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Using Recycled Asphalt Materials as an Alternative Material Source in Asphalt Pavements

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Abstract

Using recycled materials in pavement applications is a viable option to reduce costs and limit the environmental impact of road construction. During the past decades, many agencies in the U.S. have investigated the effect on pavement performance of adding Reclaimed Asphalt Pavement (RAP), and, more recently, Recycled Asphalt Shingles (RAS) to asphalt mixtures, and limits were proposed on the amount of recycled materials which can be used. This paper investigates the effect of adding both RAP and RAS to virgin asphalt mixtures by means of a simple low temperature creep test performed on asphalt mixture beams. From the experimental work, creep stiffness, *m*-value, thermal stress and critical cracking temperature are calculated and compared statistically and graphically. Based on the results, it is concluded that most of the mixtures prepared with combinations of RAP and RAS perform similarly to standard mixtures at low temperature. For a limited number of mixtures, a negative effect is observed.

Keywords: *RAP, RAS, TOSS, MWSS, BBR mixture creep test, creep stiffness, m-value, thermal stress, critical cracking temperature*

1. Introduction

Using recycled materials is a high priority in pavement industry not only for reducing the construction costs but also for minimizing the environmental impact of road construction. Over the past decades, the use of different recyclable materials has been investigated, such as Reclaimed Asphalt Pavement (RAP), reclaimed Portland cement concrete, iron blast-furnace slag, fly ash, waste tire rubber, waste glass, and roofing shingles. Two sources in particular, Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS), have been increasingly used in asphalt pavement construction.

Reclaimed Asphalt Pavement (RAP) has been used in U.S. for more than three decades (NCHRP, 2001; McNichol, 2005). According to a recent report by Federal Highway Administration (FHWA), almost 73 million tons of RAP are reclaimed and 84% of those (62 million tons) are used annually in asphalt pavement construction, making RAP the most recycled material in the U.S (Hansen *et al.*, 2011). A number of specifications that regulate the amount of RAP have been already in place for many years. Most of these limits were developed from observations of field performance of asphalt pavements built with RAP.

In the past decade, another significant source of recycled materials for pavement construction has emerged: Recycled Asphalt Shingles (RAS). Asphalt shingles are extensively used in roofing construction in the U.S. According to the different studies, almost 11 million tons of waste bituminous roofing materials are generated each year in U.S. and most of them are discarded into landfills (Dannhausen, 1997; Marks and Petermeier, 1997; Hansen *et al.*, 2011). Currently, almost 1.14 million tons of RAS, which represents 10% of the total available asphalt shingles market, are used for Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) pavement constructions in U.S. (Hansen *et al.*, 2011) Asphalt shingles consist of four major components: asphalt binder, a paper backing, sand and mineral fillers. The binder is stiffer than the asphalt binder used in pavement applications and represents approximately 20% to 30% by weight of newly manufactured shingles and more than 30% of old roofing shingles that lost some of the particles during service life (Foo *et al.*, 1999; Hansen *et al.*, 2011). Two different types of RAS are available for use: Manufacturer Waste Scrap Shingles (MWSS) that are new shingles, and Tear-off Scrap Shingles (TOSS) from old roofs that have been exposed, for extended periods of time, to high temperatures and solar radiation. Examples of processed MWSS and TOSS are shown in Fig. 1.

MWSS was used in asphalt mixtures as early as 1990 and specifications for their use were developed and implemented starting with 1996. For example, Minnesota Department of

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(a) (b)

Fig. 1. (a) MWSS and (b) TOSS (Johnson *et al.*, 2010)

Transportation (MN/DOT) allows up to 5% MWSS (MN/DOT, 2008). The use of TOSS also started mid 1990's, however, because of concerns with presence of hazardous materials (i.e. asbestos), specifications were not developed until 2007. For example, in 2010, MN/DOT introduced a specification that allows for up to 5% of TOSS for HMA construction (MN/DOT, 2010). The limitations imposed on the use of recycled asphalt materials are mostly related to the aged, oxidized binder present in RAP and RAS, which is stiff and brittle and has a negative effect on pavement performance at low temperature.

2. Research Objectives and Scope

In this study, the effect of adding different amounts of RAP, MWSS, and TOSS on low temperature properties of asphalt mixtures was investigated. Creep tests were performed at low temperature on asphalt mixture beams using the Bending Beam Rheometer (BBR) currently used as part of the PG system in U.S. (AASHTO T 3113-02, 2006; Marasteanu *et al.*, 2009) The experimental data was then used to calculate creep stiffness, *m*-value, thermal stress, and critical cracking temperature, and statistical and graphical comparisons were performed as follows:

- Compare the effect of adding different amounts of RAP (0%, 15%, 25% and 30%)
- Compare the effect of adding different amounts of MWSS (level of 0%, 3%, and 5%)
- Compare the effect of adding different amounts of TOSS (level of 0%, 3%, and 5%)
- Compare the combined effect of adding different amounts of RAP&MWSS and RAP&TOSS
- Compare the effect of using different binder grades (PG 58-28 and PG 52-34).

3. Literature Review

A vast amount of literature on the use of RAP and RAS is available. Some of the more relevant with respect to the present study are briefly summarized. Little *et al.* (1981) and McDaniel *et al.* (2000) investigated the effect of adding RAP in asphalt mixtures and observed an increase in viscosity and stiffness at high temperature and intermediate temperatures, which can improve rutting resistance, and an increase in stiffness and brittleness at low temperature, which negatively affects relaxation properties and fracture resistance.

Newcomb *et al.* (1993) investigated asphalt mixture properties containing different amounts of MWSS and TOSS. It was observed that adding MWSS did not change the moisture susceptibility significantly however, TOSS did. Lower tensile strength was observed with increase of MWSS and TOSS content. Moreover, the mixtures with TOSS were more brittle than mixtures with MWSS. It was found that adding up to 5% of MWSS in asphalt mixtures did not have a significant effect on mechanical properties compared to standard mixtures; however, addition of TOSS had a negative on low temperature cracking resistance.

Button *et al.* (1996) investigated changes in tensile strength, creep stiffness, freeze-thaw resistance, and moisture damage, for mixtures containing 5% and 10% roofing shingles. A decrease in tensile strength and creep stiffness and decrease in freeze-thaw resistance and increased moisture damage were observed proportional to the amount of roofing shingles addition.

Li *et al.* (2008) used dynamic modulus test and Semicircular Bend (SCB) fracture test to investigate the effect of adding RAP. Higher dynamic modulus, E^*, were observed in mixtures with RAP; the source of RAP did not affect the E^* values. A significant decrease in SCB fracture energy, G_f, was observed in asphalt mixtures with RAP.

Burak and Ali (2005) investigated several mechanical properties of asphalt mixtures containing roofing waste shingles from 1% to 5%. They observed that shingles could be used to improve Marshall-stability and rutting resistance.

McGraw *et al.* (2007) investigated the effect of adding RAP, MWSS, and TOSS on low temperature properties of asphalt mixtures. Analysis of the experimental results on extracted binder and corresponding mixtures showed that adding MWSS did not affect the strength and critical cracking temperature, while the addition of TOSS had a negative effect.

4. Experimental Work

The asphalt mixtures used in this paper were provided by Minnesota Department of Transportation (MN/DOT) and are part of a MN/DOT recent research project 2010-08: performed by MN/DOT and Minnesota Pollution Control Agency (MPCA) to investigate the effects of using various proportions of RAP, RAS and two different virgin binders: PG 58-28 and PG 52-34, on pavement performance (Johnson *et al*., 2010). Thirty two gyratory compacted specimens, two for each of the 16 mixtures investigated, were delivered to the Asphalt Pavement Laboratory of the Department of Civil Engineering at University of Minnesota (U of MN). No specific information was available about gradation of aggregates and recycled materials used in each mixture.

Table 1. Summary of Tested Mixtures

Mix ID	Recycled materials, %			Binder Type
	RAP	TOSS	MWSS	
1	0	0	0	PG58-28
2	15	0	0	PG58-28
3	25	0	0	PG58-28
4	30	0	0	PG58-28
5	15	0	5	PG58-28
6	15	5	0	PG58-28
7	25	5	0	PG58-28
8	25	0	5	PG58-28
9	25	5	0	PG52-34
10	25	0	5	PG52-34
11	25	3	0	PG58-28
12	25	0	3	PG58-28
13	15	3	0	PG58-28
14	15	0	3	PG58-28
15	10	5	0	PG58-28
16	0	5	0	PG58-28

Fig. 2. BBR Mixture Beam and BBR Binder Beam used for Creep Testing

The virgin aggregate materials used in the asphalt mixtures consisted of a pit-run-sand, a quarried ¾ in. (19 mm) dolostone and quarried dolostone manufactured sand. The recycled material included in the mixtures consisted of ¾ in. (19 mm) RAP and RAS (either MWSS or TOSS). A plain PG 58-28 asphalt binder with specific gravity of 1.036, was used in all mixtures except two of the RAS/RAP mixtures that were prepared with a plain PG 52-34 asphalt binder. Table 1 presents the mixture design for the 16 mixtures investigated in this study:

The creep tests on asphalt mixtures were performed with the Bending Beam Rheometer using the testing protocol developed by Marasteanu *et al*. (2009). Pictures of the test specimen and BBR equipment and loading set up are shown in Figs. 2 and 3. More detailed information can be found elsewhere (Marasteanu *et al*., 2009; Moon, 2010). Tests were performed at two temperatures, -6℃ and -18℃, and 6 replicates were prepared and tested at each temperature.

5. Data Analysis

5.1 Background Information

From the experimental load and deflection data, creep stiffness,

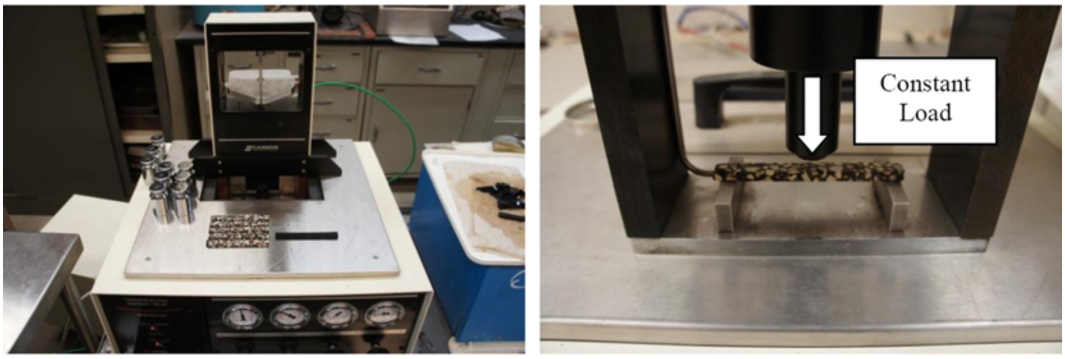

Fig. 3. BBR (Bending Beam Rheometer) Mixture Creep Testing Set Up

$S(t)$, and m-value, $m(t)$, are calculated as follows:

$$S(t) = \frac{\sigma}{\varepsilon(t)} = \frac{P \cdot l^3}{4 \cdot b \cdot h^3 \cdot \delta(t)} = \frac{1}{D(t)} \tag{1}$$

Where,

b = Width of specimen (12.5 mm)
$D(t)$ = Creep compliance
h = Height of specimen (6.25 mm)
l = Length of specimen (101.6 mm)
P = Constant applied load
$S(t)$ = Flexural creep stiffness
t = Test time
$\delta(t)$ = Deflection at the mid-span of the beam
$\varepsilon(t)$ = Bending strain
σ = Maximum bending stress in the beam

The m-value, which is the absolute value of the slope of log stiffness versus log time curve, is calculated according to:

$$m(t) = \left| \frac{d \log S(t)}{d \log t} \right| \tag{2}$$

Creep compliance, $D(t)$, can be converted to relaxation modulus, $E(t)$, using Hopkins and Hamming algorithm (1957) and used to calculate thermal stresses in an idealized viscoelastic pavement. First, $E(t)$ master curve is generated using CAM model (Marasteanu and Anderson, 1999).

$$E(t) = E_g \cdot \left[1 + \left(\frac{t}{t_c} \right)^{v} \right]^{-w/v} \tag{3}$$

Where,

E_g = Glassy modulus (assumed 30 GPa for mixtures and 3 GPa for binders)
t_c, v and w = Fitting parameters in CAM model

Then thermal stress is calculated from the one dimensional hereditary integral as:

$$\sigma(\xi) = \int_{-\infty}^{\xi} \frac{d\varepsilon(\xi')}{d\xi'} \cdot E(\xi - \xi')d\xi' = \int_{-\infty}^{t} \frac{d(\alpha \Delta T)}{dt} \cdot E(\xi(t) - \xi'(t))dt' \tag{4}$$

Where,

$\varepsilon(\xi')$ = Strain
ξ = Reduced time

Equation (4) can be solved numerically using Gaussian quadrature with 24 Gauss points as described elsewhere (Basu, 2002; Basu *et al.*, 2003; Moon, 2010).

To determine the critical cracking temperature, T_{CR}, the Single Asymptote Procedure (SAP) is used since no strength tests were performed in this study (Shenoy, 2002). In SAP method, a line is fitted to the lowest temperature part of the thermal stress curve and the intersection point with the temperature axis is considered the critical cracking temperature, T_{CR}. An example is shown in Fig. 4.

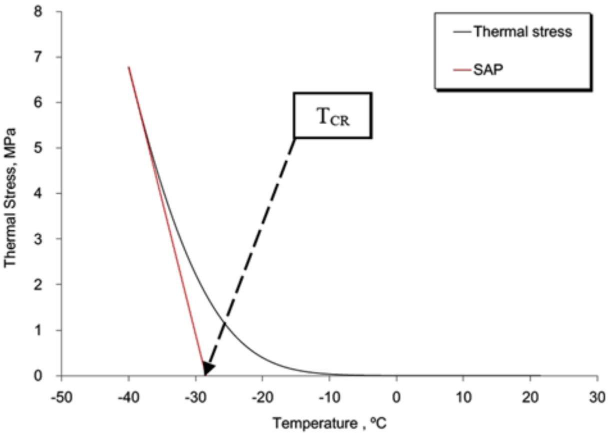

Fig. 4. Single Asymptote Procedure (SAP) Method

The creep stiffness, $S(t)$, and m-value, $m(t)$, at 60 seconds, thermal stress and critical cracking temperature, T_{CR}, were calculated then compared statistically and graphically. In case of $S(60s)$ [MPa] and $m(60s)$, analysis of variance (ANOVA) was performed using a 5% of critical level ($\alpha = 0.05$). The results of thermal stress at -18°C (PG+10°C) and T_{CR} were compared only graphically.

In ANOVA, $S(60s)$ and $m(60s)$ were set as dependent variables and different levels of temperature, RAP, TOSS, MWSS and binder type were set as independent variables with assumptions of linear relationship between dependent and independent terms. Also, two way interactions between each independent term were considered. A full linear model including all possible interaction terms was first considered in ANOVA procedure. Then, if the interaction terms were not statistically significant, they were neglected and finally, the main terms and only statistically significant interaction terms were considered to reduce residual errors. In the case of $S(60s)$ comparison, all $S(60s)$ values were converted to log scale based on the results from the Box-Cox analysis (Cook and Weisberg, 1999).

5.2 Effect of Adding RAP on $S(60s)$, $m(60s)$, Thermal Stress and T_{CR}

To investigate the effect of adding RAP on $S(60s)$ and $m(60s)$ computation, mixture 1 was set as a control group and mixtures 2, 3, and 4 were set as test groups, as seen in Table 2. Table 3 and Fig. 5 show the summary of tested results of $S(60s)$ and $m(60s)$ for each mixture.

ANOVA was performed with Log$S(60s)$ and $m(60s)$ as dependent variables and RAP (0%, 15%, 25% and 30%, 4 levels) and temperature (-6°C and -18°C, 2 levels) as independent

Table 2. ANOVA Test Group to Investigate Effect of RAP

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder Type	Remarks
1	0	0	0	PG58-28	Control
2	15	0	0	PG58-28	Test
3	25	0	0	PG58-28	Test
4	30	0	0	PG58-28	Test

Table 3. Summary of $S(60s)$ and $m(60s)$

Mix ID	Temp [°C]	Creep stiffness [MPa]				m-value	
		$S(60s)$	C.V. [%]	Log$S$ (60s)	C.V. [%]	$m(60s)$	C.V. [%]
1	-6	4627	20.2	3.66	2.2	0.287	5.6
	-18	12886	11.6	4.11	1.2	0.153	8.0
2	-6	6628	19.5	3.81	2.2	0.177	14.8
	-18	15198	14.2	4.18	1.6	0.123	15.0
3	-6	8626	4.5	3.94	0.5	0.159	9.8
	-18	16885	21.3	4.22	2.3	0.119	6.6
4	-6	7524	8.4	3.88	0.9	0.168	4.3
	-18	13249	13.0	4.12	1.4	0.117	13.6

variables. In addition, 0% RAP content and -18℃ of test temperature were set as control terms. The results are presented in Table 4.

For $S(60s)$, the only significant increase was found for 25% RAP. No significant increase in $S(60s)$ were observed with adding 15% and 30% RAP. To investigate if there are any statistical differences on $S(60s)$ among RAP mixtures (mixtures 2, 3 and 4), two multiple comparison methods: Tukey's HSD and Least Square Difference (LSD) methods, were performed (Cook and Weisberg, 1999). As a result no significant differences on $S(60s)$ were observed between RAP15% and RAP30% mixtures (mixtures 2 and 4) however, RAP25% mixtures showed significant increase in $S(60s)$ among the three compared mixtures. This can be due to the increased amount of RAP, for which, beyond a 25% threshold, the aged-clustered binder presents a limited ability in blending with the new virgin binder. It can be hypothesized that, at higher RAP content, the recycled material act like an aggregate, resulting in a dry mixture with lower stiffness as shown by RAP30% mixture. In addition, significant decreases of $m(60s)$ was found for all levels of RAP addition and significant interactions between RAP and temperature were observed for both $S(60s)$ and $m(60s)$ comparisons.

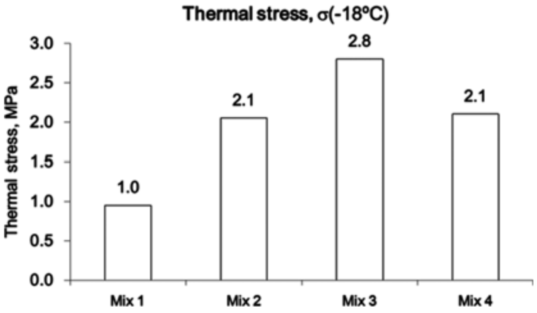

Fig. 6. Results of Computed Thermal Stress at -18°C

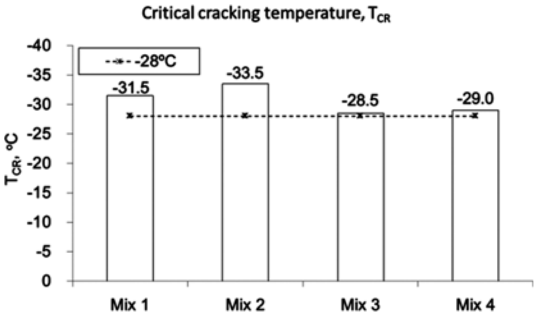

Fig. 7. Results of Computed Critical Cracking Temperature, T_{CR}

Figures 6 and 7 show the plots of the calculated thermal stress

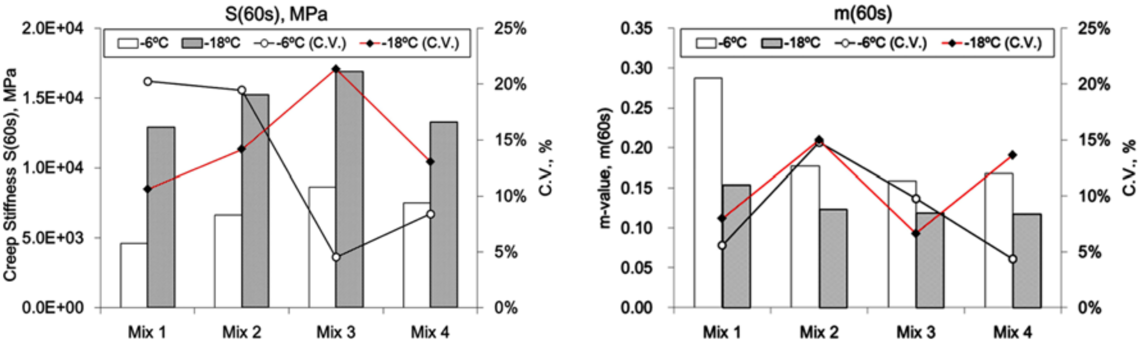

Fig. 5. Results of $S(60s)$ and $m(60s)$

Table 4. ANOVA Results for $S(60s)$ and $m(60s)$

Coefficient	Creep stiffness, Log$S(60s)$, [MPa]				m-value, $m(60s)$			
	Estimate	Std. error	t-score	p-value	Estimate	Std. error	t-score	p-value
Intercept	4.108	0.027	153.94	0.000	0.154	0.006	24.08	0.000
RAP 15%	0.070	0.038	1.85	0.072	-0.030	0.009	-3.34	**0.002**
RAP 25%	0.111	0.038	2.94	**0.006**	-0.035	0.009	-3.86	**0.000**
RAP 30%	0.011	0.038	0.29	0.774	-0.036	0.009	-3.99	**0.000**
Temp -6°C	-0.449	0.038	-11.90	**0.000**	0.134	0.009	14.83	**0.000**
RAP*Temp	0.206	0.053	3.851	**0.000**	-0.084	0.013	-6.563	**0.000**

at -18°c and the T_{CR} values, respectively. In the T_{CR} plot the dashed line indicates the low temperature limit of the binder (i.e. -28°C for PG58-28 binder).

The addition of RAP increased thermal stresses at -18°C and the highest value (2.8 MPa) was observed in the mixture that contains 25% of RAP (mixture 3). The mixtures with 15% and 30% RAP (mixture 2 and mixture 4) had similar thermal stress values that were two times higher than the standard mixture thermal stress. With respect to T_{CR}, the results were mixed; for 15% RAP (mixture 2) the temperature decreased while for 25% and 30% RAP mixtures (mixtures 3 and 4), it increased as expected.

5.3 Effect of adding MWSS and TOSS on *S*(60*s*), *m*(60*s*), Thermal Stress and T_{CR}

Similar to the previous section, Log*S*(60*s*) and *m*(60*s*) were set as dependent variables and temperature, different level of MWSS and TOSS were set as independent variables; two-way interaction terms were considered in ANOVA analysis. Two different ANOVA were performed based on the RAP content: 15% and 25%. The test groups are presented in Table 5; mixture 2 and mixture 3 were set as control group in ANOVA procedure in each group.

The *S*(60*s*), Log*S*(60*s*) and *m*(60*s*) values are summarized in Table 6 and plotted in Fig. 8.

Table 7 shows the computed results of ANOVA for Group 1. It was observed that adding MWSS up to 5% (mixtures 5 and 14) resulted no significant differences in *S*(60*s*) and *m*(60*s*) compared to the control mixture (mixtures 2). In the case of adding 3% level of TOSS (mixture 13), a significant decrease in *m*(60*s*) was observed, as expected; however, a significant decrease in *S*(60*s*) was also observed, which is the opposite of what was expected. For the case of adding 5% level of TOSS (mixture 6), no significant differences in *S*(60*s*) and *m*(60*s*) were observed in comparison with the control mixture, which is the opposite of what was expected if full blending of the old and new binder had occurred.

Table 5. ANOVA Test Group to Investigate the Effect of MWSS and TOSS

(1) Group 1 (15% RAP content)

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder	Remarks
2	15	0	0	58-28	Control
5	15	0	5	58-28	Test
6	15	5	0	58-28	Test
13	15	3	0	58-28	Test
14	15	0	3	58-28	Test

(2) Group 2 (25% RAP content)

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder	Remarks
3	25	0	0	58-28	Control
7	25	5	0	58-28	Test
8	25	0	5	58-28	Test
11	25	3	0	58-28	Test
12	25	0	3	58-28	Test

Table 6. Summary of *S*(60*s*) and *m*(60*s*)

(1) Group 1 (15% RAP content)

Mix ID	Temp [°C]	Creep stiffness [MPa]				*m*-value	
		S(60*s*)	C.V. [%]	Log*S* (60*s*)	C.V. [%]	*m*(60*s*)	C.V. [%]
2	-6	6628	19.5	3.81	2.2	0.177	14.8
	-18	15198	14.2	4.18	1.6	0.123	15.0
5	-6	7653	12.0	3.88	1.3	0.174	8.1
	-18	16617	11.5	4.22	1.2	0.129	6.4
6	-6	9612	9.7	3.98	1.1	0.154	12.9
	-18	14943	18.6	4.17	2.0	0.120	8.2
13	-6	7416	7.8	3.87	0.9	0.153	8.1
	-18	12513	10.6	4.10	1.1	0.117	15.6
14	-6	6568	14.1	3.81	1.6	0.172	4.0
	-18	13596	9.0	4.13	1.0	0.122	14.7

(2) Group 2 (25% RAP content)

Mix ID	Temp [°ýC]	Creep stiffness [MPa]				*m*-value	
		S(60*s*)	C.V. [%]	Log*S* (60*s*)	C.V. [%]	*m*(60*s*)	C.V. [%]
3	-6	8626	4.5	3.94	0.5	0.159	9.8
	-18	16885	21.3	4.22	2.3	0.119	6.6
7	-6	9279	16.2	3.96	1.7	0.132	15.2
	-18	15875	20.0	4.19	2.2	0.104	18.9
8	-6	9596	13.2	3.98	1.4	0.136	12.3
	-18	15193	18.1	4.18	1.8	0.114	23.7
11	-6	11086	20.5	4.04	2.1	0.131	19.8
	-18	16996	10.7	4.23	1.1	0.106	14.6
12	-6	9312	17.0	3.96	1.8	0.146	11.8
	-18	15514	10.0	4.19	1.1	0.131	8.8

The results of ANOVA for Group 2 are presented in Table 8. No significant differences in *S*(60*s*) were found for adding MWSS or TOSS up to 5% (mixtures 8 and 12 for MWSS mixture and mixtures 7 and 11 for TOSS mixture). In case of *m*(60*s*), no significant differences were observed for adding MWSS up to 5% (mixtures 8 and 12); however, significant decrease in *m*(60*s*) was observed in TOSS mixtures both for 3% and 5% levels (mixtures 7 and 11). From the results in Tables 7 and 8, it can be concluded that adding up to 5% MWSS in RAP mixtures (up to 25%) is acceptable because no significant differences in *S*(60*s*) and *m*(60*s*) were found. However, in case of adding TOSS to RAP mixtures, although no significant changes in *S*(60*s*) were observed, significantly lower *m*-values (relaxation ability) were observed compared to the control mixtures.

Figures 9 and 10 show the results of computed thermal stress at -18°C and critical cracking temperature, T_{CR}, for Group 1 and Group 2, respectively.

Higher values of thermal stresses were observed for the mixtures that contain TOSS and MWSS. The mixtures with 5% TOSS (mixture 6 for 15% of RAP and 7 for 25% of RAP) and 5%

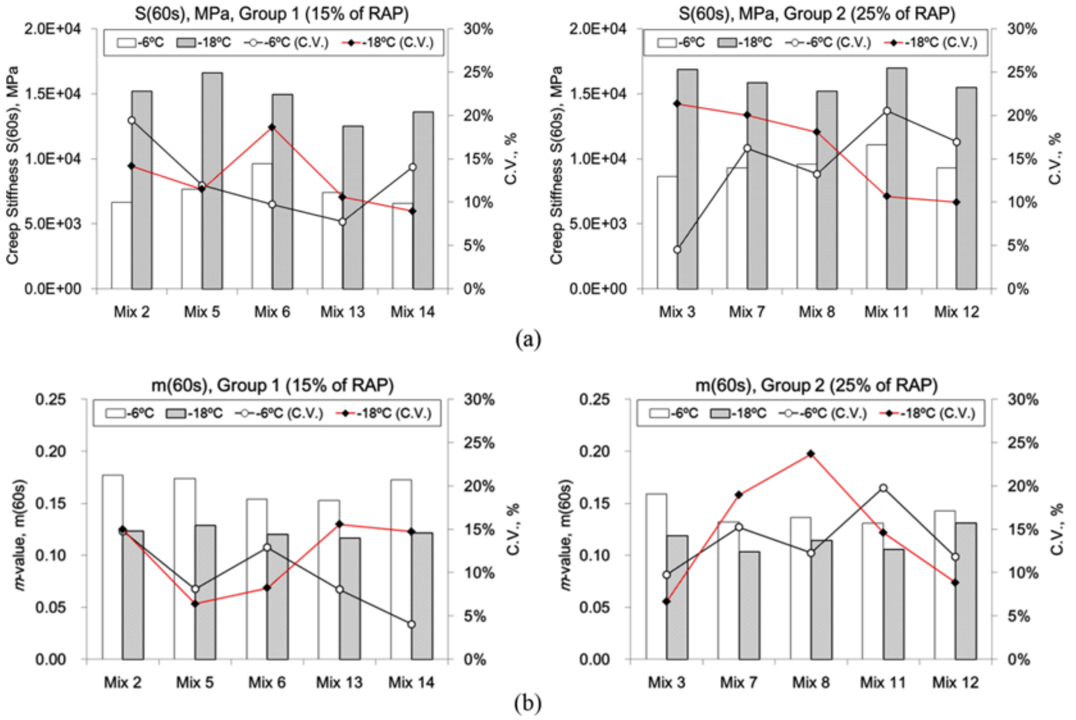

Fig. 8. Results of *S*(60*s*) and *m*(60*s*): (a) Creep Stiffness, *S*(60*s*), Group 1 and Group 2, (b) *m*-value, m(60*s*), Group 1 and Group 2

Table 7. ANOVA Results for *S*(60*s*) and *m*(60*s*), Group 1 (RAP 15%)

Coefficient	Creep stiffness, Log*S*(60*s*), [MPa]				*m*-value, *m*(60*s*)			
	Estimate	Std. error	*t*-score	*p*-value	Estimate	Std. error	*t*-score	*p*-value
Intercept	4.178	0.024	177.089	0.000	0.128	0.005	24.821	0.000
TOSS 3%	-0.082	0.033	-2.469	**0.017**	-0.015	0.007	-2.266	**0.028**
TOSS 5%	-0.010	0.033	-0.303	0.763	-0.013	0.007	-1.895	0.064
MWSS 3%	-0.046	0.033	-1.375	0.175	-0.003	0.007	-0.400	0.691
MWSS 5%	0.040	0.033	1.209	0.233	0.002	0.007	0.231	0.818
Temp -6°C	-0.363	0.035	-10.376	**0.000**	0.044	0.004	10.500	**0.000**
Temp*TOSS	0.176	0.048	3.648	**0.001**				

Table 8. ANOVA Results for *S*(60*s*) and *m*(60*s*), Group 2 (RAP 25%)

Coefficient	Creep stiffness, LogS(60s), [MPa]				*m*-value, m(60s)			
	Estimate	Std. error	*t*-score	*p*-value	Estimate	Std. error	*t*-score	*p*-value
Intercept	4.191	0.022	189.658	0.000	0.126	0.006	21.668	0.000
TOSS 3%	0.056	0.030	1.888	0.065	-0.021	0.008	-2.644	**0.011**
TOSS 5%	0.001	0.029	0.035	0.973	-0.021	0.008	-2.770	**0.008**
MWSS 3%	0.000	0.030	-0.019	0.985	-0.002	0.008	-0.260	0.796
MWSS 5%	0.002	0.029	0.065	0.949	-0.014	0.008	-1.815	0.076
Temp -6°C	-0.227	0.019	-12.030	**0.000**	0.026	0.005	5.221	**0.000**

MWSS (mixture 5 for 15% of RAP and 8 for 25% of RAP) had higher thermal stresses than the mixture with 3% TOSS (mixture 13 for 15% of RAP and 11 for 25% of RAP) and 3% MWSS (mixture 14 for 15% of RAP and 12 for 25% of RAP). The highest values of thermal stresses were observed in the mixtures with 5% TOSS (mixture 7) in Group 2. Note that higher amount of thermal stresses were observed in the mixtures contain 25% of RAP in comparison with the mixtures contain 15% of RAP. No significant differences of thermal stress at -18ºC were observed between the mixtures with 3% TOSS (mixture 13) or MWSS (mixture 14) and the control mixture in Group 1 (mixture 2, RAP 15%).

Values of T_{CR} higher than the binder low temperature limit (-28ºC, PG 58-28) were found for mixtures with 5% TOSS (mixture 6) in Group 1 and 5% TOSS (mixture 7) and 5% MWSS (mixture 8) in Group 2.

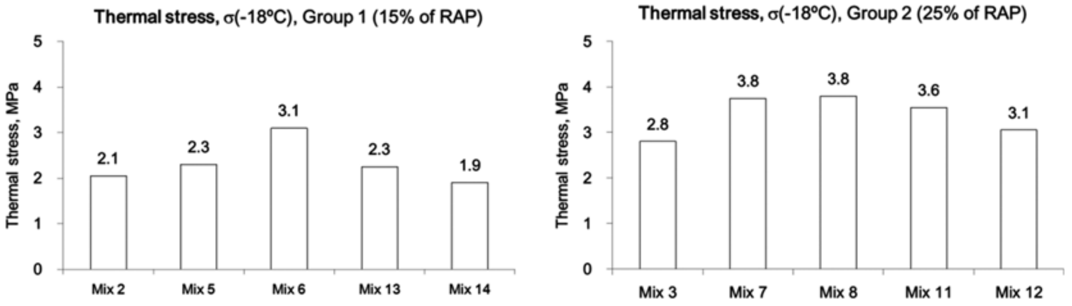

Fig. 9. Thermal Stress, σ(Temp = -18°C), Group 1 and Group 2

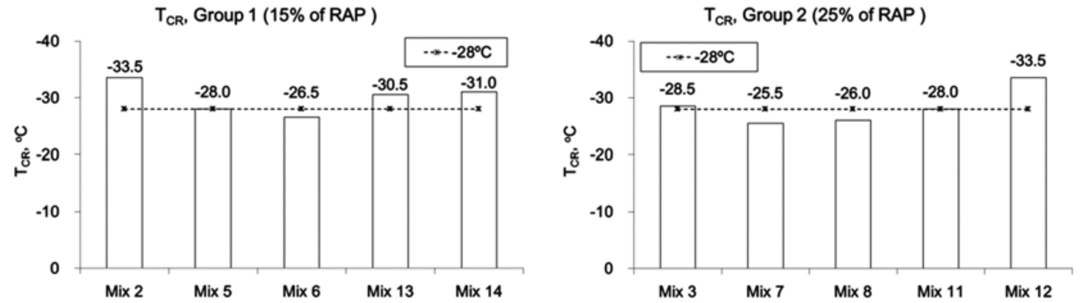

Fig. 10. Critical Cracking Temperature, T_{CR}, Group 1 and Group 2

5.4 Effect of mixing RAP and RAS (MWSS and TOSS) on *S*(60*s*) and *m*(60*s*)

In this section, the effect of combining RAP and RAS on *S*(60*s*) and *m*(60*s*) was investigated to evaluate whether RAP and RAS (MWSS and TOSS) can be mixed together as a recycled materials in virgin asphalt mixture. Similar to the previous section, two independent groups were selected based on different amount and types of RAP and RAS (MWSS and TOSS). The values of Log*S*(60*s*) and *m*(60*s*) were set as dependent variables and different level of RAP and RAS (MWSS and TOSS) were set as independent variables. Table 9 shows the two independent ANOVA test groups in this section.

Table 9. ANOVA Test Group to Investigate the Effect of Combining RAP and RAS

(1) Group 1 (Combining RAP and MWSS)

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder	Remarks
1	0	0	0	58-28	Control
2	15	0	0	58-28	Test
3	25	0	0	58-28	Test
5	15	0	5	58-28	Test
8	25	0	5	58-28	Test
12	25	0	3	58-28	Test
14	15	0	3	58-28	Test

(2) Group 2 (Combining RAP and TOSS)

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder	Remarks
1	0	0	0	58-28	Control
2	15	0	0	58-28	Test
3	25	0	0	58-28	Test
6	15	5	0	58-28	Test
7	25	5	0	58-28	Test
11	25	3	0	58-28	Test
13	15	3	0	58-28	Test

The ANOVA results for Group 1 and Group 2 are presented in Tables 10 and 11. Since the main terms were analyzed previously in the paper, only the results of interaction terms are considered in this section. The statistical output of the effect of RAP*MWSS and RAP*TOSS on *S*(60*s*) and *m*(60*s*) are shown in Tables 10 and 11, respectively.

Tables 10 and 11 show there are no significant effects of interaction terms on *S*(60*s*) and *m*(60*s*) for both combinations of the two different recycled materials: RAP*MWSS and RAP*TOSS. Therefore, no significant and random effects on creep stiffness and relaxation ability of the material (i.e., *m*-value) are expected when combining RAP and RAS (MWSS and TOSS) together up to 25% and 5% content level, respectively.

5.5 Effect of Asphalt Binder Grade on *S*(60*s*), *m*(60*s*), Thermal Stress at -18°C and T_{CR}

In this study, two different types of non-polymer modified binder, PG 58-28 and PG 52-34, were used. Similar to the previous sections, two independent groups were built based on the different amount of TOSS and MWSS, respectively. Table 12 presents the summary of ANOVA test groups in this section.

The *S*(60*s*) and *m*(60*s*) results for Group 1 and Group 2 are presented in Table 13 and plotted in Fig. 11, respectively. Higher values of *S*(60*s*) and lower values of *m*(60*s*) were observed for mixtures prepared with PG58-28 binder.

Table 10. ANOVA Results for *S*(60*s*) and *m*(60*s*), RAP*MWSS

Coefficient	Creep stiffness, LogS(60s), [MPa]				*m*-value, m(60s)			
	Estimate	Std. error	*t*-score	*p*-value	Estimate	Std. error	*t*-score	*p*-value
Intercept	3.833	0.052	75.035	0.000	0.220	0.011	20.815	0.000
R15*M3	-0.039	0.107	-0.367	0.714	0.001	0.022	0.061	0.951
R15*M5	0.060	0.107	0.564	0.575	0.012	0.022	0.553	0.582
R25*M3	0.039	0.107	0.367	0.714	-0.001	0.022	-0.061	0.951
R25*M5	-0.060	0.107	-0.564	0.575	-0.012	0.022	-0.553	0.582

*R: RAP, M: MWSS

Table 11. ANOVA results for *S*(60*s*) and *m*(60*s*), RAP*TOSS

Coefficient	Creep stiffness, LogS(60s), [MPa]				*m*-value, m(60s)			
	Estimate	Std. error	*t*-score	*p*-value	Estimate	Std.error	*t*-score	*p*-value
Intercept	3.883	0.048	81.225	0.000	0.220	0.011	20.890	0.000
R15*T3	-0.086	0.099	-0.873	0.386	0.008	0.022	0.345	0.731
R15*T5	0.050	0.098	0.514	0.609	0.012	0.022	0.539	0.592
R25*T3	0.086	0.099	0.873	0.386	-0.008	0.022	-0.345	0.731
R25*T5	-0.050	0.098	-0.514	0.609	-0.012	0.022	-0.539	0.592

*R: RAP, T: TOSS

Table 12. ANOVA Test Group to Investigate the Effect of Binder

(1) Group 1 (TOSS 5%, MWSS 0%)

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder	Remarks
7	25	5	0	58-28	Control
9	25	5	0	52-34	Test

(2) Group 2 (TOSS 0%, MWSS 5%)

Mix ID	RAP [%]	TOSS [%]	MWSS [%]	Binder	Remarks
8	25	0	5	58-28	Control
10	25	0	5	52-34	Test

The ANOVA results for Group 1 and Group 2 are shown in Table 14. No significant interaction terms were observed therefore, only main terms were considered.

From the results above, it can be concluded that the mixtures prepared with the softer PG 52-34 binder was less affected by the addition of TOSS compared to the mixtures prepared with the stiffer binder PG 58-28. This effect was not observed when MWSS was added since the binder in MWSS is less aged than the binder in TOSS.

Table 13: Summary of *S*(60*s*) and *m*(60*s*)

(1) Group 1 (TOSS 5%, MWSS 0%)

Mix ID	Temp [°C]	Creep stiffness, [MPa]				*m*-value	
		S(60*s*)	C.V. [%]	Log*S* (60*s*)	C.V. [%]	*m*(60*s*)	C.V. [%]
7	-6	9279	16.2	3.96	1.7	0.132	15.2
	-18	15875	20.0	4.19	2.2	0.104	18.9
9	-6	6850	19.5	3.83	2.2	0.180	9.7
	-18	14140	16.0	4.15	1.8	0.130	24.1

(2) Group 2 (TOSS 0%, MWSS 5%)

Mix ID	Temp [°C]	Creep stiffness, [MPa]				*m*-value	
		S(60s)	C.V. [%]	Log*S* (60*s*)	C.V. [%]	*m*(60*s*)	C.V. [%]
8	-6	9596	13.2	3.98	1.4	0.136	12.3
	-18	15193	18.1	4.18	1.8	0.114	23.7
10	-6	7599	23.4	3.87	2.5	0.193	9.2
	-18	14483	13.8	4.16	1.5	0.145	12.1

Similar to the previous sections, thermal stress at -18ºC and critical cracking temperature, T_{CR}, were calculated and compared, graphically. The results are plotted in Fig. 12 and Fig. 13.

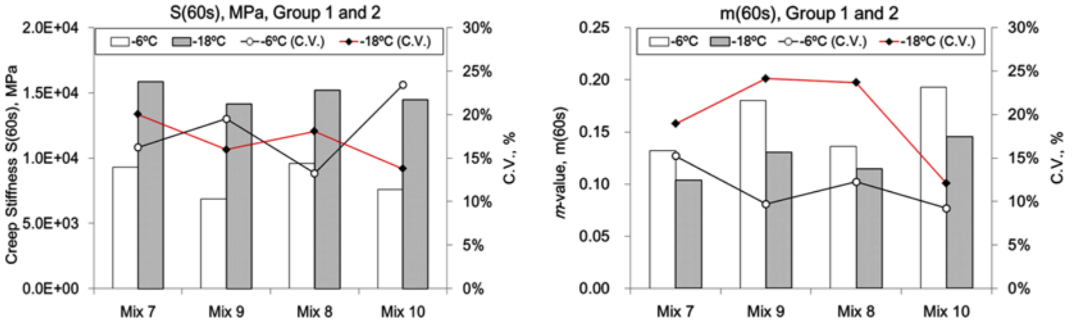

Fig. 11. Results of *S*(60*s*) and *m*(60*s*)

Table 14. ANOVA Results for *S*(60*s*) and *m*(60*s*)

(1) Group 1 (TOSS 5%, MWSS 0%)

Coefficient	Creep stiffness, Log*S*(60*s*), [MPa]				*m*-value, *m*(60*s*)			
	Estimate	Std. error	*t*-score	*p*-value	Estimate	Std. error	*t*-score	*p*-value
Intercept	4.214	0.029	143.781	0.000	0.098	0.008	11.942	0.000
Binder PG52-34	-0.089	0.034	-2.585	**0.018**	0.037	0.010	3.813	**0.001**
Temp -6°C	-0.275	0.034	-8.007	**0.000**	0.040	0.010	4.127	**0.001**

(2) Group 2 (TOSS 0%, MWSS 5%)

Coefficient	Creep stiffness, Log*S*(60*s*), [MPa]				*m*-value, *m*(60*s*)			
	Estimate	Std. error	*t*-score	*p*-value	Estimate	Std. error	*t*-score	*p*-value
Intercept	4.202	0.029	145.419	0.000	0.107	0.008	13.821	0.000
Binder PG52-34	-0.065	0.032	-2.049	0.054	0.044	0.009	5.179	**0.000**
Temp -6°C	-0.244	0032	-7.635	**0.000**	0.035	0.009	4.104	**0.001**

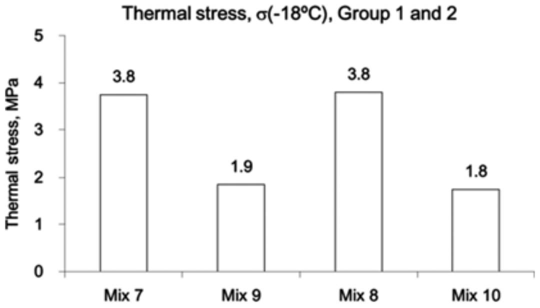

Fig. 12 Results of Computed Thermal Stress at -18°C

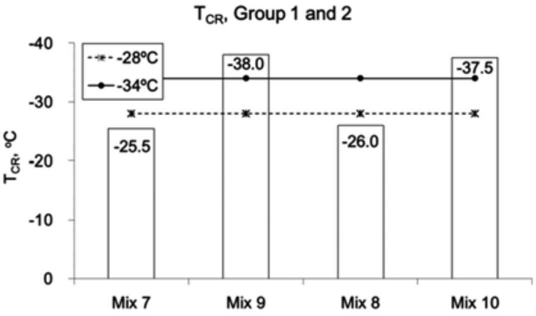

Fig. 13 Results of Computed Critical Cracking Temperature, T_{CR}

Higher thermal stresses at -18°C were observed in the mixtures prepared with the PG 58-28 binder (mixtures 7 and 8) compared to the mixtures prepared with the PG 52-34 binder (mixtures 9 and 10), as expected. In addition, it was observed that the mixtures prepared with PG 58-28 binder (mixtures 7 and 8) had T_{CR} values higher than -28°C, and the mixtures prepared with PG52-34 binder (mixtures 9 and 10) had T_{CR} values lower than -34°C. These results indicate that using a softer binder (PG 52-34) is a better choice when adding MWSS and TOSS in asphalt mixtures.

6. Conclusions

In this paper, the effect of adding recycled materials (e.g., RAP, MWSS and TOSS) on low temperature properties of asphalt mixtures was investigated. A total of 16 mixtures were prepared with different combinations of RAP (0%, 15%, 25% and 30%), MWSS (0%, 3% and 5%), TOSS (0%, 3% and 5%) and different types of binder, PG 58-28 and PG 52-34. Bending Beam Rheometer (BBR) was used to perform three point bending test on asphalt mixture beams and creep stiffness, *m*-value, thermal stress and critical cracking temperature were calculated and compared statistically and graphically.

From the analyses performed, a number of conclusions were drawn.

1. In case of RAP addition, the only significant increase in *S*(60*s*) was found for 25% RAP. No significant differences were observed with adding 15% and 30% RAP. However, significant decreases of *m*(60*s*) were found for all levels of RAP addition. No consistent pattern was observed for changes in thermal stress and T_{CR}.
2. For the scenarios in which MWSS and TOSS are added to RAP mixtures, it can be concluded that adding up to 5% MWSS in RAP mixtures (up to 25%) is acceptable because no significant differences in *S*(60*s*) and *m*(60*s*) were found. However, in case of adding TOSS to RAP mixtures, although no significant changes in *S*(60*s*) were observed, significantly lower *m*-values (relaxation ability) were observed compared to the control mixtures. More research is recommended to determine the acceptable level of TOSS addition.
3. When considering the combined effects of RAP and RAS (MWSS and TOSS) on *S*(60*s*) and *m*(60*s*), no significant differences were observed up to 25% and 5% addition of RAP and RAS, respectively. This indicates that there is a significant potential for using both types of recycled materials in the preparation of asphalt mixture. Nevertheless, a follow up study with different combined percentages of RAP and RAS is need for clearly determining the recommended content levels when using RAP together with MWSS and TOSS.
4. Higher thermal stresses were observed in the mixtures prepared with the PG 58-28 binder compared to the mixtures prepared with the PG 52-34 binder, as expected. It was also observed that the mixtures prepared with PG 58-28 binder

had T_{CR} values higher than -28°C, while the mixtures prepared with PG52-34 binder had T_{CR} values lower than -34°C. Using a softer binder (PG 52-34) is a better choice when adding MWSS and TOSS to RAP mixtures.

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