Laboratory Evaluation of Warm Mix Asphalt Incorporating High RAP Proportion by Using Evotherm and Sylvaroad Additives

Dai Xuan Lu,[1] Mofreh Saleh[2]

[1] Postgraduate student, University of Canterbury, Christchurch, New Zealand.

[2] PhD, P.E., F.ASCE, Associate Professor in Civil Engineering, University of Canterbury, Christchurch, New Zealand.

ABSTRACT

Warm mix asphalt (WMA) has gradually become more popular in the roading industry. Compared to traditional hot mix asphalt (HMA), WMA can bring numerous benefits, such as lower energy consumption, lower emissions, and higher ability of incorporating a high proportion of reclaimed asphalt pavement (RAP) in WMA mixtures. Incorporating RAP in WMA is an interesting topic as RAP and WMA can increase the sustainability benefits, and they can enhance the performance of WMA. This study investigated the performance of WMA adding RAP with different proportions, from 0 to 70% by mass of WMA. The performance of mixtures was compared with a control HMA. One type of binder, 80/100 penetration grade, and two types of additives were used, namely Evotherm 3G and Sylvaroad. Evotherm is a well-known additive, which has been used worldwide. Conversely, Sylvaroad is a relatively new additive, of which there are few studies so far. Tests were done on the binder's viscosity and mechanical performance of mixtures such as moisture resistance, fatigue cracking and rutting resistance. The results showed that Evotherm and Sylvaroad reduced the viscosity of the binder. Mixtures with Evotherm performed better than other mixtures in terms of moisture resistance. Only WMA-Sylvaroad showed a higher number of cycles to fatigue failure than the control HMA. For rutting resistance, the increase in RAP proportion greatly improved the performance of WMA mixtures. WMA without RAP had a lower number of cycles to reach maximum rut depth than the HMA. All WMA-RAP mixtures showed considerably better rutting resistance than the HMA.

Keywords: RAP, Evotherm, Sylvaroad, Aged binder, Mechanical performance

1. Introduction

Warm mix asphalt (WMA) technologies were introduced for the first time in Europe in 1996 (Yang et al. 2012), and have become increasingly popular in the roading industry in the United States and Europe (Lee et al. 2009). There have been numerous trial road sections paved with WMA in Europe (D'Angelo et al. 2008) and the United States (Zhang 2010). WMA is usually produced at lower temperatures, from 30°C to 50°C lower than conventional hot mix asphalt (HMA) (D'Angelo et al. 2008, Yang et al. 2012). There has been limited information about long-term performance of WMA so far (D'Angelo et al. 2008, Mogawer et al. 2011), but using WMA clearly has many benefits compared to traditional HMA, such as lower energy consumption, lower emissions, better working conditions (D'Angelo et al. 2008, Mogawer et al. 2011). Moreover, WMA enables to add high proportions of reclaimed asphalt pavement (RAP) to asphalt mixtures. Using RAP in the mix design utilises the aggregate and binder of reclaimed asphalt. This reduces the material requirement for new materials as well as the amount of old pavement going to landfill.

Because of the oxidation during pavement service life, the binder in RAP becomes stiffer. This can compensate for the softness of the binder in WMA due to lower mixing temperatures compared to HMA. This improves rutting resistance of WMA-RAP mixtures (Mallick et al. 2008, Nejad et al. 2014, Rogers 2011, Zhao et al. 2013). However, aged binder in RAP also makes mixtures harder and more brittle which may reduce the fatigue (Guo et al. 2014, Rogers 2011) and low temperature cracking resistance (Guo et al. 2014).

In 2013, Arizona Chemical Company released a WMA technology product called Sylvaroad™ RP 1000. This product is made from Crude Tall Oil and Crude Sulphate Turpentine, pine chemicals produced by the pulp and paper industry (Kristina 2015). The product was developed to increase the ability of adding higher RAP proportion while still maintaining good performance of warm mixtures (Chemical 2013). So far, there have been limited published research articles about this new product although its information can be found on unpublished media such as the company's website. The objective of this is to investigate the potential of Sylvaroad as a warm mix additive and compare it with other additives such as Evotherm. In order to do so, WMA and WMA-RAP mixtures using Evotherm 3G, and HMA were prepared for comparison with WMA and WMA-RAP mixtures using Sylvaroad. The authors carried out the investigation into the effect of additives on binder's viscosity, moisture susceptibility, fatigue and rutting resistance based on laboratory tests.

2. Materials and mixture designs

2.1 Materials

To prepare specimens for testing, one type of bitumen with penetration grade 80/100, two types of chemical additives, Evotherm 3G and Sylvaroad were used. Virgin aggregates, bitumen and RAP were secured from a local contractor in Christchurch, New Zealand. The basic properties of RAP are shown in Table 1.

Evotherm and Sylvaroad are used to enhance coating and workability of mixtures at lower production temperatures. Both of the two additives are in liquid form. In this research, both Evotherm and Sylvaroad were directly added to the heated binder at 115°C before mixing. The addition percentages of Evotherm and Sylvaroad were 0.5% and 2% by mass of the total binder, respectively.

Table 1. Basic properties of RAP

Sieve Size (mm)	Percentage Passing of extracted aggregates	New Zealand specification for AC10 M10:2014 aggregate gradation	RAP properties

13.2	100	100	
9.5	98	90-100	Bitumen content in RAP
6.7	83.3	68-82	P_b = 4.8 (%)
4.75	68.3	50-70	
2.36	49.3	32-51	Extracted aggregate bulk specific density
1.18	36.9	22-40	
0.6	30.2	15-30	G_{sb} = 2.607 (g/cm^3)
0.3	23.3	10-22	
0.15	15	6-14	
0.075	9.7	4-7	

2.2 Mix design

There were five mixtures designed in this study, comprising HMA, WMA and WMA with 25%, 50% and 70% of RAP. New Zealand standard AC 10 dense graded asphalt mix was used in this research. The AC 10 is a dense graded mix with a maximum nominal aggregate size of 10 mm. For HMA, the mixing and compacting temperatures were same at 142°C according to the AS/NZS 2891.2.1:2014 (AS/NZS 2014a) and AS/NZS 2891.2.2:2014 (AS/NZS 2014b). The WMA and WMA-RAP mixtures were mixed and compacted at 115°C and 110°C respectively, for both Evotherm and Sylvaroad. The WMA aggregate gradation was utilized the same as the HMA. The WMA-RAP aggregate gradations were almost the same as HMA and WMA as shown in Figure 1.

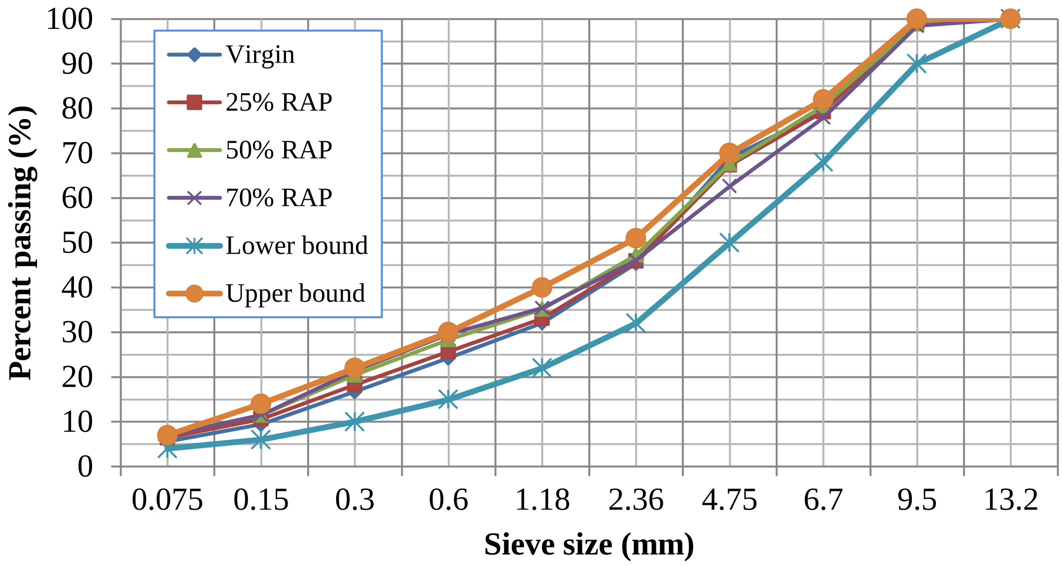

Figure 1. Gradation curves of mixes

The gyratory compactor was used to compact the asphalt mix specimens in this study. All asphalt mix specimens for the mix design purpose were prepared with a height of 85 mm and a diameter of 150 mm. According to the AS/NZS 2891.2.2:2014(AS/NZS 2014b) standards, the number of gyrations was adjusted at 120; the ram pressure was 240 kPa for heavy traffic; and the gyration angle was maintained at 3°. Optimum binder contents were chosen at the target air void of 4% as shown in Table 2. In the case of WMA and WMA-RAP, optimum binder contents were designed for mixtures with Evotherm. These optimum binder values were adopted for mixtures with Sylvaroad, for the purpose of comparisons the effectiveness of Sylvaroad with that of Evotherm for the same mixture design.

Table 2. Mix design properties

Mix type	**HMA**	**WMA**	**25RAP**	**50RAP**	**70RAP**
V_a(%)	4	4	4	4	4
P_b(%)	5.1	4.8	4.6	4.3	4.2

VMA (%)	15.1	14.6	13.9	13.6	13.2
VFB(%)	73.5	72.5	71.1	70.6	69.7
G_{mm} (g/cm^3)	2.452	2.459	2.468	2.463	2.47

Where: V_a: air void content, P_b: optimum binder content by mass of the total mix, VMA: void in mineral aggregate, VFB: voids filled with bitumen, G_{mm}: maximum specific gravity

3. Test methodology

3.1 Viscosity test

In this study, the viscosity test was carried out on the unaged and aged binder with and without Evotherm and Sylvaroad, to evaluate the effect of the two additives on the binder's consistency. In the case of unaged binder, the additives were added directly into the heated virginbinder for testing. In the case of aged binder, the virgin binder was aged by using the rolling thin film oven. The authors used the rolling thin film oven with the aim to age the binder, simulating the binder oxidation at different levels similar to the long-term ageing in the field. The purpose of this was to study the effect of the additives on the viscosity of aged binder and therefore determining their ability and effectiveness in rejuvenating aged binders in the RAP.

For the long term ageing simulations in this study, the procedure used to age the binder was in accordance with the ASTM D2872 – 12 “Standard test method for effect of heat and air on a moving film of bitumen (Rolling thin-film oven test)” (ASTM 2013). However, the ageing temperature was chosen at 125°C, and the tests were conducted for 24 hours. Similar to the unaged binder, the aged binder was also subjected to the viscosity tests with and without the additives. The viscosity tests were conducted at 100, 115, 130, 145 and 160°C. The tests were carried out from the lowest temperature to the highest temperature consecutively.

Table 3: Viscosity results of unaged and long-term agedbinder with and without Evotherm

	Unaged binderviscosity (m.Pa.s)					Aged binderviscosity (m.Pa.s)				
Temp (Deg. Celsius)	100	115	130	145	160	100	115	130	145	160
80/100 virgin	4554	1690	728	363	198	19200	5179	1770	761	352
80/100 virgin + 0.5% Evotherm	4188	1545	677	341	182	14150	4242	1554	664	328
80/100 virgin + 1% Evotherm	3530	1350	593	306	166	11192	3500	1355	600	302
80/100 virgin + 1.5% Evotherm	3275	1265	540	276	N/A	9200	3087	1195	560	282
80/100 virgin + 2% Evotherm	3100	1165	520	265	N/A	N/A	3040	1189	529	273

Table 4: Viscosity results of unaged and long-term aged binder with and without Sylvaroad

	Unaged binderviscosity(m.Pa.s)					Aged binderviscosity (m.Pa.s)				
Temp (Deg. Celsius)	100	115	130	145	160	100	115	130	145	160
80/100 virgin	4554	1690	728	363	198	19200	5179	1770	761	352
80/100 virgin + 0.5% Sylvaroad	3888	1485	630	315	166	15550	4621	1660	733	344
80/100 virgin + 1% Sylvaroad	3588	1340	588	288	159	12250	3925	1495	650	325
80/100 virgin + 2% Sylvaroad	3095	1207	529	264	147	9892	3400	1385	630	311
80/100 virgin + 4% Sylvaroad	2040	825	388	205	N/A	7475	2695	1123	516	264

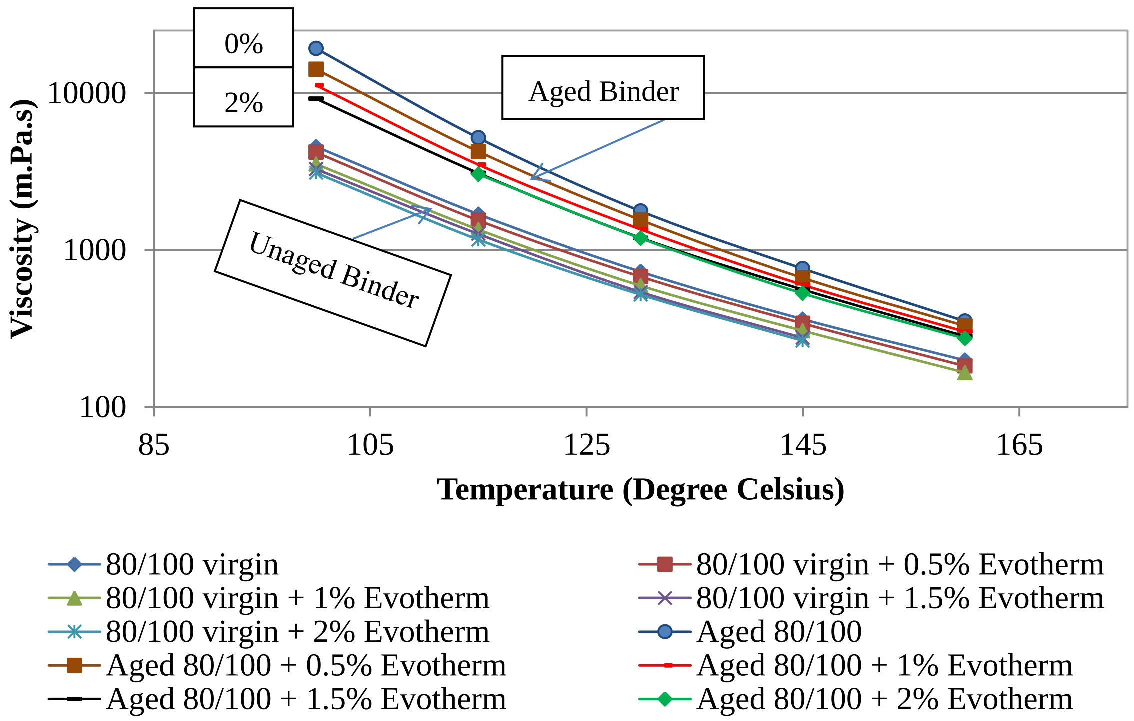

Figure 2. Viscosity results of unaged and long-term aged binder with and without Evotherm

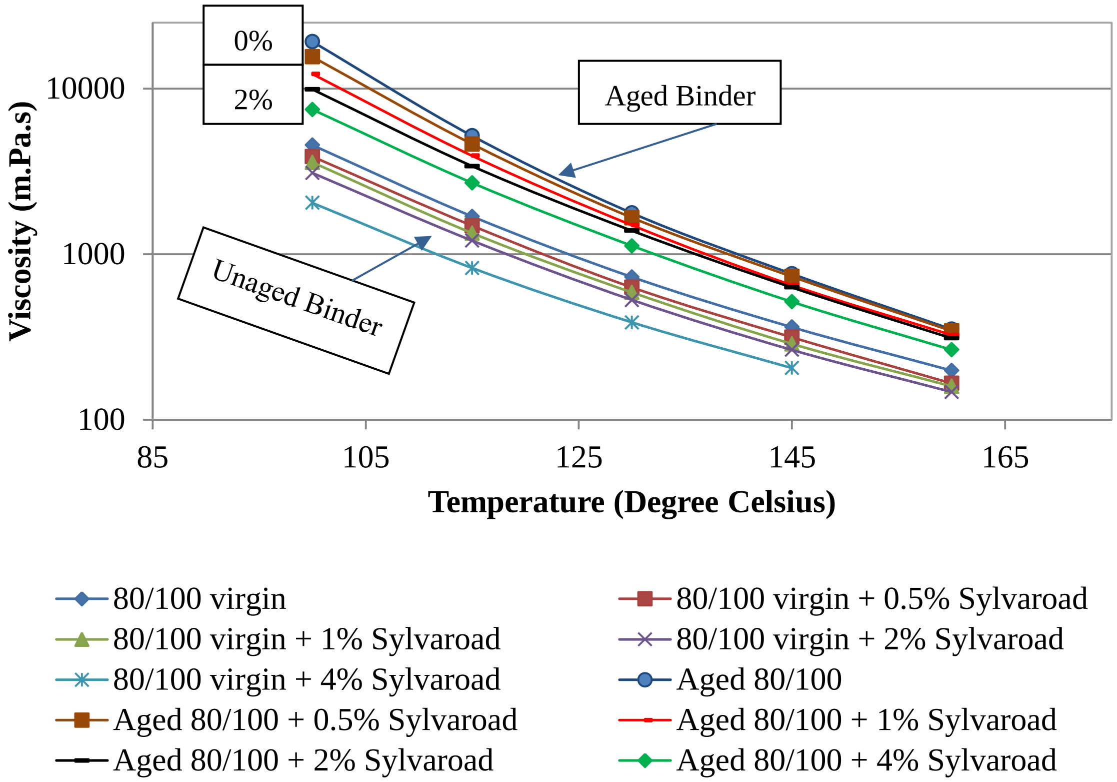

Figure 3. Viscosity results of unaged and long-term aged binder with and without Sylvaroad

Tables 3, 4 and Figures 2, 3 show the results from the viscosity test. It can be seen clearly that both Evotherm and Sylvaroad reduced the binder's viscosity in both unaged and aged cases. Furthermore, increasing the proportions of additives decreased the binder's viscosity. In the case of unaged binder, Sylvaroad performed slightly better in viscosity reduction than Evotherm at the same additive proportions. This effect was observed for the proportions of additives used later in mixtures for mechanical performance testing, the binder with 0.5% Evotherm had relatively higher viscosity compared to that of the binder with 2% Sylvaroad.

In terms of aged binder, it can be seen that the binder became harder after a long-term ageing. This was indicated via considerably higher viscosities of the aged binder at all test temperatures than unaged binder. Evotherm and Sylvaroad greatly reduced the binder's viscosity. The aged binder with 0.5% Evotherm still showed considerable higher viscosities than when 2% Sylvaroad was added to it.Unlike the unaged binder, Evotherm reduced the binder’s viscosity slightly more than Sylvaroad at the same additive addition proportions. It may be that Evotherm is more of WMA product rather than the rejuvenator Sylvaroad, as Sylvaroad was developed with the purpose to be an rejuvenator to act directly with RAP (Chemical 2013) rather than being a WMA additive.Further investigation into the effect of Evotherm and Sylvaroad on the viscosity of aged binder is recommended to come up with a more robust conclusion.

3.2 Mechanical performance tests

3.2.1 Moisture resistance

To investigate the moisture susceptibility of the mixes , the moisture resistance test was carried out according to the AG:PT/T232 (AG:PT/T232 2007). Cylindrical samples were produced with a diameter of 150 mm and a height of 85 mm.All the test samples had the air voids in a range of $8.0 \pm 1.0\%$. The test results were evaluated based on the tensile strength ratio (TSR) of each mixture. The TSR is the ratio of the average indirect tensile strength (ITS) of samples in wet condition to the average ITS of samples in dry condition. To determine the TSR values, six samples were produced for each mixture, and they were divided into dry and wet subsets. Three samples of dry and wet conditions were subjected to ITS test. For dry samples, they were conditioned in a temperature control chamber at 25°C for 2 hours before testing. For wet samples, firstly they were saturated in vacuum at 50°C to achieve 55-80% saturation degree. After that, they were conditioned in water at 60°C for 24 hours. Finally, the samples were conditioned in water at 25°C for 2 hours before testing. TSR values of 80% or greater are recommended for the moisture resistance of asphalt mixtures.

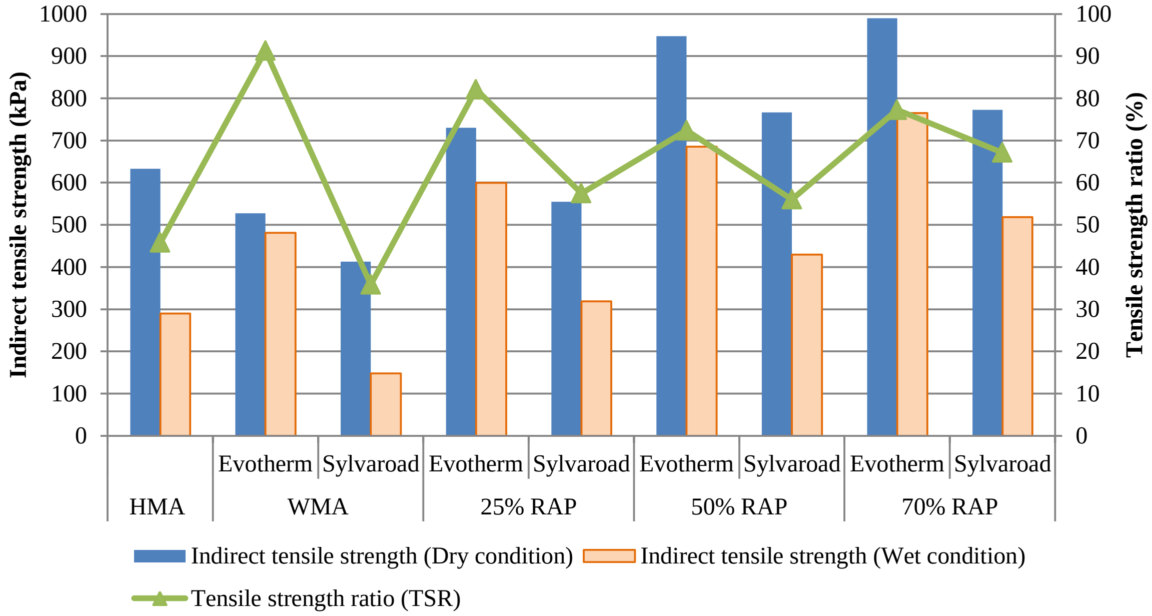

Figure 4. Moisture resistance test results

Figure 4 shows the results from the moisture resistance test of HMA, WMA and WMA-RAP mixtures using Evotherm and Sylvaroad. The majority of the mixtures in this study had a lower tensile strength ratio than 70% with the exception of WMA and WMA-RAP mixtures using Evotherm. The addition of Evotherm is observed to greatly improve the moisture resistance of the mixtures compared to HMA. TSR values of both WMA and WMA-25%RAP mixtures using Evotherm passed 80%.

It can also be observed from Figure 4 that the HMA and the mixtures with Sylvaroad had TSR values lower than 70%. Considerable stripping was observed in the cases of these mixtures. The HMA and WMA with Sylvaroad were the most severe cases of stripping, while the WMA-RAP with Sylvaroad mixtures showed less stripping, but still to an unacceptable level. The results indicate that Sylvaroad may have a negligible effect on moisture resistance of the mixtures. Conversely, when increasing the RAP portions in the mixtures with Sylvaroad, the TSR increased. These results point out that RAP may enhance the moisture resistance of mixtures. The reason for that is the bond between the aged binder and aggregate in RAP is stronger than the bond between virgin binder and aggregate. Thus, with the increase in RAP content, the moisture resistance of mixtures enhanced. Similar results can also be found in a research of Zhao (Zhao et al. 2013).

So far, Sylvaroad is still a relatively new product and there are not many publications regarding its performance. In the very latest report (Turner et al. 2015) which discusses Sylvaroad performance characteristics, the WMA mixtures with 50% of RAP were produced with and without Sylvaroad to study the moisture resistance. Sylvaroad was directly added and mixed with RAP for 30 seconds before adding virgin aggregate and binder.The results showed that the mixture with Sylvaroad was softer than the mixture without Sylvaroad. This was shown to be true in both wet and dry conditions although the TSR values were the same at 80%. There was no conclusion drawn from this study for the effect of Sylvaroad on the moisture resistance of the mixtures. Although the way to produce mixtures with RAP and the additive in the report (Turner et al. 2015) is different from this study, the results from the report seems to agree with the aforementioned statement about the effect of Sylvaroad on moisture resistance of mixtures.

From the viscosity and moisture resistance tests results, it can be summarized that Sylvaroad greatly reduced the viscosity of binder. However, as aforementioned, Sylvaroad seems not be greatly affect the moisture resistance of mixtures. On the other hand, 0.5% Evotherm reduced the viscosity of mixtures significantly less than 2% Sylvaroad, while it increased the adhesion between aggregate and binder. Because 0.5% Evotherm showed its limitation in the viscosity reduction, the binder in RAP might not mobilize enough to thoroughly cover virgin aggregate in the case of adding too much RAP. For this reason, the authors extended the investigation of moisture resistance by adding Evotherm and Sylvaroad together in the binder with the portion of 0.5 and 1% by mass of total binder respectively. The extension was expected to have better moisture resistance of mixtures, based on adhesion improvement owing to Evotherm, and significant viscosity reduction due to Sylvaroad.

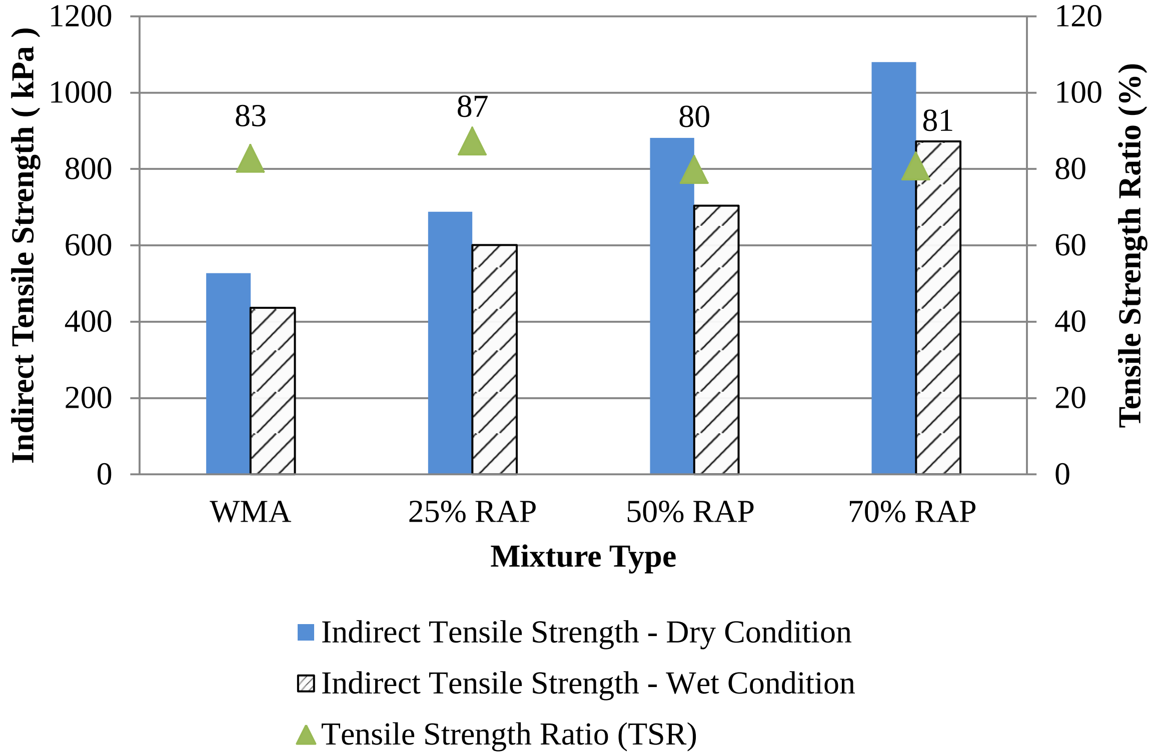

Figure 5. Moisture resistance results of mixtures using both Evotherm and Sylvaroad

Figure 5 shows the results of moisture resistance tests of mixtures using both Evotherm and Sylvaroad. It can be clearly seen from Figure 3 that the moisture resistance of all mixtures was considerably improved compared to the case of using Sylvaroad or Evotherm separetly. All TSR values were equal to or greater than 80%. The WMA-25% RAP demonstrated best among the mixtures. Moreover, the indirect tensile strengths of WMA-70%RAP mixture with Evotherm and Sylvaroad were higher than those of WMA-70%RAP with only Evotherm or Sylvaroad, in both wet and dry conditions. Although the results exhibit an important improvement in moisture resistance, this study did not investigate whether there was chemical reaction between the two additives in the mixtures, and how it affected the behaviors of the mixtures. Thus, further investigation is recommended to study the possibility of combining of these two additives in asphalt mixtures to improve the mechanical performance of the asphalt mixes.

3.2.2 Fatigue test

The four-point bending beam test was utilized to investigate the fatigue resistance of the mixtures. Sample dimension and test set up were prepared according to the AG:PT/T233 “Fatigue life of compacted bituminous mixes subject to repeated flexural bending”(AG:PT/T233 2006). Compacted slabs with a dimension of 305 x 405 x 75 mm were cut into beams, which were 50 mm high, 65 mm wide and 405 mm long. The air void target for test samples was $7 \pm 0.5\%$. The air voids content of test beams in this study werein a range of 6.1% to 7.9%. Constant displacement mode with sinusoidal load wave form with frequency 10 Hz, and maximum strain amplitude of 400 microstrain were applied to all samples. The samples were maintained in a temperature-control chamber for 2 hours before testing. Fatigue life was determined as the number of cycles at which the stiffness of the mix degrades to 50% of the initial flexural stiffness.

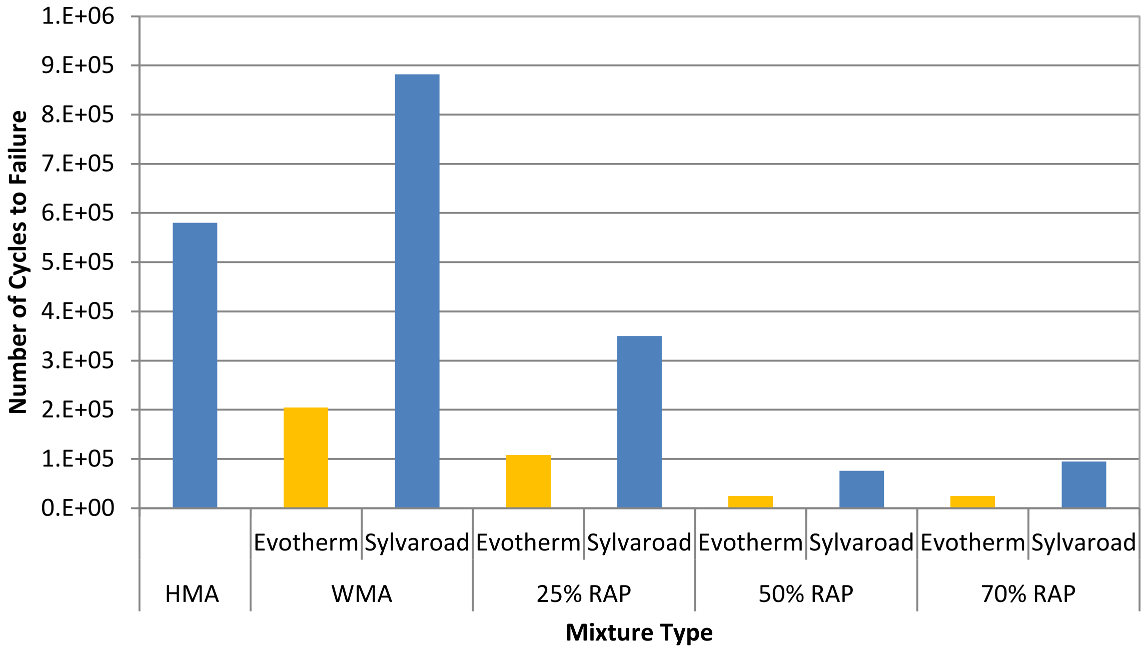

Figure 6. Fatigue lives of the mixtures

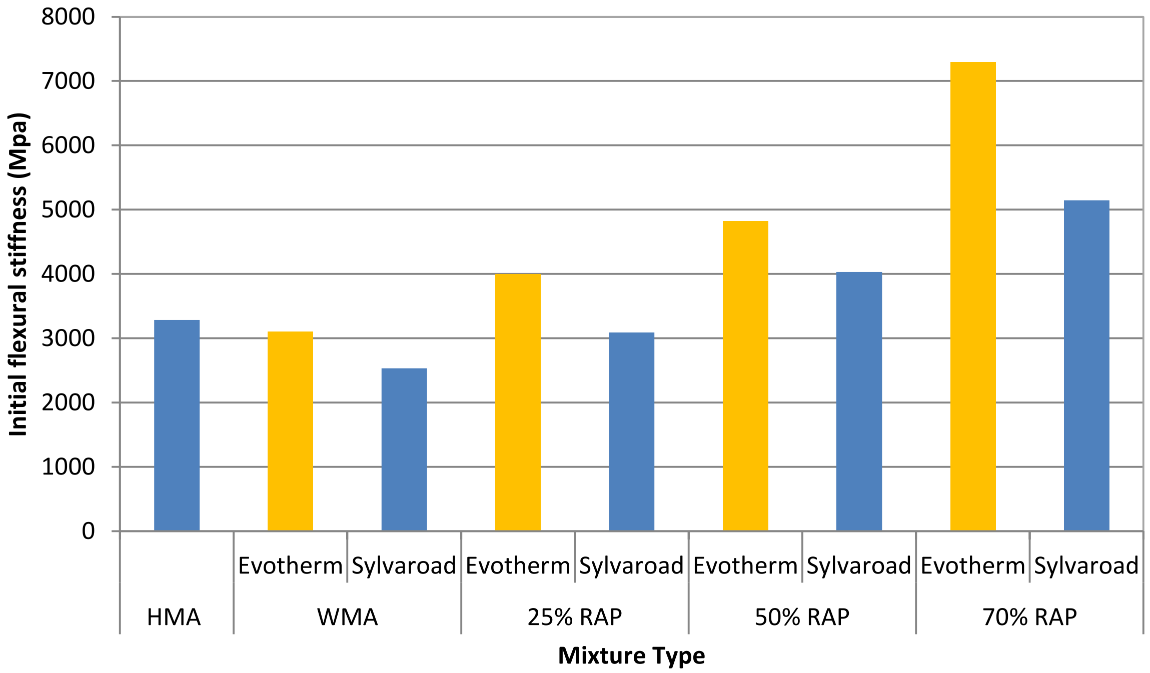

Figure 7. Initial flexural stiffness of the mixtures

Figure 6 shows the fatigue resistance of the mixtures, while Figure 7 displays the initial flexural stiffness of the mixtures in this study. As can be seen in Figure 6, the WMA with Sylvaroad performed best with regard to fatigue resistance. All the other WMA and WMA-RAP mixtures had significantly lower numbers of cycles to reach fatigue failure than that of HMA.

It can also be observed from Figures 6 and 7 that the increase in the RAP proportion enhanced the flexural stiffness, but reduced the number of cycles to fatigue failure for both Evotherm and Sylvaroad mixes. Mixtures with Sylvaroad showed better fatigue resistance compared to the corresponding Evotherm mixtures while Evotherm mixtures were stiffer than Sylvaroad mixtures. It is clearly observed that Sylvaroad made WMA softer; therefore enhancing the flexibility for the mixture. This improved the fatigue resistance of the mixture.

The authors also consider whether adding Sylvaroad directly to the RAP will achieve better softening the aged binderand therefore enhancing the fatigue resistance. Therefore, further investigation on fatigue performance bydirectly adding Sylvaroad to the RAP is recommended.

In this study, to maintain the good fatigue performance, RAP addition proportion is recommened to be limited at 25% for mixtures prepared with Evotherm, and 70% for mixtures with Sylvaroad.

3.2.3 Dynamic modulus test

Dynamic modulus ($|E^*|$) test was conducted to investigate the stiffnesses of the different mixes and therefore to study the permanent deformation resistance of these mixtures. The test was carried out according to the NCHRP Report 614 “Refining the Simple Performance Tester for Use in Routine Practice” (Bonaquist 2008). Cylindrical samples with a diameter of 150 mm and a height of 177 mm were prepared. These samples were cored and sawn to create samples with a diameter of 100 mm and a height of 150 mm. For each mixture, three replicas were prepared. The air voids of the test samples were in a range of 5 ± 1%. The dynamic modulus tests were performed at temperatures of 4.4, 21.1, 37.8, and 50°C, and frequencies of 0.1, 0.5, 1, 5 and 10 Hz. Normally, to avoid damaging samples during testing, the tests were carried out from the lowest temperature to the highest temperature, and from the highest frequency to the lowest frequency.

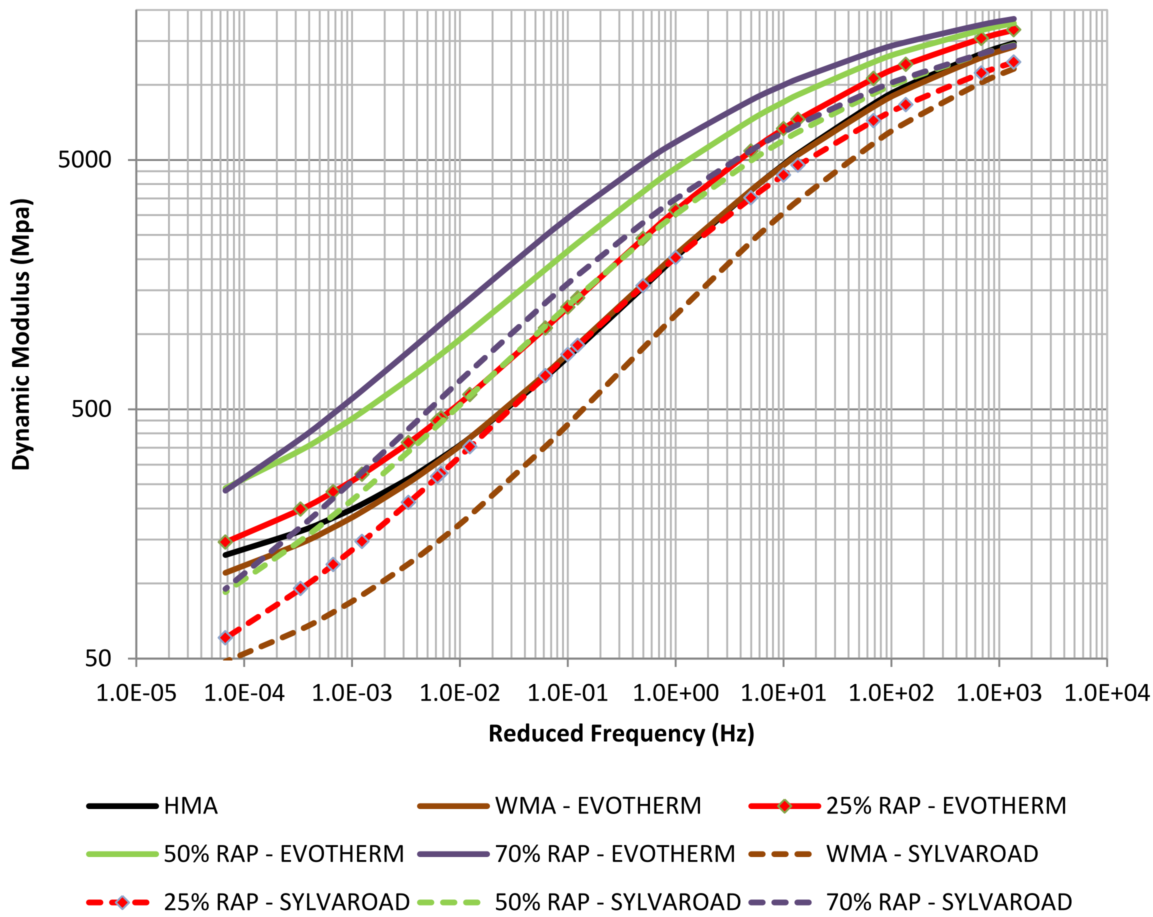

Figure 8. Dynamic modulus master curves of mixtures at the reference temperature of 20^0C.

Figure 8 shows the dynamic modulus master curves of mixtures at the reference temperature of 20°C in this study. It is evident that WMA-70%RAP using Evotherm had the greatest dynamic moduli over a range of frequencies, and WMA-Sylvaroad mixture had the lowest moduli among the mixtures. It can also be seen that WMA-RAP mixtures using Evotherm showed larger dynamic moduli than the other corresponding WMA-RAP mixtures at the same RAP proportions with Sylvaroad. WMA-50%RAP with Sylvaroad had quite similar moduli to WMA-25%RAP with Evotherm in a range from 0.01 to 1 Hz. Beyond this range, WMA-50%RAP tended to have lower moduli than WMA-25%RAP with Evotherm. A similar trend can be seen in the case of WMA-25%RAP with Sylvaroad compared to HMA. In this situation, the dynamic moduli of the WMA-RAP mixture were very similar to those of the HMA at the frequencies ranging approximately from 0.05 to 1 Hz. Outside this range, the WMA-RAP mixture's moduli were lower than the HMA. Another trend also can be observed for WMA-RAP mixtures with Sylvaroad in that they tended to have a considerable reduction in dynamic modulus when being subjected to low frequency loading. All of WMA-RAP mixtures showed lower dynamic moduli than the HMA at frequencies lower than 0.0003 Hz. For mixtures without RAP, the HMA and WMA-Evotherm exhibited quite similar dynamic moduli over a large range of frequencies except when the frequencies were below 0.003 Hz. However, both HMA and WMA-Evotherm demonstrated much greater dynamic modulus values than WMA-Sylvaroad at all frequencies.

3.2.4 Dynamic creep test

The unconfined dynamic creep test was also conducted to evaluate the rutting resistance of mixtures. Repeated haversine axial compressive load pulses were applied on samples for 0.1 second every second. The deviator stress used in this test was 140 kPa, and the contact stress was 7 kPa. As the dynamic modulus test is a non-destructive test, specimens are assumed intact after the test, thus they can be used in the dynamic creep test. Therefore, the same specimens used in the dynamic modulus test were used for this test. The dynamic creep tests were conducted at 50°C, immediately after the dynamic modulus tests finished. During the test, the permanent axial strains and the corresponding number of load pulses were recorded. The test finished when the number of load pulses reached 10000 or the strains reached 54000 micro-strain.

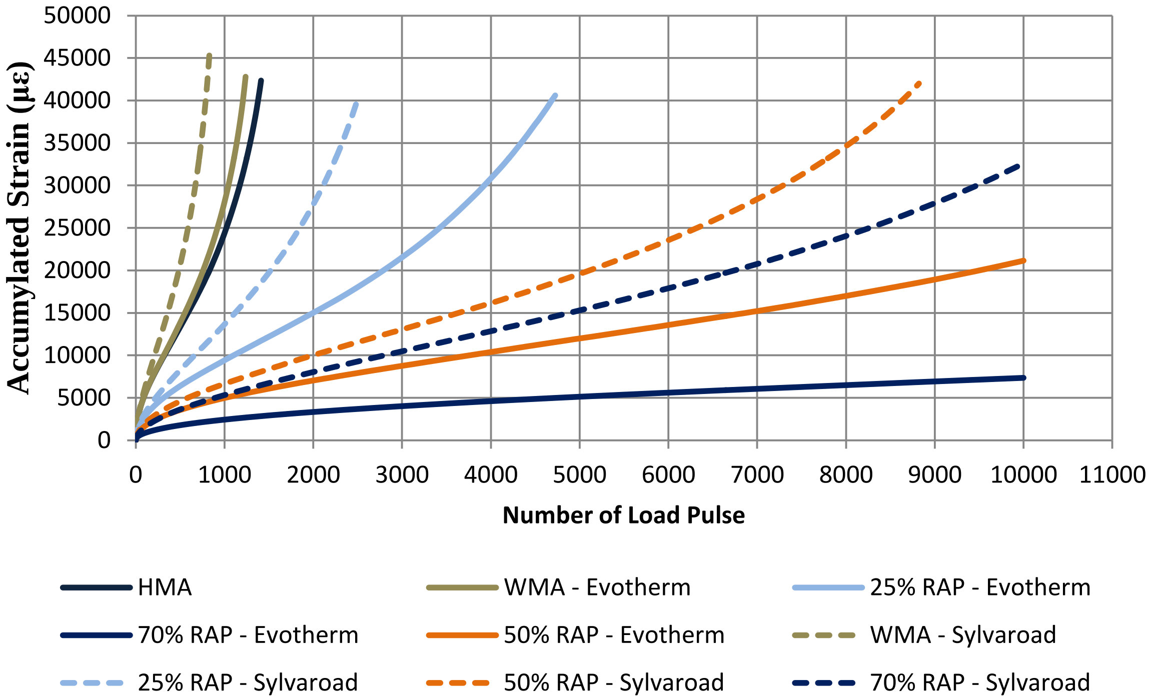

Figure 9. Dynamic creep test results

Figure 9 describes the results from the dynamic creep test in this research. Itcan be seen that, WMA and WMA-RAP mixtures with Evotherm exhibited better rutting resistance than corresponding WMA-RAP mixtures using Sylvaroad. The WMA-70%RAP with Evotherm performed best among mixtures in this study. The WMA-50%RAP with Evotherm occupied the second place. A trend can be clearly observed that with the increase of RAP portion, the rutting resistance of mixtures enhanced, resulting in the reduction of accumulated strains or the increase in the number of load pulses. For mixtures without RAP, HMA showed greater resistance to rutting than WMA. Finally, the WMA-Evotherm mixture performed better than the WMA-Sylvaroad mixture.

3.2.5 Wheel-tracking test

In addition to the dynamic creep test, the wheel-tracking test was carried out to evaluate the rutting resistance of the mixtures. The test was conducted according to the AG:PT/T231 “Deformation resistance of asphalt mixtures by the wheel tracking test”(AG:PT/T231 2006). Slab samples were prepared with dimension of 305 x 305 x 50 mm. The test setup is shown in Figure 10. The slab was restrained at two ends of the travel direction of the wheel, while the slab was free to move laterally. At least two replicates are required for the test by the standard. The air voids are required to be in a range of 5 ± 1%. Three replicates prepared for each mixture among HMA, WMA and WMA-RAP using Evotherm, while two replicates, were produced for each of WMA and WMA-RAP using Sylvaroad. The average air voids of the test samples of each mixture was kept in the range of 4.9–5.9%. To carry out the test, the samples were conditioned in a temperature-control chamber for 7 hours to make sure that the slab reached constant temperature of 60°C. After conditioning, the test was started at the same temperature. During the test, the rut depth and the corresponding number of cycle were recorded. The test terminated whenthe rut depth reached 15 mm or the number of cycle reached 100,000 whichever occurred first.

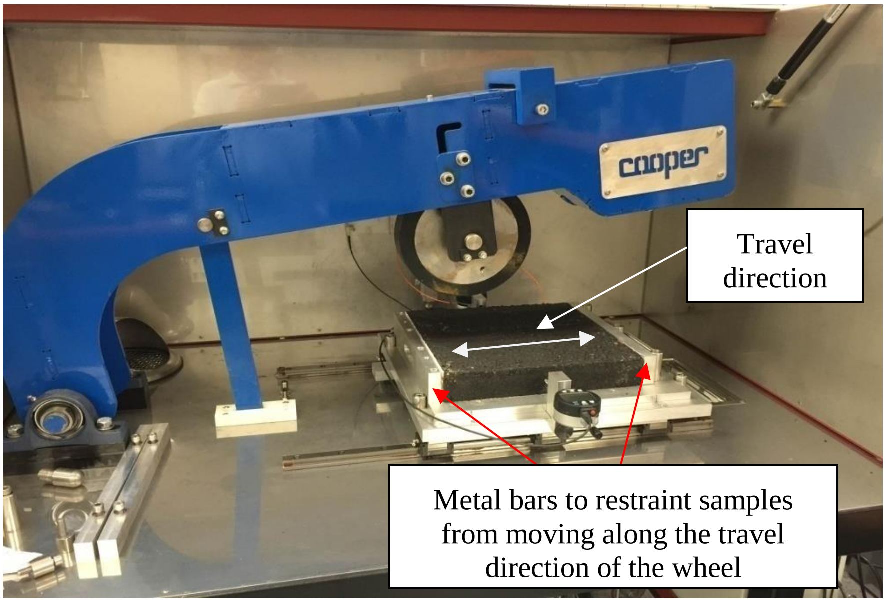

Figure 10. Wheel tracking setup for rutting resistance test

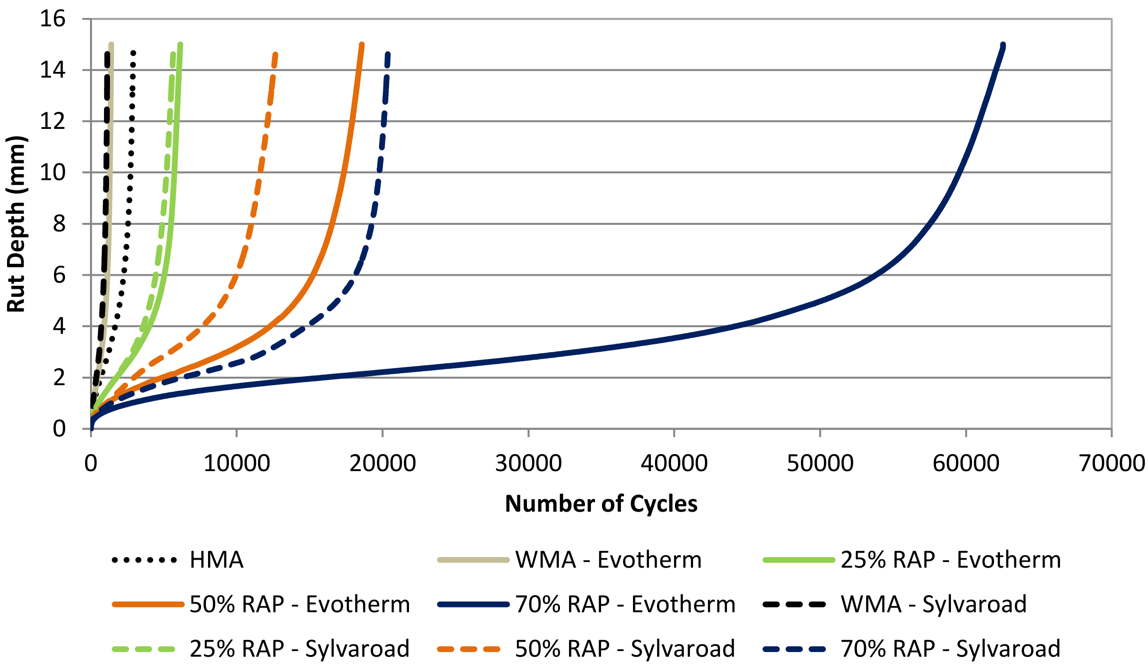

Figure 11. Number of cycles vs rut depth in wheel tracking test

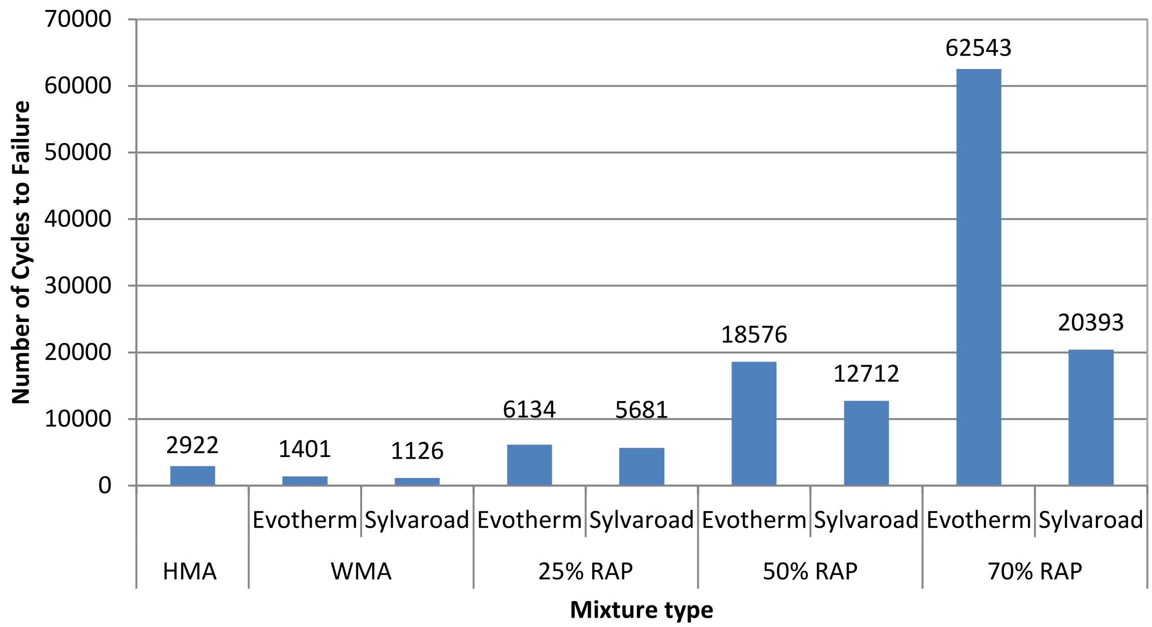

Figure 12. Number of cycles to reach maximum rut depth of 15 mm

Figures 11 and 12 exhibit the results from wheel tracking test in this study. The WMA-70%RAP with Evotherm performed best in rutting resistance compared to all mixes which confirms the results from the dynamic creep test and dynamic modulus test. Conversely, WMA with Sylvaroad had the lowest number of cycles to reach the maximum rut depth.

In terms of mixtures without RAP, HMA showed greater rutting resistance than WMA mixes All WMA mixtures showed considerable improvement in rutting resistance when increasing RAP content.

WMA with 25% RAP increased the number of cycles to reach the maximum rut depth by a factor of 4 to 5 times than the corresponding WMA mixtures without RAP, for Evotherm and Sylvaroad respectively. WMA-50% RAP with Evotherm had slightly lower number of cycles to reach the maximum rut depth than WMA-70% RAP with Sylvaroad, and approximately 1.5 times higher than that of WMA-50% RAP with Sylvaroad. WMA-70%RAP mixture had the greatest number of cycles to reach the maximum rut depth, and approximately 3 times greater than that of the second best performed mixture, WMA-70% RAP with Sylvaroad.

5. Conclusions

To investigate the possibility of adding high RAP content in WMA, WMA mixtures were produced with RAP contents ranging from 0 to 70%, by using one type of binder and two types of warm mix additives. The viscosity tests of the binder and mechanical performance tests of WMA-RAP mixtures were carried out at the Transportation Laboratory, University of Canterbury. The results were compared to those of a control HMA. From the lab-based results, the following conclusions were drawn:

1. Both Evotherm and Sylvaroad reduced the binder's viscosityAnd the reduction increases with the increase of additivecontent. For producing samples for mechanical performance tests, Evotherm was added into the binder at apercentageof 0.5% by mass of the binder while Sylvaroadwas used at 2%. The addition of Sylvaroad showed greater reduction in viscosity than Evotherm.

2. Evotherm enhanced coating and adhesion between aggregate and binder in WMA-RAP mixtures. This greatly improved the moisture resistance of mixtures. All WMA-RAP mixtures with Evotherm showed higher TSR than HMA. WMA and WMA-25%RAP with Evotherm had TSR larger than 80%, while WMA-Evotherm with 50 and 70% RAP showed TSR values greater than 70%. Conversely, Sylvaroad showed negligible effect on the moisture resistance of mixtures. No mixtures with Sylvaroad passed the TSR value of 80 % threshold, and considerable stripping was observed in these mixtures.

3. The combination between Sylvaroad and Evotherm improved the moisture resistance of WMA-RAP mixtures. All of them had the TSR values equal to or higher than 80%.

4. With those results in minds, the authors believe that a 0.5% addition of Evotherm was not a sufficient proportion in the case of 50 and 70% RAP. At this 0.5% addition, the binder was not viscous enough to cover the aggregate thoroughly. For this reason, TSR of WMA-Evotherm, with 50 and 70% RAP, did not pass 80%. From the case of Sylvaroad, it can be deduced that RAP might enhance the moisture resistance of mixtures.

5. The WMA with Sylvaroad had the lowest flexural stiffness, but the greatest resistance to fatigue cracking. Except for WMA-Sylvaroad, HMA showed better fatigue resistance compared with other mixtures. All WMA-RAP with Sylvaroad mixtures had greater fatigue lives than mixtures with Evotherm at the same RAP proportions.

6. WMA mixtures showed considerable improvement in rutting resistance with the addition of RAP. Although WMA with Evotherm and Sylvaroad performed worse than the HMA, other WMA-RAP mixtures exhibited better performance than the HMA. WMA-70% RAP with Evotherm required the greatest number of cycles to reach maximum rut depth. WMA-RAP mixtures with Evotherm performed better thanthe WMA-Sylvaroad with the similar RAP proportions.

7. The maximum recommended RAP proportion is 25% for mixtures with Evotherm in this study. For mixtures with Sylvaroad, RAP proportion can be added up to 70% if the moisture resistance of the mixture is satisfied. As the moisture resistance issue of Sylvaroad mixtures was solved by combining Evotherm into the mixtures, the RAP addition proportion of 70% is possible.

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