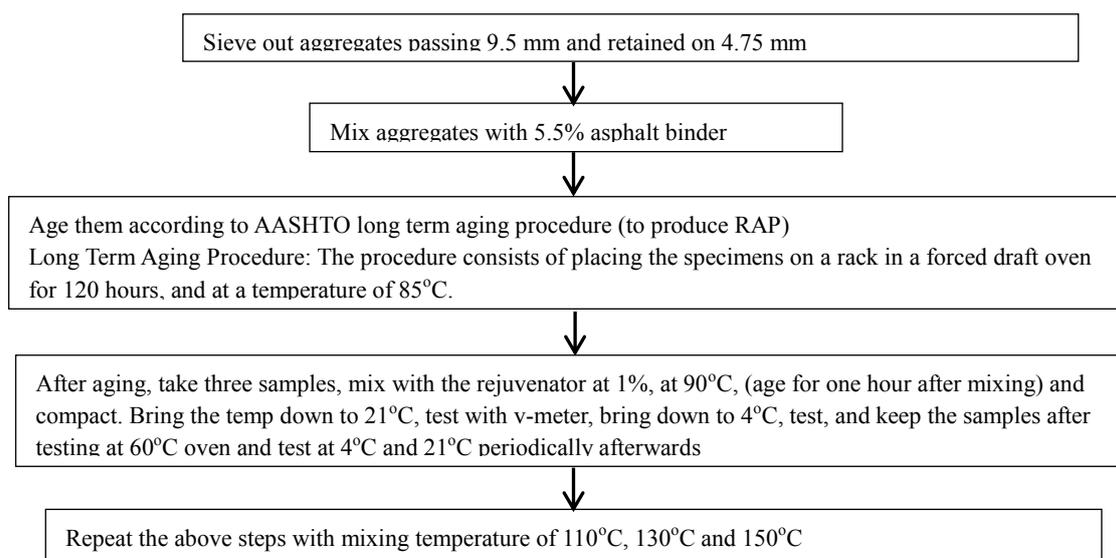


Fig. 10. Effect of Aged Binder Film Thickness on Time Required for Equilibrium Condition.

Note that the initial concentration (C_a) of the rejuvenator in the aged binder is considered as 1% of the concentration of the rejuvenator, 38.16 mol/m^3 . The analytical solution for predicting the equilibrium state was based on Fick’s second law (diffusion kinetics). The results of the solution are shown in Fig. 9. It is evident that the equilibrium condition is achieved faster for the higher temperature. Fig. 10 shows the effect of film thickness of the aged binder (for a temperature of 120°C) – the thinner the film, sooner is the equilibrium condition reached.

Experimental Study

In order to evaluate the effect of mixing temperature on the rejuvenation of RAP material, the following experimental study was conducted. Four mixes were prepared, artificially “aged” in the laboratory, and then “recycled” with a rejuvenator, at four different temperatures - 90, 110, 130 and 150°C . These recycled mix samples were then tested for their seismic modulus, using a Ultrasonic Pulse Velocity Device (V-meter) at regular intervals of time, while



Aggregate: bulk specific gravity: 2.653; absorption: 1.41%;

Binder: PG 64-28

Rejuvenator: Renoil 1736; 65.3% Alkyl Aromatic Oil and 27.7% Saturate Oil

Voids in Total Mix (VTM) of samples:

Sample No.	Bulk Specific Gravity	Theoretical Maximum Density (g/cm ³)	Voids in Total Mix (VTM) (%)
90C-1	2.198	2.448	10.2
90C-2	2.216		9.5
90C-3	2.102		14.1 (not considered)
110C-1	2.173		11.2
110C-2	2.234		8.7
110C-3	2.177		11.1
130C-1	2.217		9.4
130C-2	2.161		11.8
130C-3	2.217		9.4
150C-1	2.204		10.0
150C-2	2.162		11.7
150C-3	2.225		9.1

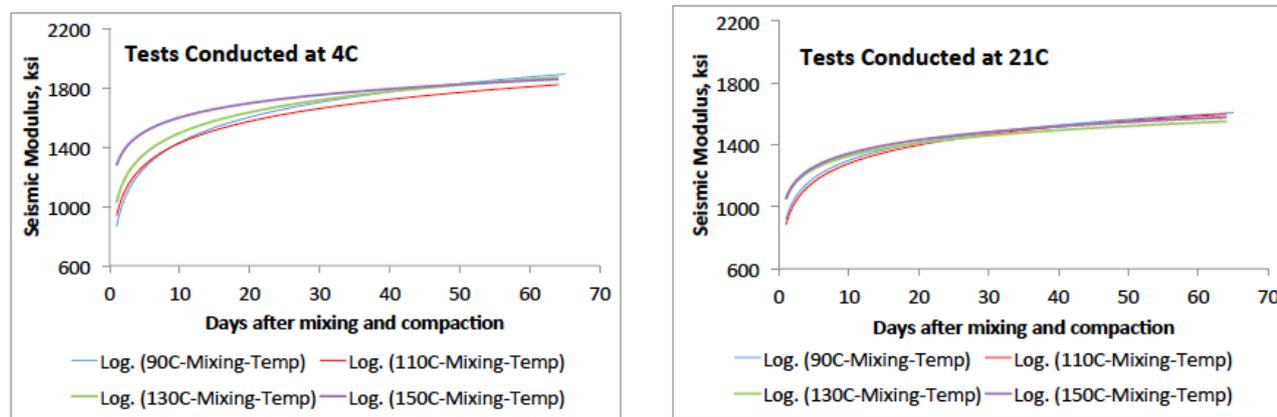
Fig. 11. Test Plan for Evaluation Study and Voids in Total Mix of Samples.

Table 3. Properties of Rejuvenator Renoil (1736, source: Renkert Oil) Properties.

Viscosity SUS @ 37.8°C (100 °F), 494	Pour Point °C (°F), -23 (-10)
Viscosity SUS @ 98.9°C, (210 °F), 51	Flash Point °C (°F), COC 216 (420) min.
Viscosity cSt @40°C, 92.2	Sulfur wt %, 4.3
Viscosity cSt @100°C, 7.4	Aniline Point °C (°F), 13 (55)
Specific Gravity@ 15.5°C (60°F), 0.966	Clay Gel Analysis:
	Asphaltenes %, 0; Polars %, 7; Aromatics %, 65; Saturates %, 28
Density lb/gallon @ 15.5°C (60°F), 8.04	Carbon Analysis:
	Aromatic %, 30; Naphthenic %, 15; Paraffinic %, 55; Refractive Index, 1.5218

maintaining the samples at 60°C in a forced draft oven. The test plan, along with the voids in the samples, is shown in Fig. 11. Three samples (except at 90°C) were used at each temperatures of recycling. The voids (VTM) of the compacted samples ranged from 8.7 to 11.8 percent. A rejuvenator with 65.3% aromatic oil and 27.7% saturate oil was utilized to rejuvenate the binder in the artificially aged samples. The properties of the rejuvenator are shown in Table 3. 1% rejuvenator was used on the basis of

manufacturer’s mix design guidelines as explained in [26]. The hypothesis for the experimental study was that a higher temperature would facilitate the rejuvenation process since the diffusion of recycling agent into the aged RAP asphalt depends significantly on the temperature. In order to consider a specific film thickness, only one size aggregates have been used to prepare the mixes. The V-meter was used to determine the seismic modulus at 4°C and 21°C.



Recycling Temperature, C	Average Seismic Modulus, ksi, at 4°C, on Day									
	1	8	15	22	29	36	43	50	57	65
90	925	1186	1651	1604.5	1669.5	1751	1758	1936.5	1888	1843.5
110	946	1313	1508	1673	1659	1685	1814	1820	1743	1740
130	1022	1397	1579	1797	1748	1712	1765	1756	1923	1800
150	1340	1453	1619	1723	1766	1815	1763	1817	1963	1803

Recycling Temperature, C	Average Seismic Modulus, ksi, at 21°C, on Day									
	1	8	15	22	29	36	43	50	57	65
90	944.5	1157	1422.5	1485	1446.5	1453	1609	1594.5	1667.5	1488.5
110	878	1213	1350	1446	1489	1497	1653	1562	1538	1491
130	1113	1182	1367	1452	1403	1443	1524	1680	1546	1498
150	1029	1320	1446	1462	1504	1499	1490	1605	1539	1522

Fig. 12. Plots of Time Versus Seismic Modulus and Average Moduli Value Ones Prepared at Higher Temperature Tend to Change Less - Indicating that Most of the Diffusion/Rejuvenation Has Taken Place During Mixing.

Results

The results are shown in Fig. 12. The data, specifically the ones at 4°C, tend to confirm the hypothesis. The values increase over time, but the ones prepared at higher temperature tend to change less - indicating that most of the diffusion/rejuvenation has taken place during mixing. The more prominent results at 4°C are expected since the mix stiffness is more sensitive to the binder stiffness at lower temperatures. The data show that the difference in increase in stiffness is less prominent between 90°C and 110°C than between 150°C and all of the lower temperatures. If the rejuvenation is not sufficiently completed, that means that the rejuvenator has not penetrated into the aged binder, and hence there will be a lubricated surface over the mix and this can lead to lower stiffness and instability problems under traffic. Fig. 12 shows that recycling at 150°C will ensure that a significant part of the achievable rejuvenation (> 70%) has taken place during mixing, and there is no extra time needed for the completion of the rejuvenation. Since waiting for opening of the roadway to traffic after the recycling process is not practical in most cases, this highlights the importance of using a sufficiently high temperature for recycling in order to achieve the bulk of the achievable rejuvenation within a relatively short period of time. To facilitate rejuvenation (or most of it) within the available time, it is advisable to spread the rejuvenator over the aged mix as soon as it is possible, even before the mixing process

during recycling. This will ensure sufficient time that is required for rejuvenation.

Conclusions

The high heat capacity and the low thermal conductivity of HMA make the artificial heating of HMA layers and hence its diffusion dependent rejuvenation process a challenging job. From a study of heating of pavements and diffusion of rejuvenator with finite element models and experimental study, the following conclusions can be made:

1. Incident radiation level, wind speed and ambient temperatures have significant effects on the heating of pavements, and hence they must be considered appropriately.
2. The temperature rise that results from heating dissipates very quickly along the depth of the pavement. A very high surface temperature does not ensure a significant temperature rise, say, 25 mm below the surface.
3. A temperature of 60°C, appropriate for compaction could be achieved up to a depth of approximately 30 mm, with a radiation level, that will not produce undesirably high temperature on the surface.
4. Insulation of the heating area helps to minimize the effect of wind, if any.

5. A more uniform temperature profile (along the depth) is achieved by using hot air, compared to radiation only.
6. It seems that for the radiation levels that are desirable with respect to surface temperatures, and for conventional heating time periods, an effective increase in temperature in the pavement can only be possible within the first 30 to 50 mm of the surface.
7. The extent of rejuvenation depends on the temperature, the time of mixing, as well as the viscosity of the rejuvenator.
8. For available temperatures and time of mixing, there exists a gradient of rejuvenation across the thickness of the film of the RAP asphalt binder – the closer the asphalt binder to the aggregate surface the less is the rejuvenation.
9. A temperature $>100^{\circ}\text{C}$ is needed for any meaningful/measurable rejuvenation.
10. An evaluation of temperature, time of mixing and depth of mix should be taken into account prior to the hot in-place recycling operation.
11. A selection of the appropriate recycling agent or rejuvenator, for both hot in-place and hot mix recycling should be made on the basis of consideration of temperature and time of mixing.

Assumptions

It is important to note some of the assumptions that have been made in this paper. First, although the concept of diffusion holds and Stoke-Einsten's equation is valid, there is most likely not "a" diffusion coefficient for the process. Secondly, it is the viscosity of the maltene phase of the asphalt that governs the diffusion rate (and not the viscosity of the asphalt) [27] and hence the reported rejuvenation percentages are probably on the conservative side. Thirdly, the effect of dispersion has been ignored in the study, and it is admitted that the process of mixing and dispersion add different dimensions to the concept of rejuvenation – it is not as simple as applying a layer of rejuvenator on the surface of a mix. Next, although the viscosities in unaged and aged state have been obtained from the literature ([18], based on actual testing), the specific parameters that are used for the diffusion coefficients are obtained from a different reference [16], and are obviously for different asphalt. Finally, there is much room for discussion on the concept of "film thickness" – some believe in it, and others do not! However, it is probably fair to say, that the concept of film thickness is probably utilized by all, in some way or the other for mix design and evaluation (such as for specifying a limiting voids in mineral aggregates, VMA). Any criticism of the paper on the basis of arguments against the above assumptions is acknowledged by the authors. However, the conclusions are offered as indicative in nature – their value being more in pointing out the effect of some controllable factors on the outcome. And while lack of data is not a good excuse, the authors also submit the fact that viscosities in unaged and aged (field aged RAP) conditions as well as parameters that are required for calculation of diffusion coefficients, such as molecular weight, for any specific asphalt, are not available to them at this time.

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