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DRAFT

EST 18-07

Mix Design

ThinGap with RARX

Study realised for:

Road Commission of Kalamazoo County

July 2018

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1. Objectives and Scope

The present study objective was to design one asphalt rubberized mixture ThinGap with a bitumen stabilizer RAR (Reacted and Activated Rubber, type RARX).

2. ThinGap mix & Specifications

The formulation and characterization of the asphalt rubber mixture was carried out at Consulpav Lda., and the materials supplied by Road Commission of Kalamazoo County Table 1 shows the composition of the asphalt rubber mixture used in this study.

Table 1 – Composition of the asphalt mixture produced with AR binder

Mixture	Mixture gradation	Bitumen PG	% crumb rubber total blend	% RARX	% AR total asphalt mixture
ThinGap	Thingap-graded	58-28	-	40	11

3. Materials Used

3.1. Aggregates

The aggregates used in this study were provided by Lakeland Asphalt Corp, on 14.06.2018. The aggregates provided came with the following description, 31A, Mansand and RAP (Figure 1). It is important to note that Reclaimed Asphalt Pavement (RAP) is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. These materials are generated when asphalt pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities.

Figure 1 - Aggregates used in the study

For each of the granular materials the gradation was determined according to standard test EN 933-1 (procedure washing and sieving). Table 3 shows the particle size distribution curves obtained.

Table 2 – Aggregates gradation used in the mix design

Sieve size (mm)	Cumulative percentage of past material on The sieve (%)		
	31A	Mansand 1/4´´	RAP
12.5	100.0	100.0	100.0
11.2	100.0	100.0	100.0
9.5	98.3	100.0	100.0
8	79.2	98.9	99.1
6.3	54.5	92.4	92.1
4.75	37.1	75.4	82.6
2.36	15.1	37.7	62.5
1.18	6.8	19.6	46.6
0.6	2.8	10.7	38.9
0.3	1.8	5.7	20.1
0.15	1.4	3.4	9.1
0.075	1.1	2.4	5.2

For setting the aggregate gradation envelope of the ThinGap it was used as base the aggregate gradation envelope developed for this mixture that is showed in Table 3.

Table 3 – Specified aggregate gradation envelope for ThinGap

Sieve size (mm)	Cumulative percentage of past material on the sieve (%) ThinGap	
12.5	100	100
10	100	100
4	28	45
2	12	25
0.063	1	4

The specified aggregates gradation envelope limits are represented in Figure 2, respectively for ThinGap.

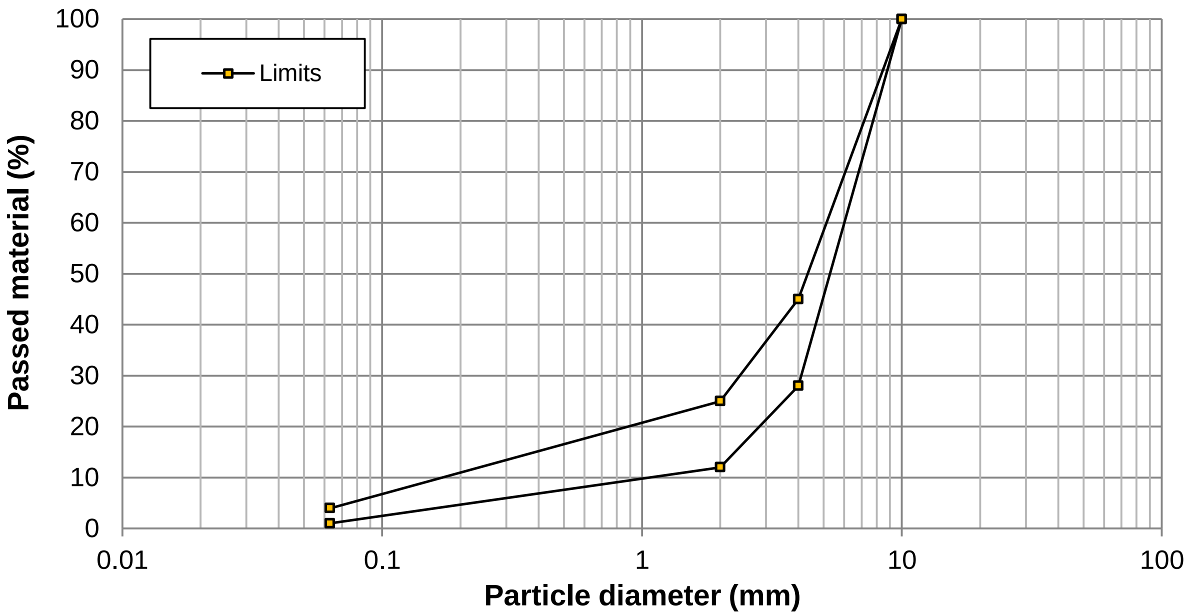

Figure 2 – Specified aggregate gradation envelope limits

Based on the aggregate gradation envelope limits defined for ThinGap, the following aggregates composition is showed in Table 4.

Table 4 – ThinGap aggregate composition

31A	Mansand	RAP	Bitumen PG 58-28	RARX
80%	10%	10%	6.6 (60%)	4.4 (40%)

With the aggregates compositions showed in Table 4 the aggregate grading and it's representation is shown in Figure 3.

Table 5 – Aggregate grading - ThinGap

Sieve size (mm)	Cumulative percentage of passed material on the sieve (%)
	ThinGap
12.5	100
11.2	100
9.5	99
8	83
6.3	62
4.75	45
2.36	22
1.18	12
0.6	7
0.3	4
0.15	2
0.075	2.0

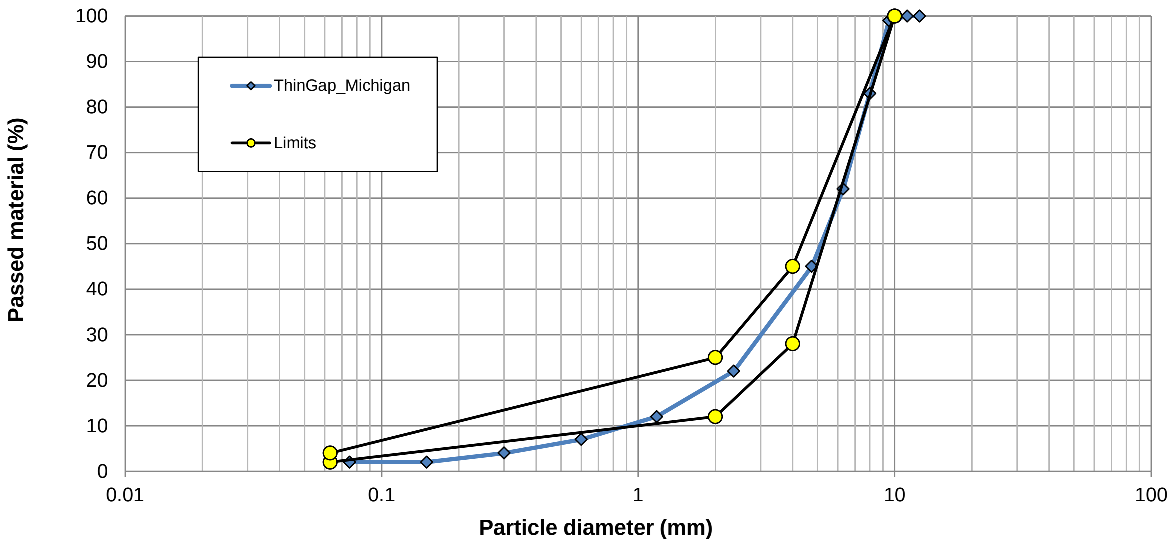

Figure 3 – ThinGap aggregate gradation and the corresponding specified gradation

3.2. Bitumen

For this study one type of bitumen was used (Figure 4) with a PG Grade 58-28 to be modified with RARX for the ThinGap, supplied by Lakeland Asphalt Corp. on 14/06/2018.

Figure 4 - Bitumen PG58-28

3.3. RARX

In the present study, RARX was used in the ThinGap to improve the mix performance. The Reacted and Activated Rubber – RAR, is composed three ingredients, soft asphalt cement (bitumen), fine crumb tire rubber (usually #30 mesh) and Fillers (see Figure 4) processed at optimized proportions.

Figure 5 – RAR essentially composed of Asphalt Cement (Bitumen), Crumb Tire Rubber and Fillers

4. Influence of RARX Percentage in Binder Properties

The influence of RARX percentage in binder (original bitumen modified with RAR) conventional properties and PG grade, was studied for several RARX percentages (20 %, 25 %, 30 %, 35 % and 40 %, relatively to binder sample mass), concerning the following laboratory tests (Table 6).

Table 6 – Laboratory tests performed

Binder tests type	Bitumen (%)	Standard	Test conditions
Conventional tests	Viscosity	AASTHO TP48	175 °C
	Softening point	ASTM D36	5 °C/min, Ring and Ball method
	Penetration	ASTM D5	25 °C; 100 g; 5 s
	Resilience	ASTM D5329	25 °C
Advanced tests	PG grade	ASTM D6373	see item 4.2

Additionally, a sample of original bitumen PG58-28 without addition of RAR was used as control sample for binder conventional properties and PG grade evaluation.

4.1. Binder Properties (Conventional Tests)

Table 7 and Figure 6 shows the results obtain in the conventional bitumen/binder tests (viscosity, ring and ball, penetration, penetration after RTFOT and resilience) performed in CONSULPAV.

Table 7 – Conventional bitumen/binder tests – summary results

Bitumen type	Additive type	Bitumen %	Additive (%)	Viscosity (cP)	Softening Point (°C)	Penetration (0,1 mm)	Resilience (%)
PG58-28	RARX	**100** [1)]	0	135	49	54	0
		80	20	800	61	40	33
		75	25	1350	63	34	38
		70	30	3200	68	30	50
		65	35	6800	72	21	58
		60	40	EEE	83	16	63

[1)] control samples

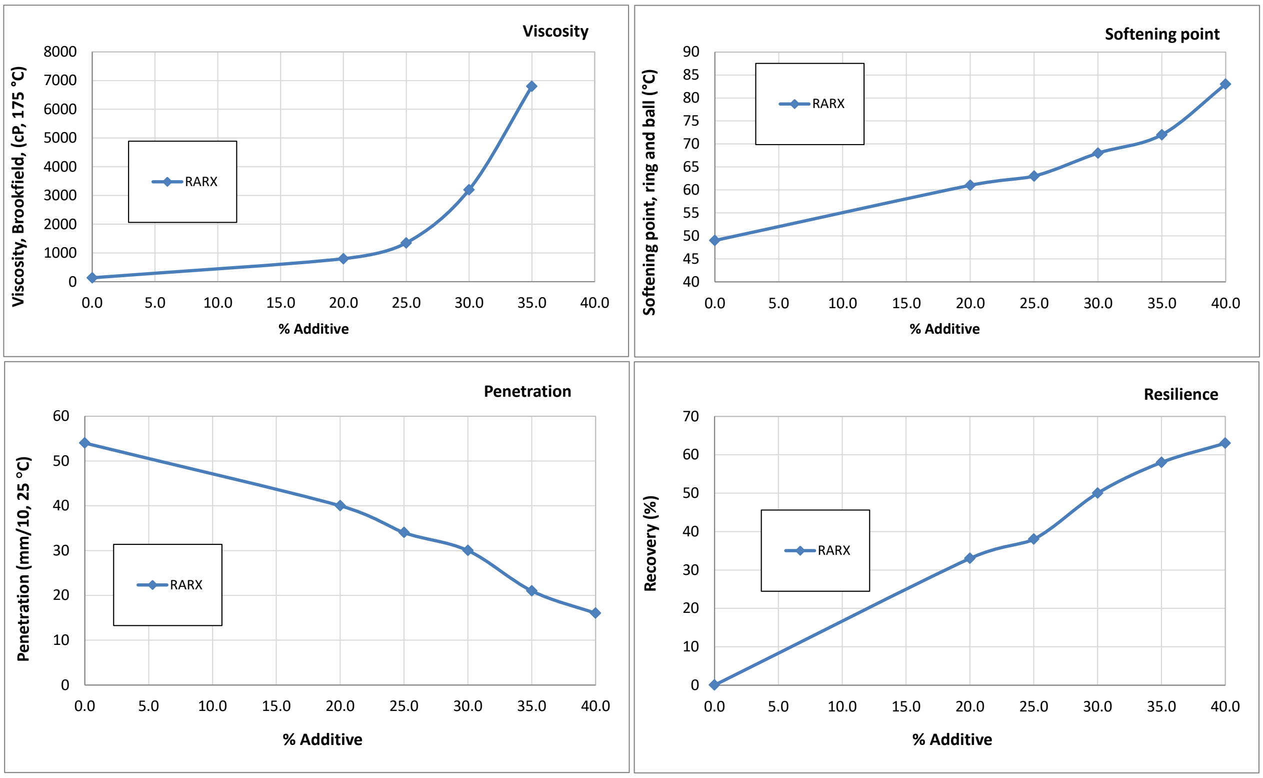

Figure 6 – Graphic results (conventional bitumen/binder tests)

According to Table 7 and Figure 6, the increase of RARX in the bitumen, increases the viscosity, softening point and resilience and reduces the penetration. However, the real improvements only tend to occur for a minimum of 20 – 25 % of RARX. For 35 % of RARX it's observed a heavy modification of the original bitumen.

Furthermore, the influence of RARX percentage on viscosity was studied. Results are presented in Figure 7.

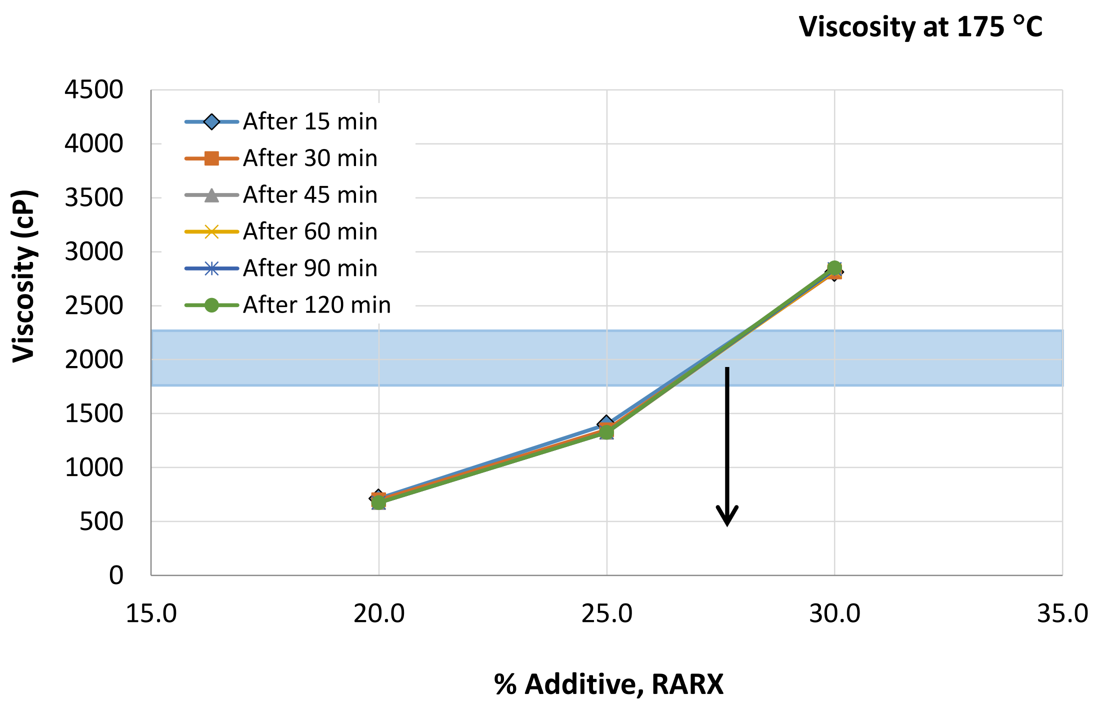

Figure 7 – Viscosity at 175 ºC vs. additive percentage

According to Figure 7, it's possible to understand that to ensure a good workability for an AR-SAMI (viscosity between 1800 and 2200 cP). It's also possible to conclude that the percentage of RARX used tends to be independent of time used to evaluate the viscosity.

4.2. Binder Properties (PG Grade System)

Superpave performance grading (PG) is based on the idea that bitumen/binder properties should be related to the conditions under which it is used. Superpave performance grading uses the following binder tests: Rolling Thin Film Oven Test (RTFOT), Pressure Aging Vessel (PAV), Rotational Viscometer (RV), Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR).

4.2.1. Rolling Thin Film Oven Test (RTFOT)

The RTFOT procedure provides simulated short term aging on binder for physical property testing. Binder is exposed to high temperatures to simulate manufacturing and placement aging. The RTFOT also provides a quantitative measure of the volatiles lost during the aging process.

Rolling Thin Film Oven Tests were carried out according to standard's AASHTO T 240 and ASTM D 2872.

- **Basic Procedure**

I. Heat a sample of binder until it is fluid to pour. Stir sample to ensure homogeneity and remove air bubbles.

II. If a determination of mass change is desired, label two RTFOT bottles and weigh them empty. These are designated as the “mass change” bottles. Record the weights.

III. Pour 1.23 oz (35 g) of binder into each bottle (Figure 8). Immediately after pouring each bottle, turn the bottles on their side without rotating or twisting and place them on a cooling rack (Figure 9).

Figure 8 – Pouring hot binder into the RTFOT bottle

Figure 9 – Turning the bottles on their side without rotating or twisting and placing them on a cooling rack

IV. Allow all bottles to cool 60 to 180 minutes.

V. After cooling, weigh the two mass change bottles again. Record the weights.

VI. Place the bottles in the RTFOT oven carousel, close the door, and rotate carousel at 15 RPM for 85 minutes (Figure 10). During this time, maintain the oven temperature at 163 °C and the airflow into the bottles at 4000 ml/min.

Figure 10 – RTFOT equipment

VII. Remove the bottles one at a time from the carousel, setting the mass change bottles aside. Residue from the remaining bottles should be transferred to a single container. Remove residue from each bottle by first pouring as much material as possible, then scraping the sides of the bottle to remove any remaining (Figure 11). There is no standard scraping utensil but at least 90 percent of the binder should be removed from the bottle. RTFOT residue should be tested within 72 hours of aging.

VIII. After cooling the two mass change bottles for 60 – 180 minutes, weigh them and discard their residue. Record the weights.

Figure 11 – Scraping the asphalt residue out of a RTFOT bottle

4.2.2. Dynamic Shear Rheometer (DSR)

The DSR is used to characterize the viscous and elastic behavior of binders at medium to high temperatures. This characterization is used in the Superpave PG binder specification. As with other Superpave binder tests, the actual temperatures anticipated in the area where the binder will be placed determine the test temperatures used.

The Dynamic Shear Rheometer tests were carried out according to standard AASHTO T 315.

- **Basic Procedure**

I. Heat the binder from which the test specimens are to be selected until the binder is sufficiently fluid to pour the test specimens.

II. Select the testing temperature according to the binder grade or testing schedule. Heat the DSR to the test temperature. This preheats the upper and lower plates (Figure 12), which allows the specimen to adhere to them.

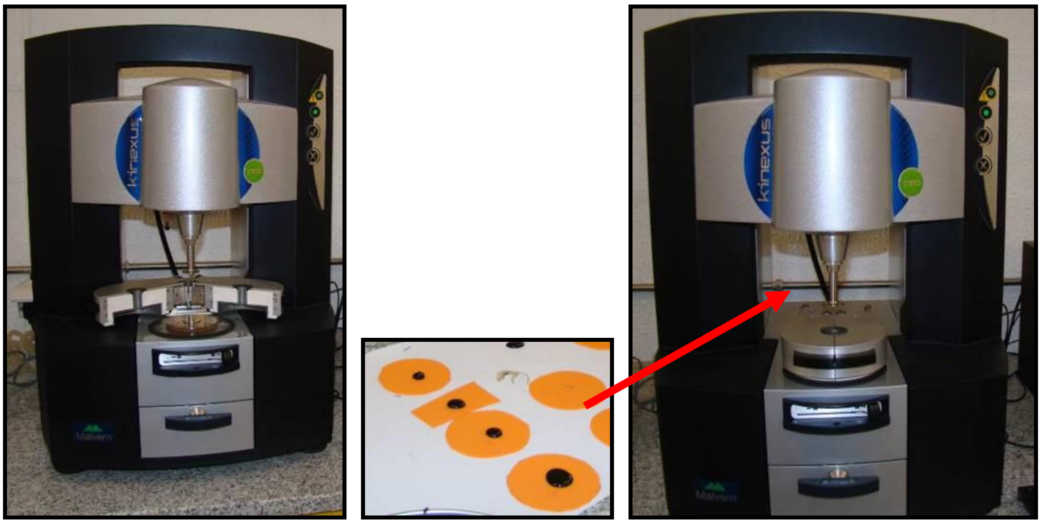

Figure 12 – DSR test equipment and samples

III. Place the binder sample between the test plates.

IV. Move the test plates together until the gap between them equals the test gap plus 0.05 mm.

V. Trim the specimen around the edge of the test plates using a heated trimming tool.

VI. Move the test plates together to the desired testing gap. This creates a slight bulge in the binder specimen's perimeter.

VII. Bring the specimen to the test temperature. Start the test only after the specimen has been at the desired temperature for at least 10 minutes.

VIII. The DSR software determines a target torque at which to rotate the upper plate based on the material being tested (e.g., unaged binder, RTFOT residue or PAV residue). This torque is chosen to ensure that measurements are within the specimen's region of linear behavior.

IX. The DSR conditions the specimen for 10 cycles at a frequency of 10 rad/sec (1.59 Hz).

X. The DSR takes test measurements over the next 10 cycles and then the software reduces the data to produce a value for complex modulus (G*) and phase angle (δ).

When testing at multiple temperatures, all testing should be completed within four hours.

4.2.3. Pressure Aging Vessel (PAV)

The PAV provides simulated long term aged binder for physical property testing. Binder is exposed to heat and pressure to simulate in-service aging over a 7 to 10 year period.

The Pressure Aging vessel tests were carried out according to standard AASHTO R 28.

- **Basic Procedure**

I. Place pans in a pan holder and place inside preheated PAV (Figure 13 and Figure 14).

Figure 13 – Pressure aging vessel (PAV) equipment (placing pan holder inside PAV)

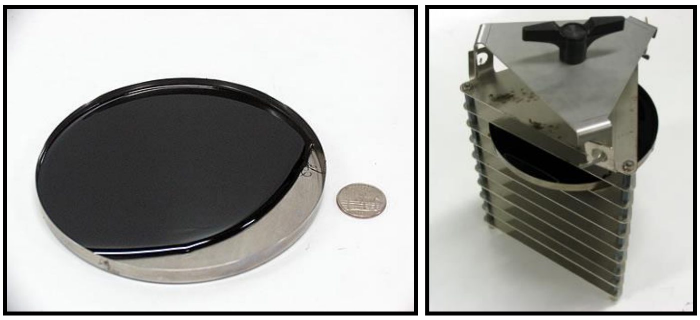

Figure 14 – PAV pan (with a quarter for scale). Pan holder with one PAV sample inserted

II. Seal the PAV and allow it to return to the aging temperature. Aging temperature is based on the climate where the material is expected to be used. For climates where a PG 52 or lower is specified, the PAV is performed at 90 °C. For climates where a PG 58 or higher is specified, the PAV is performed at 100 °C. For desert climates, it is recommended to perform the PAV at 110 °C.

III. Once the PAV has reached the desired temperature, pressurize the PAV to 300 psi (2.07 MPa) and maintained the pressure for 20 hours.

IV. At the end of the aging period, gradually release the pressure and remove the pans from the PAV.

V. Place the pans in an oven set at 163 °C for 15 minutes, and then scrape into a single container sized so that the depth of the residue in the container is between 14 and 40 mm.

VI. Place the container in a vacuum oven (Figure 15) at 170 °C and degas the sample for 30 minutes to remove entrapped air.

Figure 15 – Vacuum oven

4.2.4. Bending Beam Rheometer (BBR)

The BBR test provides a measure of low temperature stiffness and relaxation properties of binders. These parameters give an indication of a binder's ability to resist low temperature cracking. The BBR is used in combination with the Direct Tension Test (DTT) to determine a binder's low temperature PG grade. As with other Superpave binder tests, the actual temperatures anticipated in the area where the binder will be placed determine the test temperatures used.

The basic BBR test uses a small bitumen/binder beam that is simply supported and immersed in a cold liquid bath. A load is applied to the center of the beam and its deflection is measured against time. Stiffness is calculated based on measured deflection and standard beam properties and a measure of how the binder relaxes the load induced stresses is also measured. BBR tests are conducted on PAV aged binder samples. The test is largely software controlled.

The Bending Beam Rheometer tests were carried out according to standard AASHTO T 313.

- **Basic Procedure**

I. Set the BBR fluid bath to the desired test temperature (Figure 16). The fluid should be clear at all test temperatures. Suitable fluids are ethanol, methanol and glycol-methanol mixtures. The specific gravity of the fluid should be less than (1.05 kg/m^3) to prevent the binder beam from floating.

Figure 16 – BBR equipment

II. Heat long term aged (PAV) binder until fluid enough to pour. During heating the sample should be covered and occasionally stirred to ensure homogeneity.

III. Stir the heated sample to remove air bubbles and pour into two aluminum BBR molds (Figure 17), making sure to over pour so that there is excess sample along the top of the mold. This over pouring will ensure enough binder to completely fill the mold.

A sample of asphalt binder is molded into a beam measuring 6.25 x 12.5 x 127 mm.

All testing should be completed within four hours.

Figure 17 – Assembling BBR molds

IV. Allow molds to cool for 45 to 60 minutes at room temperature, and then trim the top of sample flush with mold using a hot spatula.

V. To demold samples, cool mold in an ice bath or freezer at -5 °C for 5 to 10 minutes; just long enough that the beam can be easily removed from the mold without damaging it.

VI. Place beams in the BBR bath at test temperature for 60 minutes to condition them.

VII. Place the test beam on the test supports.

VIII. To ensure that the loading head and the beam remain in contact for the entire test, manually apply a 35 mN contact load for no more than 10 seconds.

IX. Activate the automatic testing system. This system does the following:

- Apply a 980 mN seating load for 1.0 second.
- Reduce the seating load to 35 mN and allow the beam to recover for 20 seconds.
- Apply the 980 mN test load and maintain the load constant for 240 seconds. During this period, readings of deflection over time are recorded.

X. Remove the test load and end the test. Do the test for the second beam.

4.3. Results

The results of the PG grade testing made in all the binders produced with different percentages of RAR are presented in the sections below.

4.3.1. PG grade

Table 8 presents a summary of all the results. Figure 18 show graphically the influence of RAR percentage on unaged binder performance [Performance Grade, PG (+)].

Table 8 – PG grade results for bitumen PG58-28 (0,20, 25, 30, 35, 40)

Property		Bitumen (PG58-28)					
		Additive, RARX (%)					
		0	**20**	**25**	**30**	**35**	**40**
PG Grade		**64-22**	**88-22**	**88-22**	**94-22**	**124-22**	**n.a-22**
Continuous PG Grade		69.7–24.1 (24.3)	88.3–25.1 (23.4)	90.4–24.8 (22.8)	98.3–25.7 (20.3)	124.4–25.0 (15.2)	n.a-24 (14.8)
Viscosity – Rotational (cP, 135 °C)		520	3450	5987	n.a.	n.a.	n.a.
Dynamic Shear Rheometer	**Temp. Pass** (°C)	**64**	**82**	**88**	**94**	**112**	**n.a.**
	Phase Angle (°)	86.36	78.96	78.1	72.36	61.05	n.a.
	G*/sin delta (10 rad/sec., kPa)	1,893	1,350	1,232	1,405	1,037	n.a.
	Temp. Fail (°C)	**70**	**88**	**94**	**100**	**118**	**n.a.**
	Phase Angle (°)	87.62	80.2	79.18	73.09	58.63	n.a.
	G*/sin delta (10 rad/sec., kPa)	0.888	0.804	0.767	0.986	0.898	n.a.
	Pass/Fail Temp. (°C)	**69.1**	**85.5**	**90.6**	**99.8**	**113.5**	**n.a.**

n.a. – not available

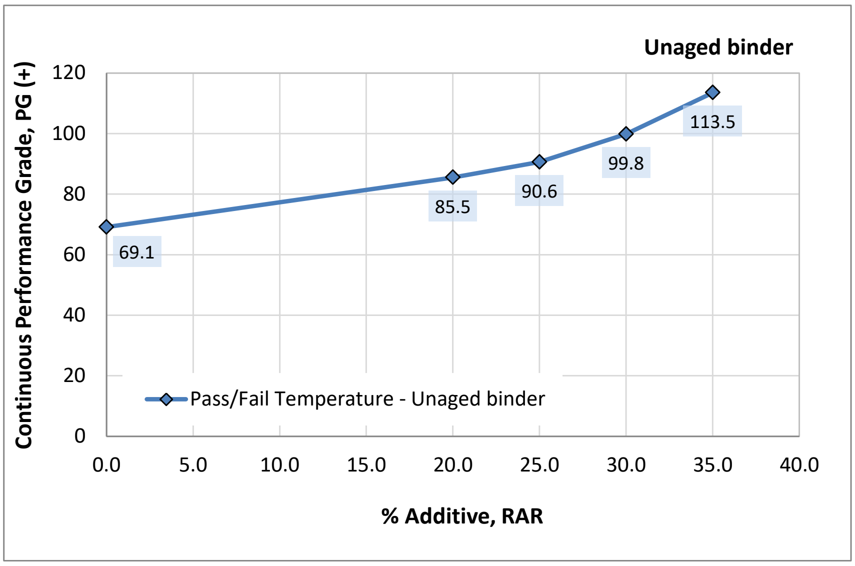

Figure 18 – Continuous Performance Grade, PG (+) (unaged binder)

4.3.2. RTFOT

Partial values of results after RTFOT are presented in Table 9. Figure 19 and Figure 20 show graphically the influence of RAR percentage on short-term aged binder performance and final classification [Performance Grade, PG (+)].

Table 9 – RTFOT results for bitumen PG58-28 (0, 20, 25, 30, 35, 40)

Property		Bitumen (PG58-28)					
		Additive, RARX (%)					
		0	20	25	30	35	40
Mass Loss (%)		0.01	0.04	0.02	0.04	0.03	0.03
Dynamic Shear Rheometer		64	88	88	94	124	n.a
Dynamic Shear Rheometer	**Phase Angle (°)**	**82.59**	**70.47**	**71.96**	**63.86**	**44.83**	**n.a**
	G*/sin delta (10 rad/sec., kPa)	4419	2244	2677	2838	2332	n.a.
	Temp. Fail (°C)	70	94	94	100	130	n.a.
	Phase Angle (°)	**84.76**	**71.13**	**73.55**	**63.59**	**50.46**	**n.a.**
	G*/sin delta (10 rad/sec., kPa)	2118	1427	1625	1991	1061	n.a.
	Pass/Fail Temp. (°C)	69.7	88.3	90.4	98.3	124.4	n.a.

n.a. – not available

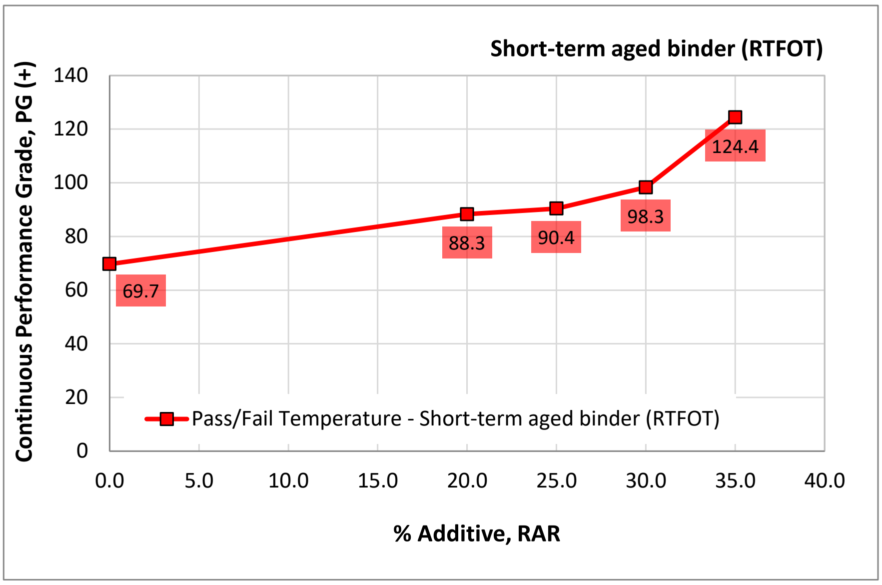

Figure 19 – Continuous Performance Grade, PG (+) (short-term aged binder, RTFOT)

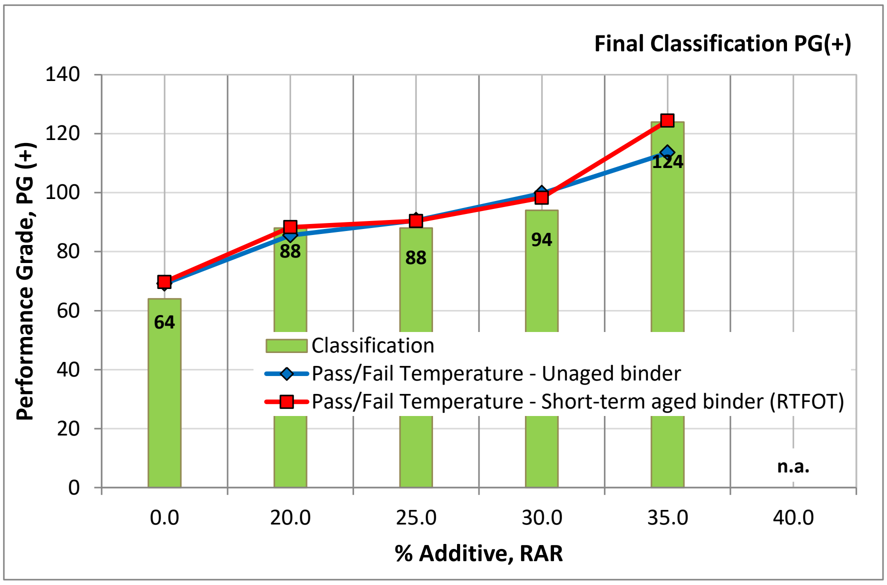

Figure 20 – Final Classification, PG (+)

4.3.3. PAV

Partial values after PAV aging are presented in Table 10. Figure 21 and Figure 22 show graphically the influence of RAR percentage on long-term aged binder performance and final classification [Performance Grade, PG (-)].

Table 10 – PAV results for bitumen PG58-28 (0, 20, 25, 30, 35, 40)

Property		Bitumen (PG58-28)					
		Additive, RARX (%)					
		0	20	25	30	35	40
Dynamic Shear Rheometer	**Phase Angle (°)**	**25**	**25**	**25**	**22**	**16**	**16**
	G*/sin delta (10 rad/sec., kPa)	44.89	41.1	41.14	40.58	37.08	36.07
	Temp. Fail (°C)	4,595	4,136	3,836	4,153	4,629	4612
	Phase Angle (°)	**22**	**22**	**22**	**19**	**13**	**13**
	G*/sin delta (10 rad/sec., kPa)	41.65	39.9	39.46	37.52	35.51	34.29
	Pass/Fail Temp. (°C)	6688	5959	5469	5710	6133	5681
Bending Beam Rheometer	**Temp. Pass** (°C)	**-12**	**-12**	**-12**	**-12**	**-12**	**-12**
	s (60 s, MPa)	182	76.6	68.7	58.4	54.1	34.6
	M-value (60 s)	**0.322**	**0.335**	**0.328**	**0.342**	**0.32**	**0.306**
	Temp. Fail (°C)	**-18**	**-18**	**-18**	**-18**	**-18**	**-18**
	s (60 s, MPa)	351	173	131	115	87	71
	M-value (60 s)	**0.263**	**0.27**	**0.271**	**0.277**	**0.281**	**0.288**

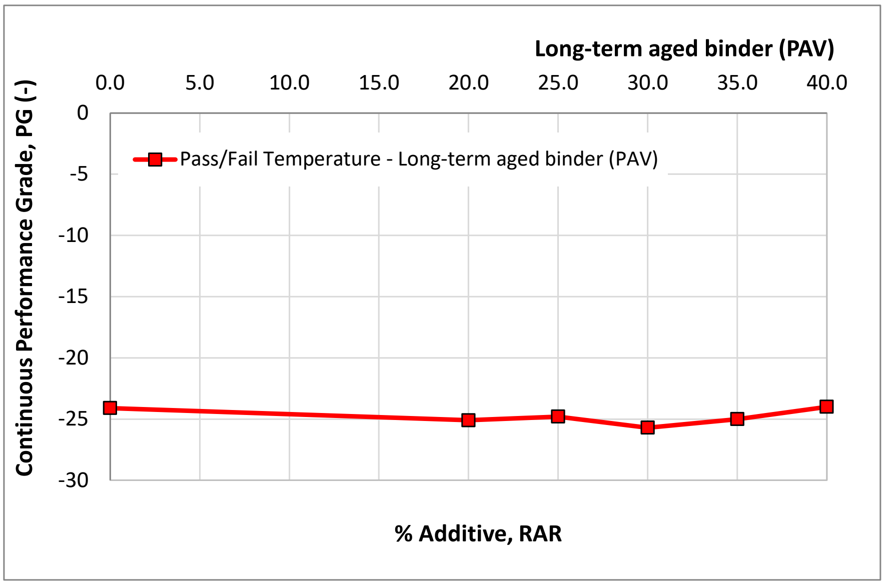

Figure 21 – Continuous Performance Grade, PG (-) (long-term aged binder, PAV)

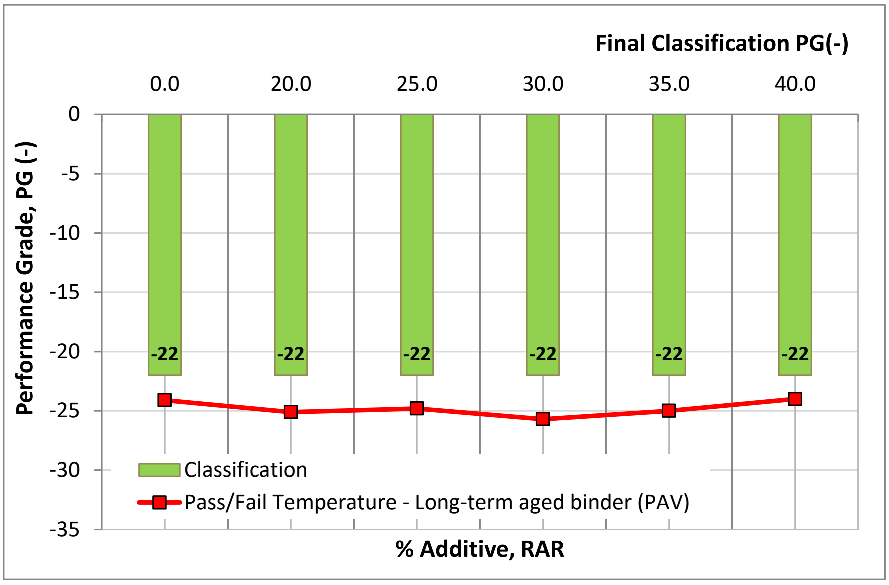

Figure 22 – Final Classification, PG (–)

4.3.4. Rutting criteria MSCR - Jnr

The Multi Stress Creep Recovery (MSCR) accordingly to AASHTO TP 70 gives an indication of the quality of the binder in order to permanent deformation resistance and general ability to recover from deformation. Loading is applied as presented in Figure 23.

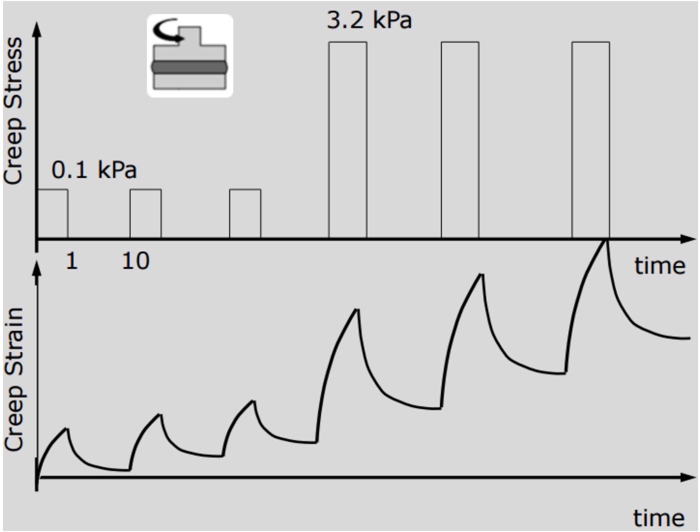

Figure 23 – MSCR loading and deformation typical patterns

Table 11 presents a summary of Jnr testing and Figure 24 to Figure 25 presents the graphically results.

Table 11 – Recovery and Jnr results for bitumen PG58-28 (0, 20, 25, 30, 35, 40)

Property	Bitumen (PG58-28)					
	Additive, RARX (%)					
	0	20	25	30	35	40
Average recovery (0.1 kPa, %)	5.07	72.84	76.06	86.41	88.91	94.62
Average recovery (3.2 kPa, %)	**1.82**	**41.94**	**46.31**	**62.53**	**68.17**	**82.95**
Difference between average recovery at 0.1 kPa and 3.2 kPa (%)	64.1	42.4	39.1	27.6	23.4	12.3
Jnr (0.1 kPa)	2.05	0.08	0.06	0.02	0.01	0.00
Jnr (3.2 kPa)	**2.20**	**0.20**	**0.15**	**0.07**	**0.04**	**0.01**
Difference in Jnr between 0.1 kPa and 3.2 kPa (%)	8.9	137.0	146.5	199.1	213.4	234.0

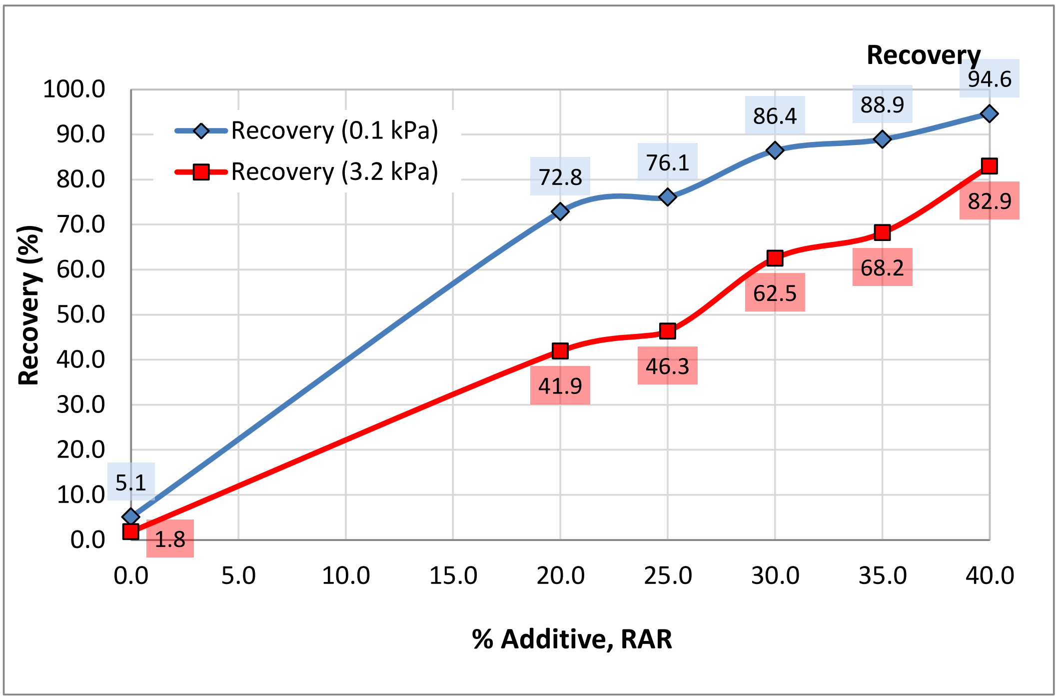

Figure 24 – Recovery results at 0.1 kPa and 3.2 kPa

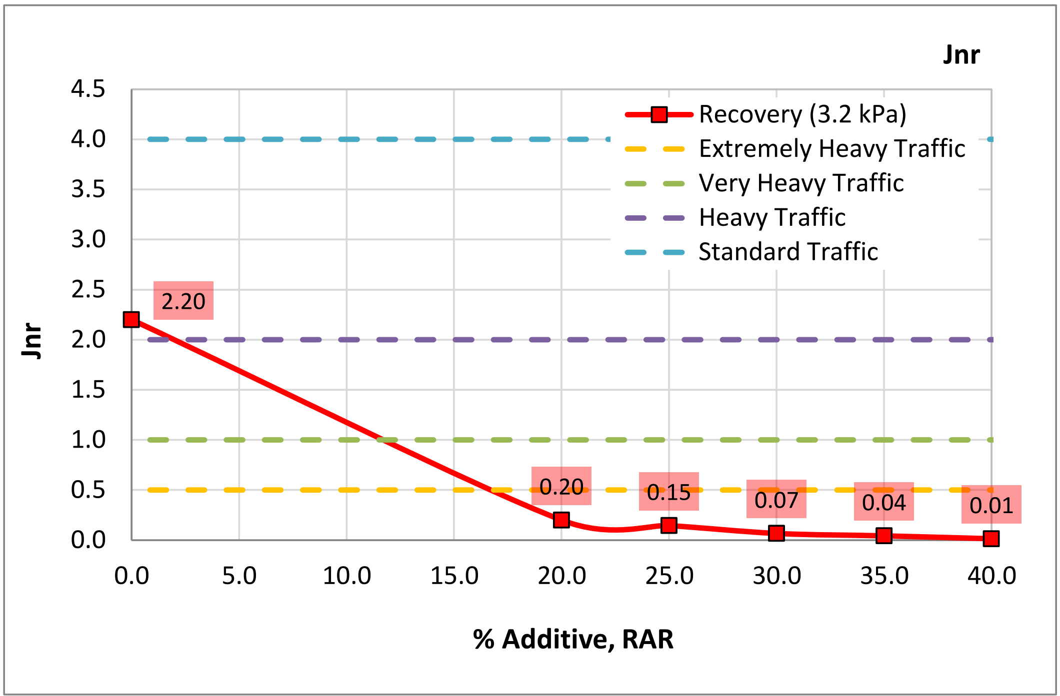

Figure 25 – Jnr at 3.2 kPa values function of the RAR percentage versus traffic type

5. Mix design

5.1. Asphalt Film Thickness

The average film thickness is calculated by dividing volume of asphalt by surface area of aggregate. Surface area of aggregate depends on the gradation of aggregate being used in the mixture and surface area factor for each sieve, where surface area calculated by multiplying percent passing of aggregate for a certain sieve by surface area factor of that sieve. For the aforementioned gradation the asphalt film thickness was determined for three different percentages of binder table 12.

Table 12 – asphalt film thickness for three different percentages of binder

Binder %	TF (μm)
10.5	15.4
11.0	15.9
12.0	16.8

5.2. Marshall Tests

5.2.1. Optimum bitumen content determination

- Preparation a series of initial samples, each different asphalt binder contents. Three samples each were made. Based on the results of the viscosity tests, mixing temperature of 180ºC was chosen for the ThinGap. A compaction temperature of 180ºC was selected.

Figure 26 - Formulation of the mixture

- Compaction of this mix using the Marshall drop hammer. This hammer is specific to the Marshall mix design method. Marshall specimens compaction of 75 blows (both sides).

Figure 27 - Mechanical compaction of Marshall specimens

- Determine the density and other volumetric properties of the samples.

Figure 28 - Determination of specific gravity and theoretical specific gravity

- Test the samples in the Marshall testing machine for stability and flow. This testing machine is specific to the Marshall mix design method.

Figure 29 - Marshall machine used for determination of stability and flow

- Select the optimum asphalt binder content. The complete Marshall test reveals: Stability, Flow, Density, Voids in Total Mix (VTM), Voids in the Mineral Aggregate (VMA), Voids Filled with Binder (VFB).

The results of these tests are summarized in Figure 30 and Table 13

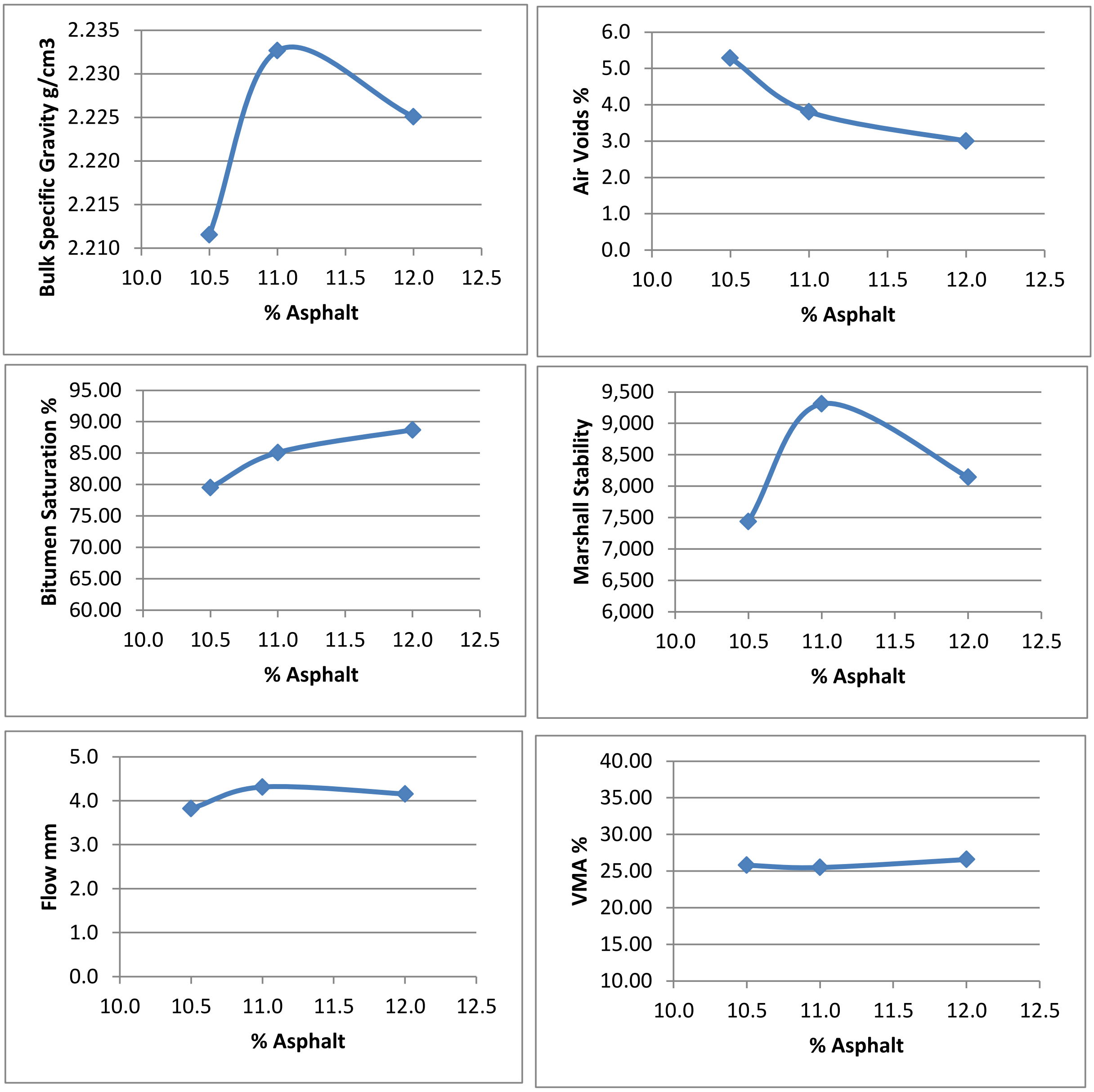

Figure 30 – ThinGap with RARX

Table 13 – Binder content for ThinGap

% Asphalt	Bulk Specific Gravity - g/cm^3	Air Voids %	Bitumen Saturation %	Marshall Stability N	Flow mm	VMA %
10.5	2.212	5.3	79.51	7,436	3.8	25.78
11.0	2.233	3.8	85.09	9,310	4.3	25.48
12.0	2.225	3.0	88.70	8,143	4.2	26.57

Analyzing the results obtained, 11% was considered as the optimal percentage of binder.

5.3. Water Sensitivity (Indirect Tensile Strenght)

A cylindrical specimen is loaded diametrically across the circular cross section. The loading causes a tensile deformation perpendicular to the loading direction which yields a tensile failure. By registering the ultimate load and by knowing the dimensions of the specimen, the indirect tensile strength of the material can be computed. Below is a figure showing the load fixture and a principal picture of the loading. The tests were conducted under the Standard EN 12697-12.

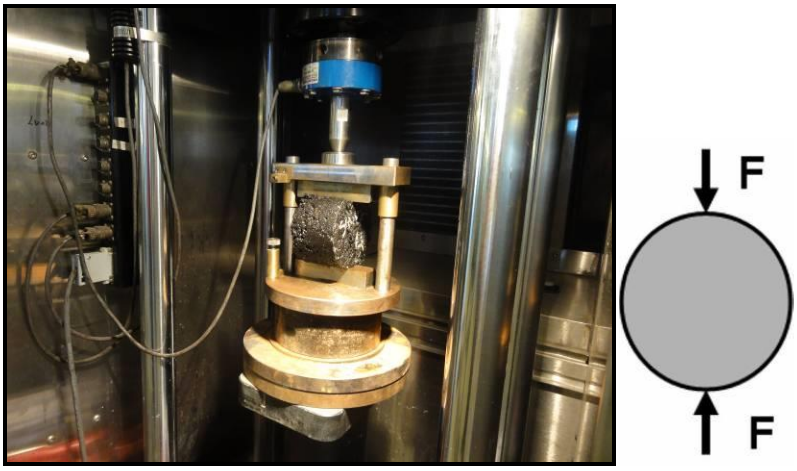

Figure 31 - A load situation for an indirect tensile strength test

Table 14 – Results of water sensitivity - ThinGap

Property		ThinGap
Dry specimens	Bulk Sp. Grav. (Mg/m^3)	2,214
	Air voids (%)	4.6
	ITS_d (kPa)	941
Wet specimens	Bulk Sp. Grav. (Mg/m^3)	2,220
	Air voids (%)	4.4
	ITS_w (kPa)	896
ITSR (%)		95.2
Recommended ITSR (%)		80

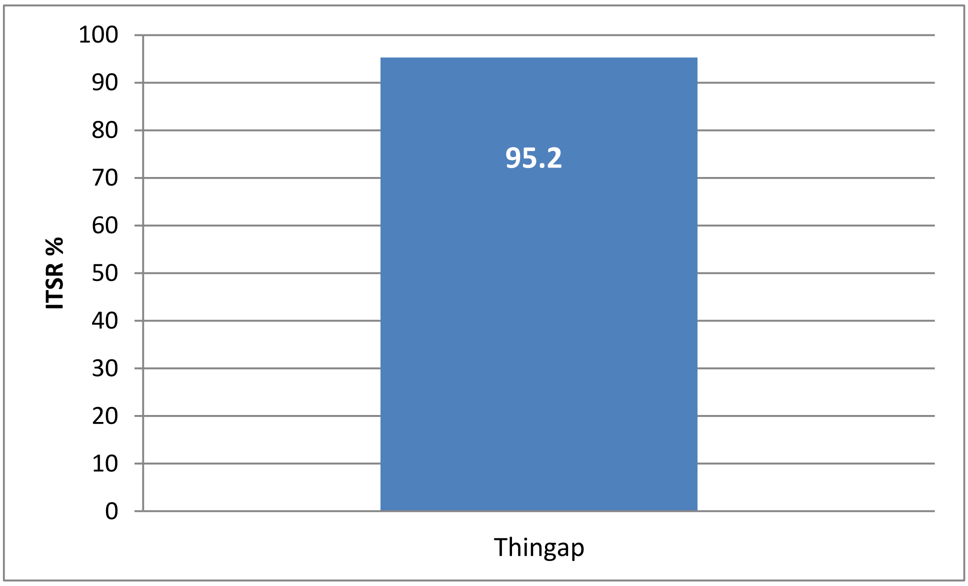

Figure 32 - Results for indirect tensile strength test – ThinGap

5.4. Wheel Tracking

The tests were conducted in controlled temperature chamber at a relatively high temperature (60°C), considered representative of conditions of service in unfavorable situations. The test was conducted under the Standard EN 12697-22 which evaluation of strain rate of Slabs of asphalt under the action of a loaded wheel as it moves along its surface.

Figure 33 - Wheel tracking

Table 15 – Results of wheel tracking test – ThinGap

Property	Mix Design Criterion	ThinGap	
Bulk Sp. Grav. (Mg/m^3)	Max.	2,251	2,256
Air voids (%)	3.0-4.5	3.0	2.8
Maximum ruth depth - RDair (mm)	-	1.74	2.96
Mean		2.4	
Maximum wheel tracking slope – WTSair (%)	-	0.04	0.29
Mean		0.16	
Maximum proportional ruth depth – PRDair (%)	-	3.49	5.93
Mean		4.7	

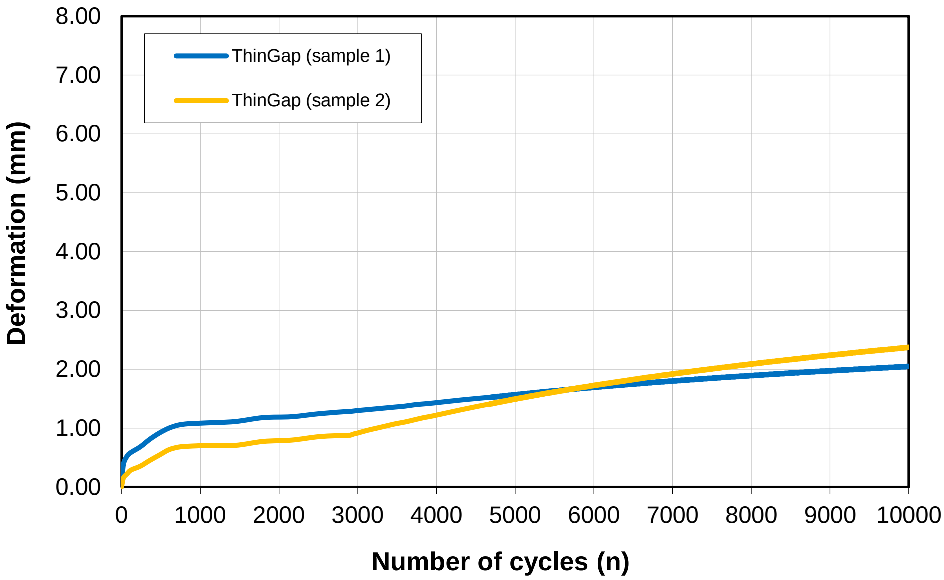

Figure 34 - Wheel tracking results

5.5. Fatigue

The tests were conducted in controlled temperature chamber at a relatively low temperature (20°C), considered representative of conditions of service in unfavorable situations. The test was conducted under the Standard EN 12697-22.

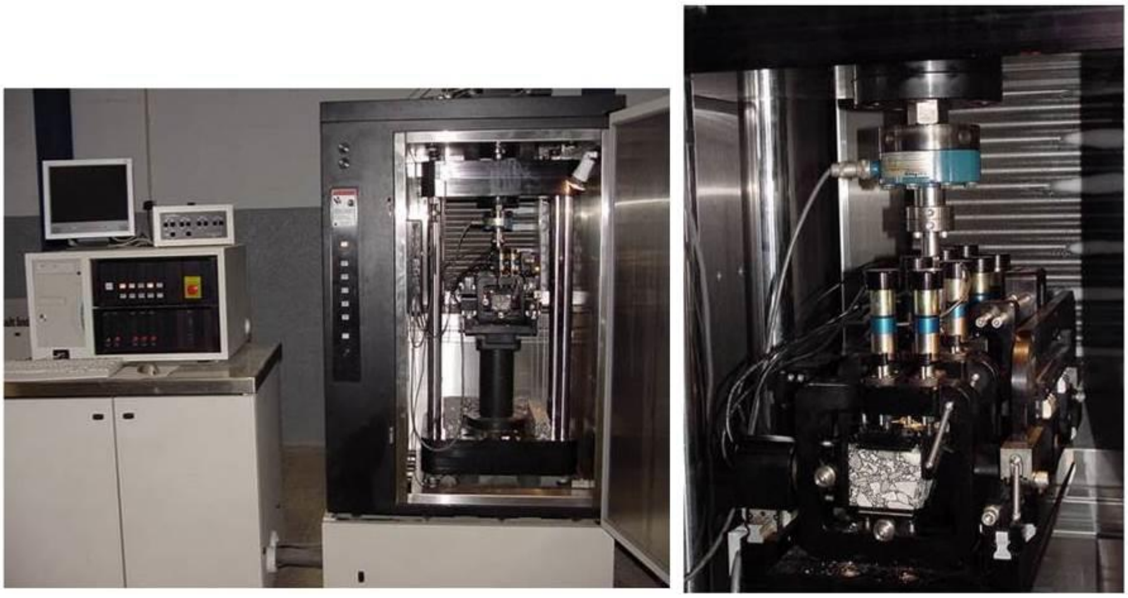

Figure 35 – Four point bending fatigue equipment

In Figure 37 below a comparison between the fatigue life of several other mix types is included so that a comprehensive understanding of the relative crack propagation resistance between this ThinGap mixture and all others is understood.

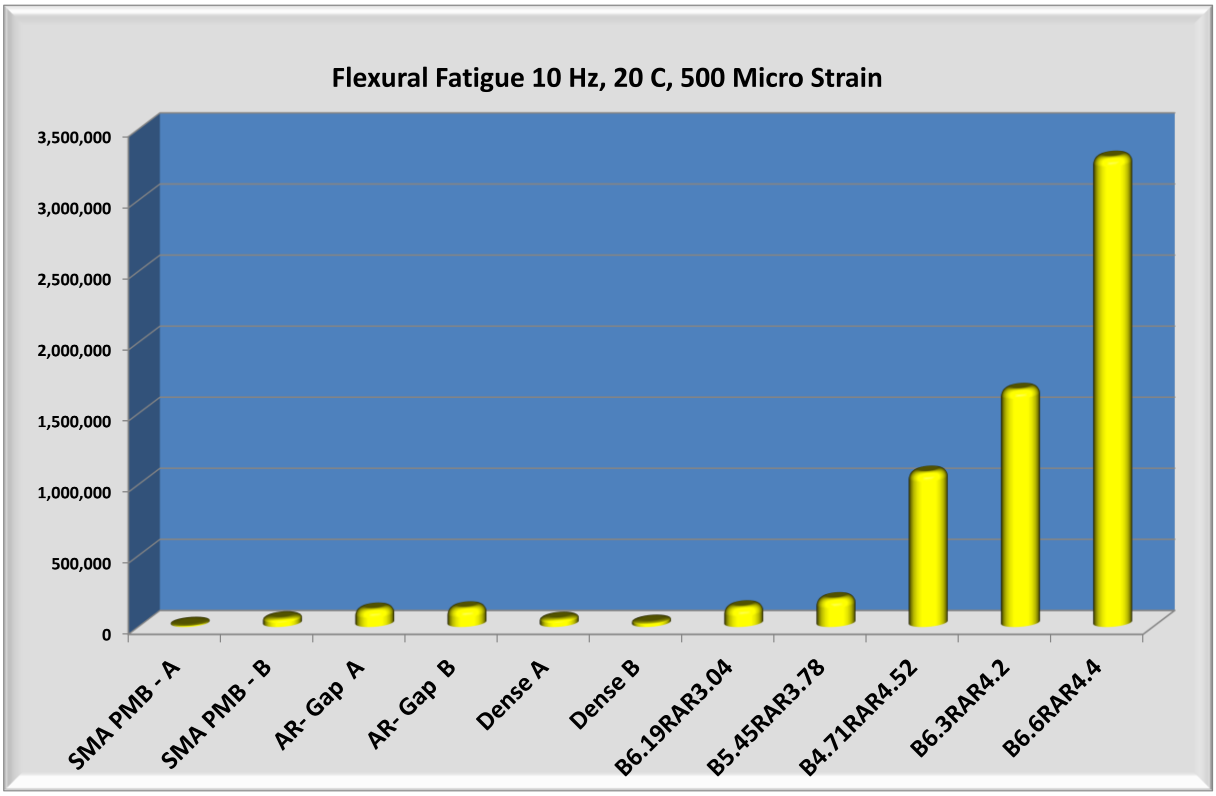

Figure 36 - Comparison between the fatigue life of (ThinGap – B6.6RAR4.4) and several other mixes

The results presented in figure 36 were obtained according to the AASTHO TP8 standard. Figure 37 shows the results obtained in the ThinGap mixture according to three different standards, AASTHO TP8, ASTM D7460 and AASTHO T321.

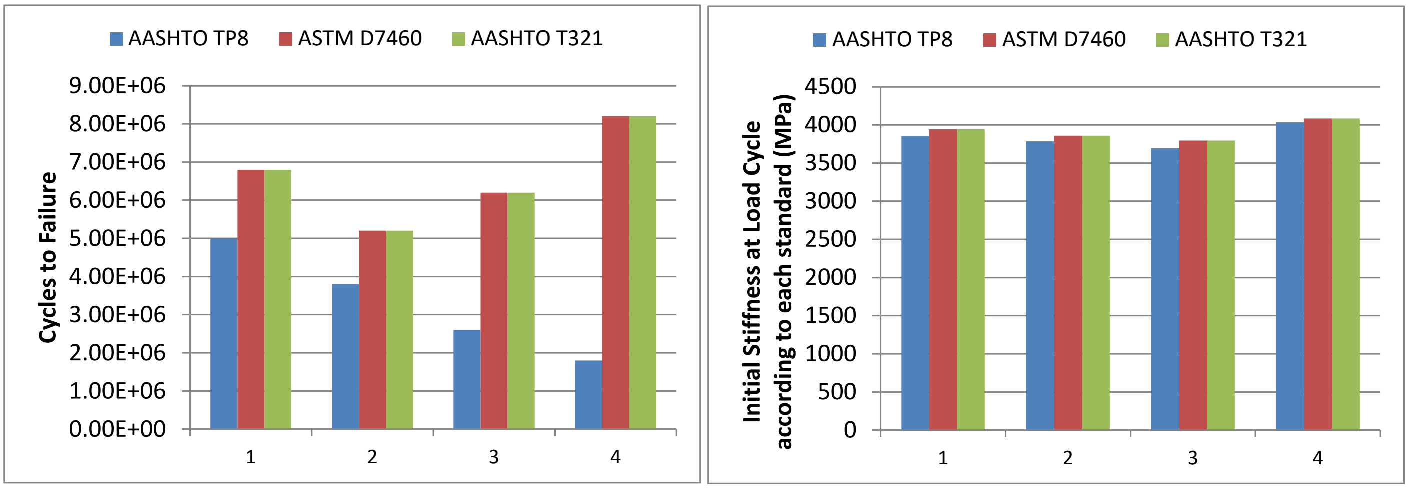

Figure 37 - Results of fatigue four point bending test (ThinGap)

Table 16 – Results of fatigue test (ThinGap)

		AASHTO TP8		ASTM D7460		AASHTO T321	
Sample	Average Amplitude Strain	Initial Stiffness at Load Cycle 100 (MPa)	Cycles to Failure	Initial Stiffness at Load Cycle 50 (MPa)	Cycles to Failure	Initial Stiffness at Load Cycle 50 (MPa)	Cycles to Failure
TGV1	0.00049689	3855	5000000	3945	6800004	3945	6800004
TGV2	0.000494084	3786	3800000	3858	5200003	3858	5200003
TGV3	0.000494866	3696	2600000	3796	6200001	3796	6200001
TGV4	0.000497225	4035	1800000	4084	8200001	4084	8200001

5.6. Presentation of the Summary of Laboratory Results

The results are summarized in Table 17. It can be observed that generally ThinGap specimens had a excellent performance. The excellent performance of the ThinGap blend in fatigue life stands out.

Table 17 – Results of specimens for optimum bitumen content – ThinGap

Material	ThinGap Composition (%)
31 A	80
MANSAND	10
RAP	10
Bitumen	6.6
RARX	4.4
Property	**Results**
ITSR (%)	95.2
RDair (mm)	2.4
WTSair (%)	0.16
PRDair (%)	4.7
Mixture Modulus (MPa)	3843
Nε500 (@ 10 Hz, 20 C)	3300000

Casais da Serra, October 25th 2018

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- Technical Director-

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