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# Back-Calculation of Binder Properties in Asphalt Mixture Containing Recycled Asphalt Materials

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**Abstract**

In this paper, the effect of adding Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) on low temperature properties of recycled asphalt mixtures is investigated through Bending Beam Rheometer (BBR) tests. A back calculation transformation, derived from analogical modeling of rheological behavior, and a micromechanical model are used to predict the asphalt binder creep stiffness from mixture experimental data. The, results are then compared with the experimentally determined BBR creep stiffness on extracted binders. Results indicate the addition of RAP and RAS significantly affects low temperature performance and the effects are related to mixing and blending processes.



*Kewywords:* Reclaimed Asphalt Pavement; Manufacturer Waste Scrap Shingles; Tear-off Scrap Shingles; Creep Stiffness; Back-calculation

## 1. Introduction

Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) are valuable materials commonly reused in asphalt mixtures due to economic and environmental benefits. Incorporating RAP in new asphalt pavements significantly reduces the usage of new materials, conserves natural resources and solves disposal problems [1] However, the aged binder contained in RAP may negatively influence the low temperature properties of the final asphalt mixtures and eventually the pavement durability. To address this important issue, the National Cooperative Highway Research Program (NCHRP) has funded several projects, such as NCHRP 9-12 [2] and NCHRP 9-46 [3].

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In the past, a number of studies were performed to investigate the effect of RAP on recycled asphalt mixtures [4], [5] with the conclusion that RAP content had a significant influence on mixture properties. More recent research efforts focused on forensic evaluation, design procedures and modeling [1]. Specifications were also developed with recommendations for selecting RAP content based on traffic level. For example, Minnesota Department of Transportation (MnDOT) Specification 2350/2360 [6] allows up to 40% (by weight) RAP based on traffic level and binder grade.

Roofing shingles represent another recyclable material available in large quantity [7]. The use of recycled asphalt shingles (RAS) in hot mix asphalt has seen increased acceptance from government agencies and construction contractors only in recent years. Two distinct categories of RAS are available in the roofing market: Tear-off Scrap Shingles (TOSS), from old roofs that have been exposed to solar radiation and high temperatures for extended periods of time, and Manufacturer Waste Scrap Shingles (MWSS). RAS contain a much harder asphalt binder compared to that used in pavement applications: at 25°C, the penetration values for asphalt binder in shingles ranges from 20 dmm to 70 dmm, while, traditional paving binders range from 50 dmm to 300 dmm [8]. The reuse of asphalt shingles in asphalt mixture poses significant challenges for pavement built in cold climates where a good material fracture resistance is required. This is particularly true for TOSS, which contain highly oxidized binders that are more prone to brittle failure. Unlike MWSS, only recently a provisional specification on the use of TOSS was released and limits the content to 5% (by weight) with the provision that at least 70% (by weight) of the required binder is new binder [9].

In one of the first comprehensive studies on the influence of RAS on HMA mixture properties, Newcomb et al. [8] found that when the use of MWSS is limited to 5% there is a limited impact on asphalt mixture performance. However, addition of TOSS resulted in an embrittlement or stiffening of the mixture that was not desirable for cracking resistance at low temperatures. Other authors [10] also proposed a 5% limit on the use of MWSS. McGraw et al. [11] investigated the combined use of RAP and RAS showing the negative effect of TOSS on mixture strength and binder's critical cracking temperature. In a recent study [12] on the use of fractionated recycled asphalt pavement (FRAP) and RAS, it was found that asphalt mixture properties can benefit of the fibers contained in RAS.

## 2. Research Approach and Objectives

In this research, the addition of RAP, MWSS and TOSS to asphalt mixtures used in pavement applications is investigated based on changes in mixtures and binders low temperature properties. Hirsch micromechanical model [13], [14] and Huet [15] analogical model [16] coupled with ENTPE transformation [17], [18] are used to investigate the effect of adding recycled material on both asphalt binder and asphalt mixture creep stiffness. Back-calculation of the asphalt binder creep stiffness is performed using mixture creep stiffness data obtained with the Bending Beam Rheometer (BBR) [19]. The goal is to determine if changes in mixture behavior are due to the addition of recycled material and more specifically to the blending of new and old binder. This is obtained by comparing the back-calculated binder creep stiffness with the corresponding extracted binder obtained from the same mixture, which represents a condition of full blending. This also provides an indication of the degree of blending between the virgin binder and the aged binder present in the added recycled materials, RAP or RAS.

## 3. Materials and Testing

Eight different asphalt mixtures (Table 1) prepared with a PG 58-28 binder were used in this study. Three types of virgin aggregates were blended to prepare the mixtures: pit-run-sand, quarried ¾ in. (19 mm) dolostone, and quarried dolostone manufactured sand. The recycled material consisted of different amounts of RAP, TOSS and MWSS. More details on these materials can be found elsewhere [11].

Table 1. Mix design for the eight mixtures investigated

| Mix | | Recycled Material | | | VMA | VFA |
|---|---|---|---|---|---|---|
| **ID** | **Description** | **RAP (% weight)** | **TOSS (% weight)** | **MWSS (% weight)** | | |
| 1 | PG 58-28 Control | 0 | 0 | 0 | 15.9 | 76.6 |
| 2 | 15% RAP | 15 | 0 | 0 | 15.2 | 72.9 |
| 3 | 25% RAP | 25 | 0 | 0 | 15.3 | 73.0 |
| 4 | 30% RAP | 30 | 0 | 0 | 15.0 | 45.4 |
| 5 | 15% RAP 5% MWSS | 15 | 0 | 5 | 15.6 | 75.0 |
| 6 | 15% RAP 5% TOSS | 15 | 5 | 0 | 15.9 | 77.2 |
| 7 | 25% RAP 5% TOSS | 25 | 5 | 0 | 15.4 | 73.9 |
| 8 | 25% RAP 5% MWSS | 25 | 0 | 5 | 14.8 | 72.5 |

Small beams of asphalt mixtures (three replicates per mixture) were tested using the Bending Beam Rheometer (Figure. 1) following a procedure described elsewhere [20]. In the same study it was demonstrated that the BBR beam is sufficiently large to be considered representative of asphalt mixture and, hence, of the binder present in the mixture.

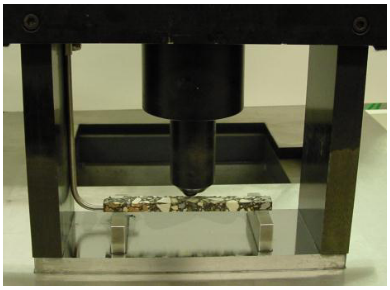

Fig. 1. Bending Beam Rheometer with thin asphalt mixture beam [20]

Asphalt binder was also extracted from mixtures 2, 3, 4, 5, 6, 7 and 8 and BBR creep [19] measured; the extraction and testing of the extracted binders were performed at MnDOT Office of Materials. BBR creep stiffness was also obtained on the original PG58-28 binder after RTFOT aging and next assumed as control in the analysis. Binder and mixture experimental data were obtained at the same test temperature of -6°C, to avoid any errors associated with time-temperature superposition.

## 4. Micromechanical and Analogical Modeling

In most research efforts, asphalt mixture is considered either as a two-phase material [21], or a three phase material [22], and different micromechanical models are applied to describe and predict mixture behavior. More recently, a different model based on the semi empirical Hirsch [13] formulation was used by several authors [1], [23], [24] as back-calculation method [14]. In this model, the effective response of the material is obtained assembling the elements of the mixture (air voids, asphalt binder and aggregate) in parallel and in series. The model formulation is given by:

$$S_{mix} = Pc\left[E_{agg}V_{agg} + S_{binder}V_{binder}\right] + (1 - Pc)\left[\frac{V_{agg}}{E_{agg}} + \frac{(1 - V_{agg})^2}{S_{binder}V_{binder}}\right]^{-1} \quad (1)$$

where $S_{mix}$ is the effective creep stiffness of the mixture, $E_{agg}$ and $V_{agg}$ are the modulus and volume fraction of the aggregate phase, $S_{binder}$ and $V_{binder}$ are the creep stiffness and the volume fraction of asphalt binder, and $Pc$ is the contact volume which is an empirical factor defined as:

$$P_c = 0.1\ln\left(\frac{E_{binder}}{a}\right) + 0.609 \quad (2)$$

where $E_{binder}$ is the relaxation modulus of the binder in GPa, and $a$ is a constant equal to 1 GPa.

In a previous study [24], analogical models were used to obtain creep stiffness of asphalt binders from creep stiffness of the corresponding asphalt mixtures (inverse problem). It was found that Huet model [15] fitted very well the experimental data obtained from BBR tests at low temperatures for both asphalt binders and mixtures. This model is composed of two parabolic elements, $D_1(t) = a(t/\tau)^h$ and $D_2(t) = b(t/\tau)^k$, plus a spring with stiffness $E_\infty$, combined in series (Figure 2).

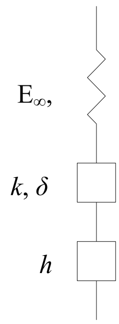


Fig. 2. Huet model

The analytical expression of the Huet model for creep compliance is:

$$D(t) = \frac{1}{E_\infty}\left(1 + \delta\frac{(t/\tau)^k}{\Gamma(k+1)} + \frac{(t/\tau)^h}{\Gamma(h+1)}\right) \quad (3)$$

where $D(t)$ is the creep compliance, $E_\infty$ is the glassy modulus, $h$ and $k$ are exponents such that $0<k<h<1$, $\delta$ is a dimensionless constant, $t$ is time, $\Gamma$ is the Euler gamma function, $\tau$ is the characteristic time varying with temperature accounting for the Time Temperature Superposition Principle (TTSP):

$$\tau = a_T(T)\tau_0(T_S) \quad (4)$$

where $a_T$ is the shift factor at temperature $T$ and $\tau_0$ is the characteristic time determined at reference temperature $T_S$. The authors [24] also found the following relationship between the characteristic time of mixture, $\tau_{mix}$, and the characteristic time of the corresponding binder, $\tau_{binder}$, at the reference temperature $T$:

$$\tau_{mix}(T) = 10^{\alpha}\,\tau_{binder}(T) \tag{5}$$

where, $\tau_{mix}$ and $\tau_{binder}$ are the characteristic times of mixture and binder at temperature $T$ and $\alpha$ is a regression coefficient depending on mixture and aging.

This expression is identical to the equation proposed by Olard and Di Benedetto [17], [18] and obtained from 2S2P1D model for complex modulus data [17], [18]. From equations (3) and (5), the following transformation that relates the creep stiffness of the asphalt binder $S_{binder}(t)$, to the creep stiffness of the corresponding asphalt mixture $S_{mix}(t)$ can be written:

$$S_{mix}(t) = S_{binder}(t10^{-\alpha})\frac{E_{\infty\_mix}}{E_{\infty\_binder}} \tag{6}$$

where $S_{mix}(t)$ and $S_{binder}(t)$ are the creep stiffness of mixture and binder respectively, and $E_{\infty\_\mathrm{mix}}$ and $E_{\infty\_binder}$ are the glassy modulus of mixture and binder. Expression (6) is independent of the model used to derive it, and it represents a special case of ENTPE transformation [17], [18] for low temperatures.

## 5. Back-Calculation Procedure

In this section, asphalt binder creep stiffness is estimated from creep stiffness experimental data of asphalt mixture with the objective of understanding whether total or partial blending occurs between the new virgin binder and the aged binder contained in RAP and RAS. Expression (6) was rearranged using Huet model [15] to obtain the following formula:

$$S_{mix}(t,h,k,\delta,\tau_{mix}) = S_{binder}(t,h,k,\delta,10^{\alpha}\,\tau_{binder})\frac{E_{\infty\_mix}}{E_{\infty\_binder}} \tag{7}$$

The five constants ($\delta$, $k$, $h$, $E_\infty$, and $\tau$) were determined through the minimization of the sum of the distances between asphalt mixture experimental data and the predicted values from equation (7) (Huet-ENTPE) at $n$ time points as:

$$\min\left(\sum_{i=1}^{n}\left[S^{\exp}(t) - S^{Huet-ENTPE}(t)\right]^2\right) \tag{8}$$

where $S^{exp}(t)$ is the experimental creep stiffness and $S^{Huet\text{-}ENTPE}(t)$ is the model creep stiffness.

In previous studies [17], [18], [24] it was found that Huet model parameters are the same for binder and for corresponding mixture. Therefore, the difference between asphalt binder and asphalt mixture is represented by $\alpha$ (see Equation 5); this parameter relates the characteristic time of binder to the characteristic time of mixture. The value of $\alpha$ was determined in the minimization process starting from initial values of , $k$, $h$, $E_\infty$, and $\tau$ found in literature [15], [17], [18], [24]. Table 2 presents the Huet model parameters for the eight asphalt mixtures tested at T= -6°C and for the corresponding back-calculated asphalt binders. The values of $\alpha$ are given in Table 3. As expected, characteristic times of binders and corresponding mixtures are significantly different. The values for parameters *h* and *k* are in agreement with the values determined in previous studies [17], [18], [24]; nevertheless, higher values of *δ* were obtained for the materials investigated in this research.

Table 2. Huet model parameters for mixtures and corresponding back-calculated binders

| | ID | Material | δ | k | h | $E_\infty$(MPa) | Log(τ) |
|---|---|---|---|---|---|---|---|
| Binder | 1 | PG 58-28 Control | 6.67 | 0.28 | 0.71 | 3000 | -0.770 |
| | 2 | 15% RAP | 6.46 | 0.24 | 0.59 | 3000 | -0.824 |
| | 3 | 25% RAP | 6.01 | 0.30 | 0.58 | 3000 | -0.658 |
| | 4 | 30% RAP | 6.84 | 0.22 | 0.61 | 3000 | -0.824 |
| | 5 | 15% RAP 5% MWSS | 6.83 | 0.27 | 0.65 | 3000 | -0.509 |
| | 6 | 15% RAP 5% TOSS | 6.84 | 0.24 | 0.63 | 3000 | -0.456 |
| | 7 | 25% RAP 5% TOSS | 6.02 | 0.28 | 0.59 | 3000 | -0.409 |
| | 8 | 25% RAP 5% MWSS | 6.11 | 0.28 | 0.59 | 3000 | -0.495 |
| Mixtures | 1 | PG 58-28 Control | 6.67 | 0.28 | 0.71 | 30000 | 2.390 |
| | 2 | 15% RAP | 6.46 | 0.24 | 0.59 | 30000 | 3.646 |
| | 3 | 25% RAP | 6.01 | 0.30 | 0.58 | 30000 | 3.492 |
| | 4 | 30% RAP | 6.84 | 0.22 | 0.61 | 30000 | 3.726 |
| | 5 | 15% RAP 5% MWSS | 6.83 | 0.27 | 0.65 | 30000 | 3.591 |
| | 6 | 15% RAP 5% TOSS | 6.84 | 0.24 | 0.63 | 30000 | 4.274 |
| | 7 | 25% RAP 5% TOSS | 6.02 | 0.28 | 0.59 | 30000 | 4.171 |
| | 8 | 25% RAP 5% MWSS | 6.11 | 0.28 | 0.59 | 30000 | 3.965 |

Table 3. *α* parameter for mixtures and corresponding back-calculated binders

| ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Material** | PG 58-28 Control | 15% RAP | 25% RAP | 30% RAP | 15% RAP 5% MWSS | 15% RAP 5% TOSS | 25% RAP 5% TOSS | 25% RAP 5% MWSS |
| **α** | 3.16 | 4.47 | 4.15 | 4.55 | 4.10 | 4.73 | 4.58 | 4.46 |

Hirsch model was also used to back-calculate asphalt binder creep stiffness. First, based on the volumetric properties of the mixtures (Table 1), plots of binder creep stiffness versus predicted mixture stiffness using Equation 2 are generated for binder stiffness values between 50 to 1000MPa. Figure 3 shows the predicted curves for mixtures 1 and 2.

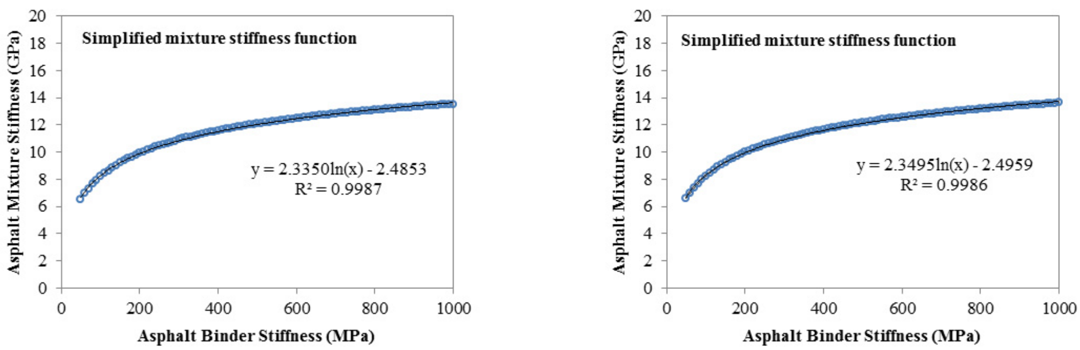


Fig. 3. Simplified mixture stiffness function for mixtures 1 and 2, T=-6ºC

Then, a simple function is fitted to the log of mixture stiffness versus log of binder stiffness curves:

$$E_{mix} = a \cdot \ln(E_{binder}) + b \tag{9}$$

where $a$ and $b$ are regression parameters. Finally, the binder stiffness is simply calculated using Equation 9 over the entire range of loading times.

## 6. Comparison of Results

The asphalt binders creep stiffness values predicted from Huet-ENTPE formulation and Hirsch model, respectively, were compared to the experimentally determined creep stiffness values obtained on the RTFOT condition of original binder and the extracted asphalt binders (mixtures 2 to 8). The recovery process of asphalt binder involves a solvent centrifuge extraction using toluene. The extract is centrifuged at high speeds to separate the mixture fines from the binder, and next the solvent is removed using a rotary evaporator [25]. The BBR data on the recovered binders were obtained at MnDOT Office of Materials for the standard time of 240s. The original binder (short term aged) and the asphalt mixtures were tested at University of Minnesota for 240s and 1000s, respectively. Therefore, in the plots shown in Figures 4 to 7, the creep stiffness curves of asphalt binders are shorter than those obtained through back-calculation from mixture data.

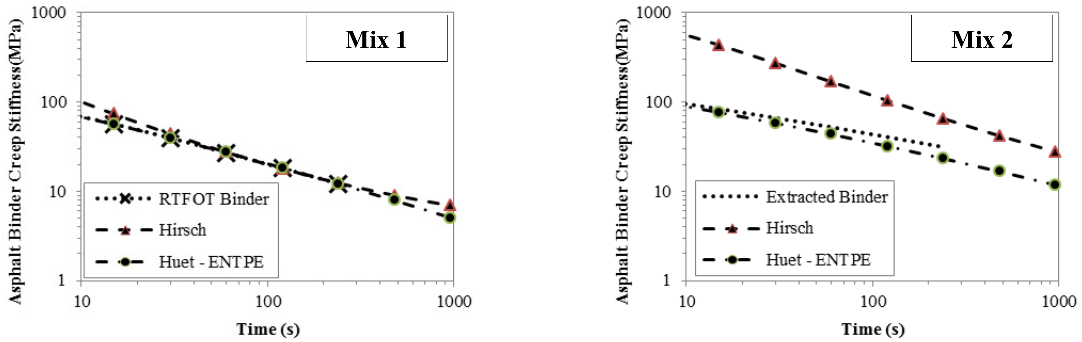


Fig. 4. Creep stiffness of back-calculated and extracted asphalt binder for mixture 1 and 2, T = -6ºC

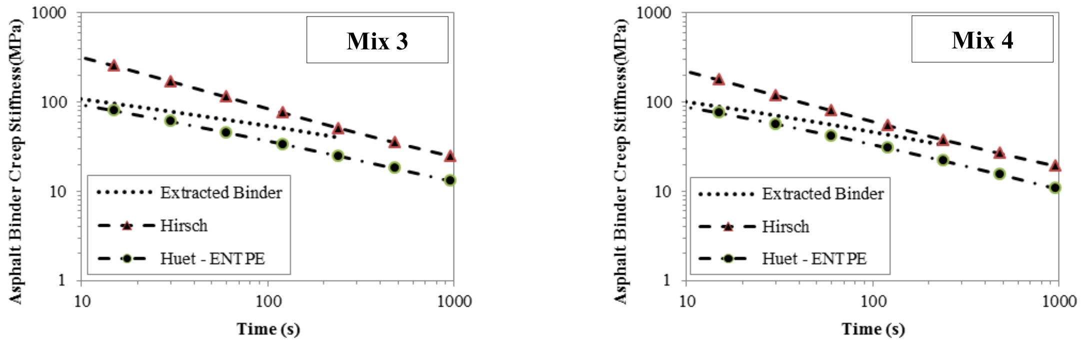


Fig. 5. Creep stiffness of back-calculated and extracted asphalt binder for mixture 3 and 4, T = -6ºC

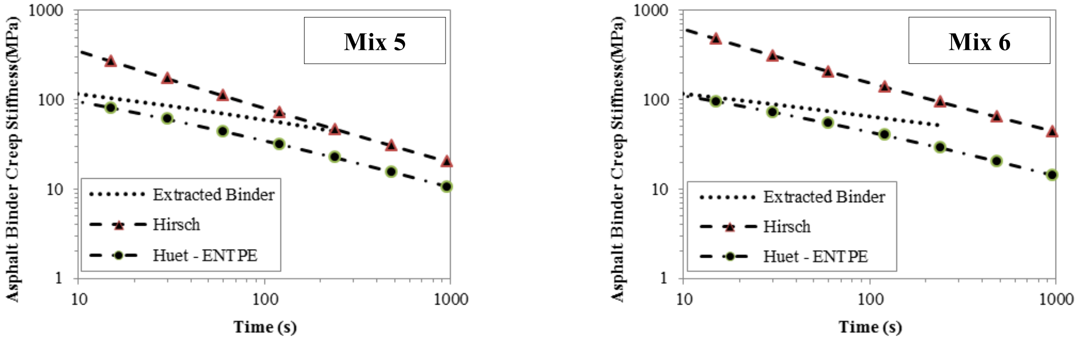


Fig. 4. Creep stiffness of back-calculated and extracted asphalt binder for mixture 5 and 6, T = -6ºC

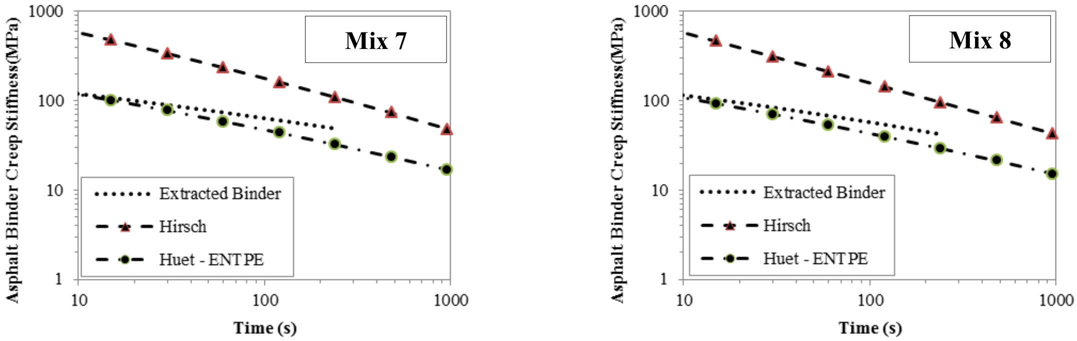


Fig. 5. Creep stiffness of back-calculated and extracted asphalt binder for mixture 7 and 8, T = -6ºC

Hirsch model predictions are higher at shorter time and tend to steeply decrease at longer time compared to the creep stiffness of the extracted binders, which, in the case of recycled mixtures, is significantly over predicted by the Hirch model. Similar trends were obtained by the authors in a different study [24]. The ENTPE transformation predicts very well the creep stiffness of the RTFOT original binder. The back-calculated stiffness curves of asphalt binders obtained from the recycled mixtures (2 to 8) experimental data underestimate the creep stiffness curves of extracted binders. However, a common trend is observed: the back-calculated and the experimental data appear to reach a common asymptote. The extracted binder curves are flatter, suggesting materials with reduced relaxation capabilities compared to the back-calculated ones. It can be reasonably assumed that two mechanisms may be responsible for this observation:

- In spite of the extraction process, very fine particles are still present in the extracted binder. This would also contribute to a higher asymptotic value, which is not observed.
- New and old binder blend only partially. Therefore, the mixture creep behavior is affected by all new binder and only part of the aged, oxidized binder. Since the extraction and recovery process results in 100% blending, the extracted binder had worse relaxation properties since all of the aged binder contributes to the properties of the blend.

The second mechanism was also discussed by other authors; Bonaquist [26] suggested that, due to insufficient heat transfer during mixing, there may be a partial or little melting of the aged RAP and shingle binder when mixed with virgin material in the asphalt mixture production plant. This can explain the discrepancy between the actual binder stiffness in the mix and that obtained from extraction.

## 7. Summary and Conclusions

In this paper, the effect on low temperature properties of asphalt mixtures due to the addition of various percentages of RAP, MWSS and TOSS was investigated. Huet model coupled with ENTPE transformation and micromechanical Hirsch model were used to back-calculate the asphalt binder creep stiffness of the binder present in the mixtures. Back-calculation results were compared to experimental creep stiffness data obtained on the RTFOT aged original binder and on the binders extracted from the other seven recycled mixtures.

Hirsch predictions overestimate the creep stiffness of RTFOT original binders and of the seven extracted asphalt binders. ENTPE transformation predicts very well the creep stiffness of the RTFOT original binder. The stiffness curves of asphalt binders back-calculated from recycled mixtures data do not match the creep stiffness curves of extracted binder. It is hypothesized that the extracted binder still contains very fine particles; however, this would also contribute to a higher asymptotic value, which is not observed. Another explanation is that blending of the new and old binder occurred only partially. Therefore, the mixture creep behavior was affected by all new binder and only a part of the aged, oxidized binder. The extraction and recovery process resulted in a 100% blending and the resulting binder relaxes less since all aged binder contributed to the properties of the blend.

The findings of this study suggest that, at low temperature, the stiffness properties of asphalt mixture are affected by the recycled materials properties. Asphalt binder blending appears to control the creep stiffness when recycled asphalt materials are added in the mixture.

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