DEVELOPMENT OF WARM IN-PLACE RECYCLING TECHNIQUE AS AN ECO-FRIENDLY ASPHALT REHABILITATION METHOD

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ABSTRACT

Cold In-place Recycling (CIR) has been widely applied in the world because it is easy to apply in the field at a low cost. However, it is not normally used as a surface layer because of its inconsistent quality due to an excessive amount of fine aggregates pulverized during the milling process. Hot In-place Recycling (HIR) can retain the original shape of the aggregates but it often produces a large amount of Volatile Organic Compounds (VOCs). Therefore, a third in-place recycling technique is introduced in this paper: Warm In-place Recycling (WIR). The WIR technique overcomes the limitations of both CIR and HIR techniques by lowering a heating temperature while adding a warm mix asphalt additive. The purpose of this WIR technology is to recycle old asphalt pavements in the field while reducing the amount of carbon dioxide generated during construction. A new WIR equipment is being developed for recycling asphalt pavements with significantly reduced amounts of emission. The emission controlled heating equipment reduces the emission by capturing the VOCs generated during the heating process, which would lead to the eco-friendly pavement recycling practices. To develop a new WIR additive, soybean oil was blended with Tetraethylenepentamine (TEPA) in the laboratory, where the formation of amide bonds was successfully achieved. To enhance the stiffness of the warm mix asphalt additive, the SBS polymer was also added to TEPA/Soybean-based WIR additive. Based on various binder and mixture tests, it can be concluded that TEPA/Soybean/SBS-based WIR additive was more effective in increasing both moisture and lower temperature cracking resistance than the WIR additive without SBS.

1 INTRODUCTION

The asphalt recycling is a one of the most effective ways to rehabilitate asphalt pavements while preserving both construction materials and the environment. Due to a very high cost of asphalt binders, a significant effort has been made to increase the content of Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt (HMA) (Shannon et al, 2016; Van Winkle et al. 2016; Mokhtari et al. 2017). Without performing a new mix design, the RAP content in HMA is commonly limited to 25% maximum (Sullivan, 1996; Howard, Cooley and Doyle, 2009). The in-place recycling techniques can be categorized into two: Cold In-place Recycling (CIR) and Hot In-place Recycling (HIR) methods. Although the in-place recycling techniques allowed the 100% of RAP to be used as a newly rehabilitated asphalt pavement, the HMA overlay is normally applied on top of the CIR layer to provide a better performing surface layer and the HIR layer has been limited to pavements with a relatively a good condition (Karlsson and Isacsson, 2006; Daniel, Pochily and Boisvert, 2010; Oner and Sengoz, 2015).

CIR is more widely applied in the world because it is less expensive and easy to apply (Kim and Lee 2011). However, it is not used as a surface layer because of its inconsistent quality due to an excessive amount of fine aggregates pulverized during the milling process (Kim et al. 2011; Woods et al. 2012). HIR process can retain the original shape of the aggregates by heating the pavement surface before milling but it often produces a large amount of Volatile Organic Compounds (VOCs), which would negatively impact the environment (Abiodun, 2014). Therefore, in this paper, a third in-place recycling technique is introduced: Warm In-place Recycling (WIR). The WIR technique overcomes the limitations of both Cold and Hot In-place Recycling techniques by lowering a heating temperature while adding a warm mix asphalt additive.

First, the newly developed emission controlled heating equipment is discussed. Second, new WIR additives for 100% RAP materials are evaluated. The optimum percentages of the additives were determined based on the viscosity and dynamic shear rheometer test. Then the moisture susceptibility of both Warm Mix Asphalt (WMA) mixtures produced using 100% RAP materials were evaluated using the Hamburg Wheel Track (HWT) testing equipment. The low-temperature cracking resistance of WMA mixtures was determined using Disc-Shaped Compact Tension (DCT) testing equipment.

2 EMISSION CONTROLLED HEATING EQUIPMENT

A new WIR equipment is being developed for recycling asphalt pavements with significantly reduced emission amounts. The purpose of this WIR technology is to recycle old asphalt pavements in the field while reducing the amount of carbon dioxide generated during the heating process. Figure 1 shows the indirect heating equipment for asphalt pavements before the recycling process. The equipment heats the existing asphalt pavement surface using an infrared heating burner with LPG fuel so than a flame does not hit the asphalt pavements directly. The equipment heats the top 5 cm of an old asphalt pavement to about 121 ºC on the average. As a result, the warm surface milling can be performed without crushing the aggregates. As shown in Figure 2, an emission hood unit is installed on top of each heating plates where the collected emission is exhausted through the emission collector module ("off" condition is shown in Figure 2a. and "on" in Figure 2b. The emission controlled heating equipment reduces the emission by capturing the volatile organic compounds generated during the heating process, which would lead to the eco-friendly pavement recycling practices.

Figure 1. Emission controlled heating equipment for asphalt pavement recycling

(a) Emission control unit off (b) Emission control unit on

Figure 2. Heating equipment for asphalt pavement recycling

3 WARM IN-PLACE RECYCLING ADDITIVES

To develop new WIR additives, soybean oil was blended with various amounts of three amide type anti-stripping additives: 1) ethylenediamine (ED), 2) 2-hydroxyethyl ethylenediamine (HEED) and 3) Tetraethylenepentamine (TEPA). The formation of amide bonds was successfully achieved in the laboratory, which has been confirmed using the FT-IR and 1H-NMR equipment. The adhesive properties of antistripping agents were measured using Bituminous Bond Strength (BBS) test. Based on the BBS test results, PG 64-22 binder with antistripping additive synthesized from TEPA exhibited the higher moisture resistance value than those synthesized from ED and HEED. To enhance the stiffness of the WIR additive, the SBS polymer was also added to TEPA/Soybean-based WIR additive.

In order to determine the optimum dosage rate of the WIR additives of 1) TEPA + San oil (A1) and 2) TEPA + SBS + Soybean oil (A2), the viscosity and dynamic modulus were measured from virgin and RTFO aged samples with various amounts of each additive.

4 VISCOSITY TEST

Viscosity was measured using a rotation viscometer from 115°C to 165°C at 10°C increments to better understand the behaviour of asphalt in a wide range of temperatures. Figure illustrates the viscosity of the RTFO aged samples and virgin PG 64-22 sample in different temperatures with additives of A1 and A2. To bring the viscosity of the RTFO aged binder to that of virgin asphalt, based on the viscosity test results, 5.2% and 10% are needed for A1 and A2 additives, respectively.

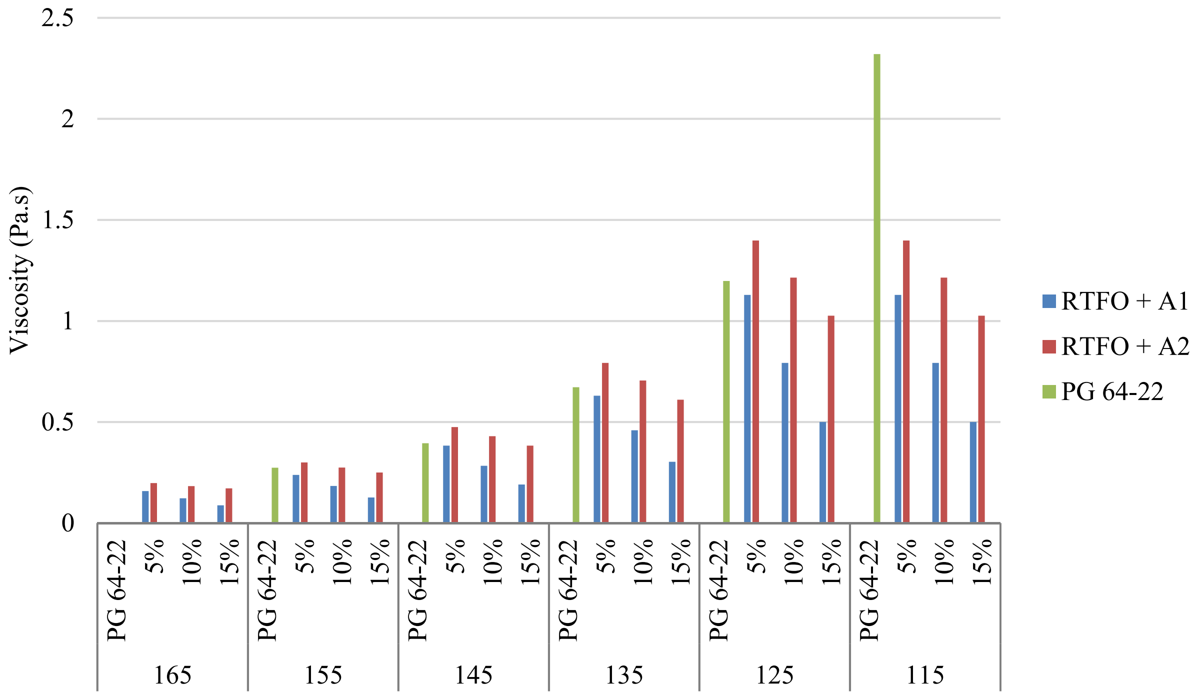

Figure 3. Viscosity of the RTFO aged samples with the additives of A1 and A2

5 DYNAMIC SHEAR RHEOMETER TEST

Dynamic Shear Rheometer (DSR) test was conducted from 46°C to 76°C at 6°C increments. All test temperatures were selected to evaluate high-temperature characteristics of asphalt.

As shown in Figure 4, the dynamic shear modulus was measured from RTFO aged binder with both Additive 1 and Additive 2. To bring the dynamic modulus value of the Rolling Thin Film Oven (RTFO) aged binder down to that of virgin asphalt, based on the dynamic shear modulus test results, about 3% would be needed for both A1 and A2 additives.

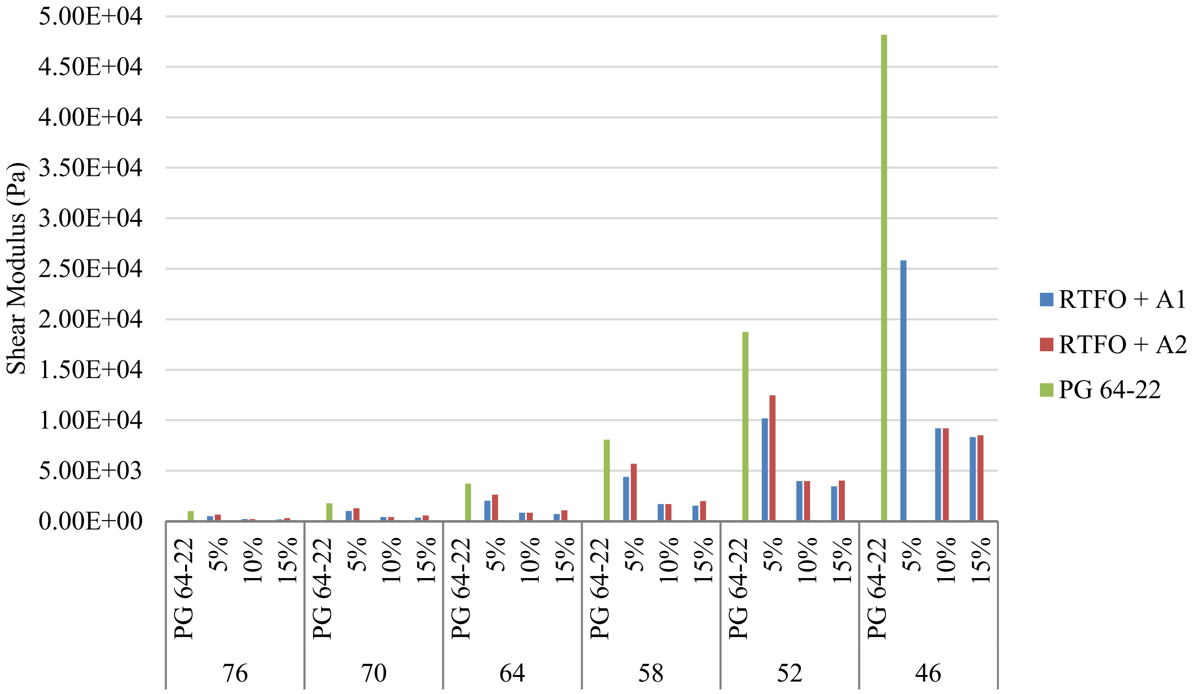

Figure 4. Dynamic modulus of the RTFO aged samples with the additives of A1 and A2

6 WIR MIXTURE PERFORMANCE TEST

The moisture susceptibility of the WIR mixtures with the additives of A1 and A2 was evaluated using the Hamburg Wheel Track (HWT) equipment. First, the optimum bitumen content of 100% RAP material was determined. Second, the 100% RAP mixture with two types of additive were prepared. Third, to evaluate the moisture susceptibility, the HWT test was performed.

6.1 Aggregate gradation

In order to determine the aggregate gradation of the RAP material and bitumen contents, five RAP samples were burned off using the burn-off oven. The average gradation of five samples are plotted in Figure 5. Although the aggregate gradation did not meet the Superpave graduation requirements, it was adopted as is for this research because the purpose of the study is to use the in-place RAP materials as is without adding additional aggregates in the field.

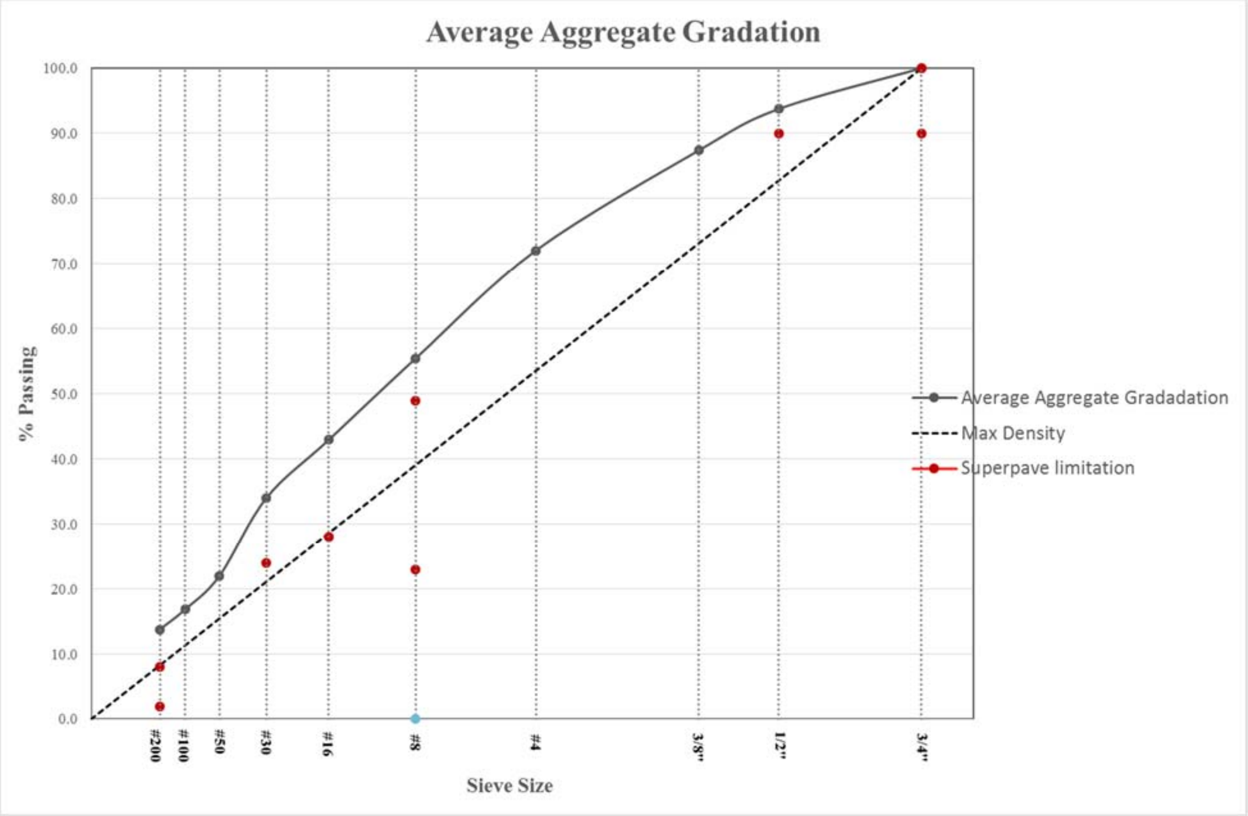

Figure 5. Gradation of extracted aggregates from the RAP stockpile

6.2 Optimum Binder Content

The mixing and compaction temperatures of the control HMA mixtures in the laboratory were selected as 155˚C and 145˚C and those of WIR mixtures were lowered by 20˚C to 135˚C and 125˚C, respectively. Since the 100% RAP materials were to be used, the bitumen content in RAP materials would play a key role in determining the optimum bitumen content. Because RAP materials were stockpiled outside, they contained high moisture contents. First, to determine the moisture content, they were dried in the oven at 120˚C. Next, to determine the bitumen content, the weights of five samples before and after the burn-off test were measured. The average bitumen and moisture contents of the five samples were 4.86% and 4.79%, respectively.

As summarized in Table 1, the Superpave mix design was performed on the 100% RAP materials and the air voids were below the optimum value of 4%. Therefore, in order to increase the air voids to 4%, the bituminous binder should be reduced or a new aggregates structure would be needed. Since neither of them can be done for in-place recycling, samples with 100% RAP materials were compacted as is.

Table 1. Mix design properties of 4.86% bitumen content existing in RAP materials

Mix Design Properties	Value	Mix Design Criteria
Air Voids	1.76%	4.00%
Binder Content (%)	4.86%	----
Bitumen Absorption Pba	0.38%	
Effective Bitumen content Pbe	4.44%	
Voids in Mineral Aggregate (VMA, %)	12.32%	Minimum 14%
Voids Filled with Asphalt (VFA, %)	84.87%	75% - 85%
Dust to Binder Ratio (P0.075/Pbe)	3.1	0.6 - 1.4
Film Thickness (µm)	14.31	8.0 - 15 µm
Gmb	2.412	
Gmm	2.458	

6.3 Hamburg Wheel Track testing of 100% RAP mixtures

The Hamburg Wheel Track test was performed to evaluate the moisture susceptibility of 100% RAP mixtures with and without WIR additives. As summarized in Table 2, three samples were prepared for each of five different mixture types of the control HMA mix and HMA and WIR mixes with two different additives.

Table 2. Mixing and compaction temperatures for each mix type

No	Material	Type of additive	Mixing Temperature	Compaction Temperature
1	100 % RAP	HMA without additive	155 ˚C	145 ˚C
2	100 % RAP	HMA with A1	155 ˚C	145 ˚C
3	100 % RAP	HMA with A2	155 ˚C	145 ˚C
4	100 % RAP	WIR with A1	135 ˚C	125 ˚C
5	100 % RAP	WIR with A2	135 ˚C	125 ˚C

The dosage rate of the additives was determined as 10% of the binder (0.486% by weight of the mix) was added to the mixes. For each type of mixtures, three test samples were gyrated up to a target air void of 7.0% ± 0.5 %. In order to prepare three HWT samples, six specimens were prepared for each mix type.

Table 33 summarizes the number of gyrations applied for each mix type to get 7% air voids. It is interesting to note that WIR with A1 required the least number of gyrations of 13.3 followed by HMA with A2. The test results for each mix type mix are summarized in

Table 14 and the average test results for all mix types are plotted in

Figure . The HMA without any additive performed best followed by the HMA with A2, WIR with A2, HMA with A1 and WIR with A1. Overall, mixtures with A2 performed better than mixtures with A1.

Table 3. Number of gyrations needed for compacting six HWT samples for each mix type

Group	Material	Mix	Samples						Average
			1	2	3	4	5	6	
1	RAP	HMA	21.5	18	19	22	26	26	21.5
2	RAP+A1	HMA	21.5	19	18	24	22	24	21.5
3	RAP+A2	HMA	16	16	14	18	15	15	15.7
4	RAP+A1	WMA	14	14	14	12	15	11	13.3
5	RAP+A2	WMA	28	22	22	21	26	20	23.2

Table 1. Hamburg Wheel Test results for all samples of all mixture groups

Mix Type	Test ID	Air Voids, %	Total Number of Passes	Slope Inflection Point	Max. Rut Depth, mm
RAP @HMA Temp	RAP 1	6.48%	20000	>20000	1.7
	RAP 2	6.95%	20000	>20000	2.1
	RAP 3	6.70%	20000	>20000	1.8
	Average	6.71%	20000	>20000	1.9
RAP+A1@HMA Temp	RAP+A1-1	7.10%	20000	10501	4.3
	RAP+A1-2	7.15%	20000	9397	10.6
	RAP+A1-3	6.56%	20000	10243	7.0
	Average	6.86%	20000	10086	7
RAP +A2 @HMA Temp	RAP+A2-1	6.56%	20000	>20000	3.2
	RAP+A2-2	6.75%	20000	>20000	4.7
	RAP+A2-3	6.86%	20000	>20000	3.0
	Average	6.72%	20000	>20000	3.6
RAP +A1 @WMA Temp	RAP+A1-1	6.87%	20000	9456	16.3
	RAP+A1-2	7.33%	15800	9238	20.0
	RAP+A1-3	7.15%	14400	2221	20.0
	Average	7.24%	16733	5025	19
RAP +A2 @WMA Temp	RAP+A2-1	6.85%	20000	13235	5.1
	RAP+A2-2	6.98%	20000	13357	5.3
	RAP+A2-3	6.74%	20000	13425	5.7
	Average	6.86%	20000	13497	5

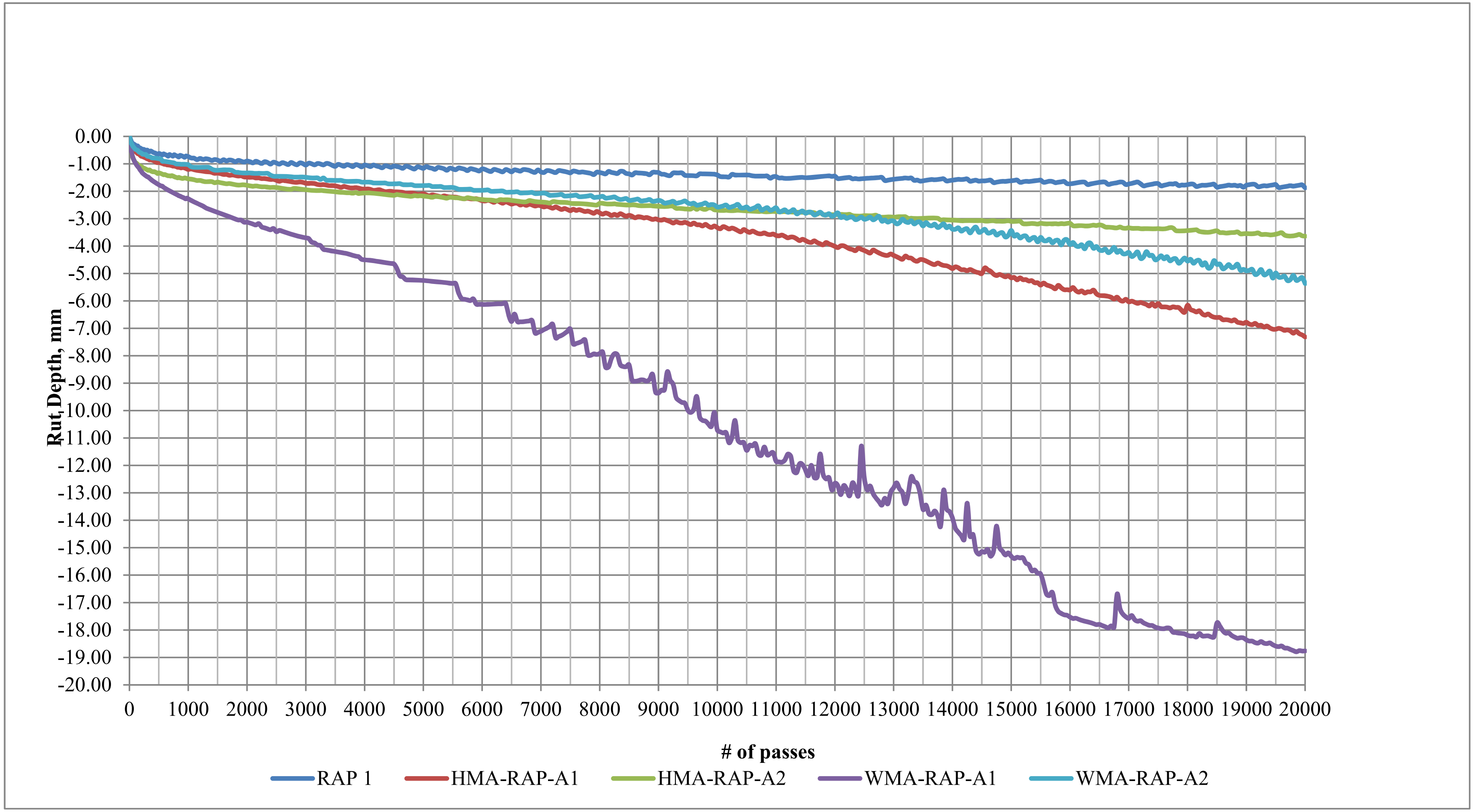

Figure 6. Average test results of Hamburg Wheel Tracking test for all mixture types

6.4 Disk-Shaped Compact Tension Test

The Disc-Shaped Compact Tension (DCT) test was performed to evaluate the low-temperature cracking properties of the 100% RAP mixtures: 1) WIR without additive, 2) WIR with A1 and 3) WIR with A2. Three WIR samples were mixed at 125 ˚C and compacted at 115 ˚C for each mix type. The dosage rate of A1 and A2 were 7% and 11% (including 4% SBS), respectively. A standard test temperature for DCT specimens was selected as a temperature that is 10°C warmer than the PG low temperature limit, which is -12 °C.

Loads applied on 100% RAP mixtures are plotted against CMOD in

Figure 77. As can be seen from this figure, RAP with A2 exhibited not only higher peak load but also higher fracture energy (calculated as an area under the curve). RAP with A1 exhibited a slightly lower peak load but its peak load did not drop as quickly as the RAP mixtures without any additive resulting in a higher fracture energy.

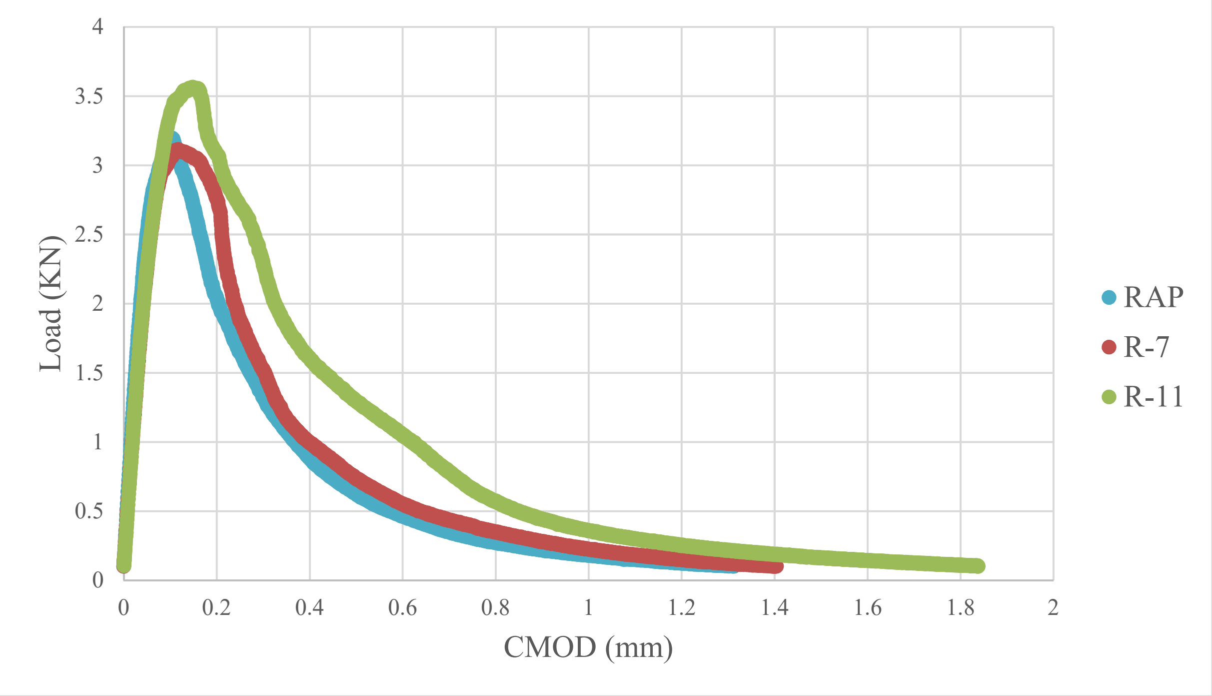

Figure 7. Load vs CMOD of RAP specimens without additive, 7% A1 and 11% A2.

Fracture energy values for all samples are summarized in

Table 5 and the average fracture energy value for each mix type is plotted in Figure 8. A fracture resistance of 100% RAP mixtures is increased as A2 or A1 is added. It can be concluded that A2 is more effective in increasing the fracture resistance than A1.

Table 5. Fracture energy (J/m) of all the specimens

100% RAP					100% RAP + 7% A1				100% RAP + 11% A2				
1	2	3	4	Average	1	2	3	Average	1	2	3	4	Average
222	247	257	213	234.75	367	294	361	340.6	391	345	426	389	387.5

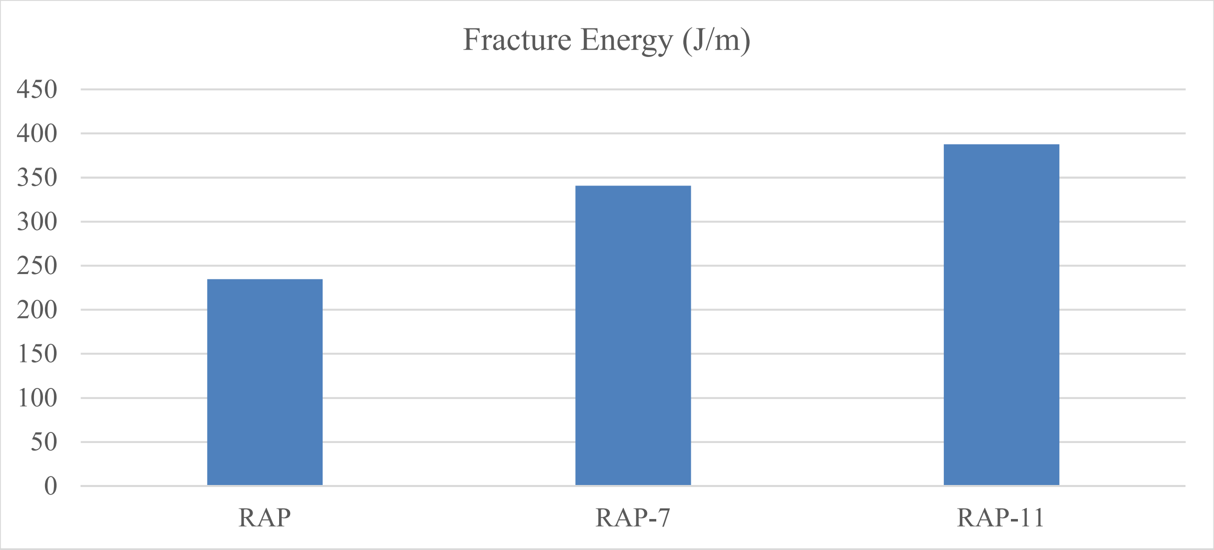

Figure 8. Average fracture energy of specimens

7 SUMMARY AND CONCLUSIONS

First, a new Warm In-place Recycling (WIR) equipment is being developed for recycling asphalt pavements with significantly reduced amounts of emission. The purpose of this WIR technology is to recycle old asphalt pavements in the field while reducing the amount of carbon dioxide generated during construction. The emission controlled heating equipment reduces the emission by capturing the volatile organic compounds generated during the heating process, which would lead to the eco-friendly pavement recycling practices.

Second, to develop new WIR additives, soybean oil was blended with various amounts of three amide type anti-stripping additives: 1) ethylenediamine (ED), 2) 2-hydroxyethyl ethylenediamine (HEED) and 3) Tetraethylenepentamine (TEPA). The formation of amide bonds was successfully achieved in the laboratory, which has been confirmed using the FT-IR and 1H-NMR equipment. Based on the bituminous bond strength (BBS) test results, PG 64-22 binder with antistripping additive synthesized from TEPA exhibited the higher moisture resistance than those synthesized from ED and HEED. To enhance the stiffness of the WIR additive, the SBS polymer was also added to TEPA/Soybean-based additive.

Third, the viscosity and dynamic modulus values were measured at different temperatures and the optimum WIR additive content should be between 5.2% and 10%

based on viscosity and 3% based on dynamic modulus values. Moisture susceptibility and low temperature cracking resistance of WIR mixtures with additives were tested using Hamburg Wheel Track (HWT) and Disc-Shaped Compact Tension (DCT) test equipment, respectively. Overall, it can be concluded that TEPA/Soybean/SBS-based WIR additive was more effective in increasing both moisture and lower temperature cracking resistance than the WIR additive without SBS.

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