Asphalt mixture performance and testing

Laboratory Investigation of Reacted and Activated Rubber Modified Gap and Dense Graded Asphalt Mixtures

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Abstract

Various methods have been proposed to address the difficulties involved with the production of rubber modified asphalt mixtures. Reacted and Activated Rubber has been introduced to alleviate the problems associated with the production of rubber modified binders. Dry mixing method can be easily implemented for the addition of this modifier to pug-mill. Although this type of rubber modification has shown promising results with dense graded asphalt mixtures, further investigation may be required to confirm its potential advantages for gap graded asphalt mixtures. The objective of this study is to determine optimum composition of Reacted and Activated Rubber asphalt mixtures based on volumetric properties for dense and gap gradations. Response surface methodology was used in the experimental design process to investigate the simultaneous effect of variations in asphalt content and modifier amount. Furthermore, volumetric properties of asphalt mixtures were supplemented with performance-related characteristics. Permanent deformation, fatigue cracking as well as reflective cracking properties were evaluated and compared to that of unmodified and wet-process rubber modified mixtures

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1. INTRODUCTION

The primary reason for using rubber modified asphalt is that it provides improved engineering properties over conventional asphalt. The rubber stiffens the bitumen and increases elasticity, which decreases pavement temperature susceptibility and improves resistance to rutting and fatigue with insignificant effect on cold temperature properties [1]. Crumb rubber use in asphalts using wet process has been in practice for years; however, it has some drawbacks that include the need for blending equipment, high temperatures, and longer waiting time at mixing plants [2]. Thus, despite the proven advantages of rubber modified asphalts, there is still no significant development in the global practical use. One solution to these disadvantages, that was found to provide a basis for an innovating and improving rubber modified asphalt, is the new "Reacted and Activated Rubber". RAR is composed of soft bitumen, fine crumb rubber, fillers, and hydrated lime. It is produced by a short time hot blending and activation in an industrial process to form a granulated reacted and activated rubber [3]. When asphalt modification is introduced, one of the key objectives is to consider how the material can be added to the asphalt plant. In the case of RAR, several paths for addition exist. With drum mix plants a particulate feed system would deliver the material to the drum. With batch plants the addition is somewhat easier since the material can be added directly to the pug-mill [4].

2. BACKGROUND

Beam fatigue tests conducted to evaluate the intermediate-and low-temperature fatigue cracking parameters have shown that rubber modified asphalt has higher fracture toughness and larger resistance to fatigue cracking than dense graded HMA [5]. The notched semi-circular bending test is employed to study the fatigue cracking property for CRM asphalt and the results have indicated that gap gradation is more suitable for CRM asphalt than dense gradation [6]. The semi-circular bending fracture test is also used in another study to evaluate the effect of CRM, binder content, and aggregate gradation on fracture performance of CRM asphalts where the results were analysed by Illinois flexibility index (FI) and fracture energy. Adding CRM into asphalts increased the optimum bitumen content. Test results showed that among dense graded asphalts, CRM asphalts exhibit superior flexibility and cracking resistance and gap graded CRM asphalts are preferred to dense graded CRM asphalts as they deliver higher flexibility [7]. Material properties and performance characteristics of unmodified and rubber modified gap graded asphalts placed on the Swedish Malmo E6 Highway have been studied by Zeiada and colleagues. They conducted bending beam for fatigue cracking and C* line integral test along with Wheel Tracking tests to evaluate crack propagation. They showed that the fatigue life of rubber modified gap graded asphalt is higher than the unmodified one. Moreover, the rubber modified asphalt had higher resistance to crack propagation [8]. Significant improvements in bitumen properties can be seen when the RAR percentage in the combined bitumen is above 15%. However, there is a point after which there is not enough bitumen to coat the aggregates. Experience has shown that there should always be at least about 4% of plain bitumen in all asphalts, to allow complete aggregate coating and enough workability [9]. It has been shown that RAR modified asphalt outperforms conventional asphalts and even regular rubber modified asphalts. In general, it was found that RAR modifies the bitumen by increasing its PG grading, resilience, softening point and recovery properties [4]. A research work by Ishai and colleagues in laboratory and in the field using RAR modified asphalts has been undertaken. The performance and results after more than two years have shown the advantages of RAR asphalts achieved in the first phase of the research [3]. A new asphalt mix named ThinGap 9.5mm, with RAR and with superior performance attributes of regular rubber modified gap graded asphalts was introduced in a research study. The mix gradation was optimized so that it could incorporate 9.5-10% bitumen content, of which about 45% would be RAR. ThinGap resulted in excellent rut resistance and fatigue lives. By conducting wheel tracking tests, it was concluded that the mix presents higher resistance to permanent deformation than the best RAR asphalts ever tested. It was also showed that ThinGap presents higher resistance to fatigue than those generally obtained for asphalts with high fatigue resistance [10]. Rheological and aging properties of RAR modified bitumen was also evaluated using PG70-10 and PG64-22 bitumen. Test results indicated that there is a higher improvement when the RAR is added to the softer, PG 64-22 bitumen [11]. RAR modified bitumen with varying dosages were also characterized by Sousa and colleagues and compared to two type of virgin bitumen and one rubber modified bitumen. RAR modification increased the upper performance grade to a higher grade than the base bitumen and decreased the non-recoverable creep compliance. The recovery was also increased with increasing RAR contents [12]. The performance of RAR modified dense graded asphalts was characterized to recommend a suitable RAR content. Rutting, fatigue, fracture, and moisture susceptibility of seven dense graded asphalts, two conventional and five modified asphalts including a commercially available rubber modified asphalt were investigated. Two levels of RAR dosage at 2 and 4 % by weight of the asphalt were included. Addition of RAR showed significant decrease in permanent strains with the rut resistance of asphalts increasing with higher RAR dosages. Fatigue resistance was also improved with higher levels of RAR content. An increase in the RAR dosage from 0 to 2% did not result in a significant change in fracture energy but a further increment to 4% decreased the fracture energy [13]. In a road pavement preservation project in Jakarta, a trial test section with RAR modified asphalt was designed to provide cracking free service. A stress absorbing membrane interlayer using RAR with 20mm aggregate chips was placed on top of the concrete pavement followed with a 4.5 cm of RAR modified SMA. It was reported that after 18 months subjected to traffic, rain and UV, the overlay was still in perfect condition [14]. In a research work by Shah, Superpave mix design was performed to determine optimum bitumen content with 35% RAR and to compare the performance of RAR asphalts to that of

CR asphalts prepared using the wet process. A gap gradation of 12.5 mm maximum size with a PG64-22 bitumen were used for RAR and CRM asphalts, while dense gradation of 19 mm maximum size with a PG70-10 bitumen were used for control asphalt. Optimum bitumen content of 9.25% was achieved for RAR mix, 7.60% for CRM mix and 5.10% was achieved for control mix. Performance tests indicated that RAR asphalts present excellent fatigue life and cracking resistance compared to the other asphalts [2]. An open graded asphalt is investigated by Plati and colleagues to determine the optimum RAR content. It was shown that RAR asphalt has a modulus greater than the unmodified asphalt at all temperatures tested and the optimal percentage of RAR for the investigated asphalt was concluded to be 10% by weight of bitumen [15].

3. OBJECTIVE

Although many studies have been performed on mix design methods and performance related properties of RAR modified asphalts, most of them rely on changing the bitumen content to determine the optimum content of RAR and the role of fines content in aggregate gradation is usually neglected. It can be postulated that the reduction in fine particles will result in increased film thickness and consequently improved cracking performance of the asphalt. Here, it is tried to evaluate the performance-related characteristics of RAR modified asphalts with varying gradations. The mix gradations were specified so that they could incorporate reasonable bitumen contents, of which 15 and 25% would be RAR. Unmodified bitumen, CR modified bitumen using wet process as well as addition of RAR modifier using semi-wet method were considered for different gradations. Four mix gradations; two dense-graded and two gap-graded, with varying fine contents were used. Superpave mix design was performed on RAR modified asphalts, as well as CRM and unmodified asphalts. Afterwards, dynamic creep and wheel tracking tests were performed to evaluate rutting resistance of dry process RAR modified asphalts in comparison to unmodified asphalt and wet process CR modified asphalt. Beam fatigue and Illinois Flexibility Index tests were also conducted to determine fatigue and fracture cracking parameters.

4. EXPERIMENTS

4.1. Materials

A PG64-22 bitumen from Pasargad Oil Company in Iran was implemented in all mixtures as the base bitumen. The bitumen was to prepare unmodified, RAR modified and CR modified asphalts. It was used for the production of CR modified bitumen.

RAR is composed of a soft bitumen, fine crumb rubber and fillers. By mass, it is made of 58% crumb rubber, 18% bitumen and 24% fillers [2]. RAR was used at two contents of 15% and 25% by weight of total bitumen, that are about 18% and 33% by weight of base bitumen, respectively. Since RAR consists of 58% crumb rubber, 15% and 25% of RAR content would be equivalent to the 9% and 15% CR for the asphalt rubber wet process. The crumb rubber passing #24 mesh with a maximum particle size of 0.7 mm was used. The particle size distribution of crumb rubber and RAR are presented in Table 1. Crumb rubber modified bitumen was prepared using a high shear mixer set at 4000 RPM. The crumb rubber was blended in the bitumen at a temperature of 190 °C for 60 min allowing the crumb rubber to completely swell.

Table 1. Crumb rubber and RAR particle size distribution (% passing)

Sieve size (mm)	1.18	0.600	0.300	0.150	0.075
Crumb rubber	100	85	35	4.6	0.0
RAR	100	65	22	9.0	2.2

Aggregates used for preparing asphalts were Dolomite and obtained from Asbcheran quarry near Tehran, Iran. Four gradations types, two dense and two gap, were evaluated. Each gradation type consisted different contents of fine material to evaluate the effects of bitumen film thickness on performance attributes. Mix gradations and the consensus properties of aggregates are provided in Tables 2 and 3.

Table 2. The aggregate gradation of asphalts

Sieve Size (mm)	Dense Graded		Gap Graded	
	Type 1	Type 2	Type 1	Type 2
19	100	100	100	100
12.5	95	95	95	95
9.5	86	86	74	74
4.75	58	58	24	24
2.36	35	35	20	20
0.3	10	7	13	7
0.075	5	3	8	4

Table 3. Aggregate properties

Property	Test method	Result
Coarse aggregate		
Abrasion loss (%)	ASTM C131	23
Fractured particles (%)	ASTM D5821	100
Flat and elongated particles (%)	ASTM D4791	0.3
Soundness, sodium sulfate (%)	ASTM C88	0.1
Fine aggregate		
Sand equivalent (%)	ASTM D2419	84
Soundness, sodium sulfate (%)	ASTM C88	1.0
Fine aggregate angularity (%)	ASTM C1252	46
Plasticity index, PI (%)	ASTM D4318	N.P.
Plasticity limit, PL (%)		-
Liquid limit, LL (%)		N.A.

4.2. Asphalt preparation

Unmodified and rubber modified asphalts were prepared at the temperatures of 155°C and 180°C, respectively. For RAR modified asphalts, the aggregates were heated and RAR was added to the mixer container after the heated aggregate. They were mixed for 30 seconds prior to incorporation of the PG64-22 binder. After that the binder was added to the container and the contents were mixed until thoroughly coated for a minimum time of 120 seconds. All asphalts were subjected to short-term aging of 4 hours at 135°C in loose form to simulate short-term aging condition. Before compaction, all mixtures were placed into metal containers and conditioned in an oven at compaction temperature for 1 hour. During this time RAR and CRM coatings activate the bitumen and aggregate surfaces. Unmodified and rubber modified mixes were compacted at the temperatures of 138°C and 170°C.

4.3. Mix design

The asphalt characteristics; gradation types, bitumen types and additives are listed in Table 4.

Table 4. The characteristics of Asphalts for mix design

Mix designation	Gradation type	Additive type & content	Bitumen Type	Modification process
D1	Dense 1	-	PG64-22	-
D1-CR10	Dense 1	10% CRM	PG64-22-CR[1]	Wet
D1-RAR15	Dense 1	15% RAR	PG64-22	Semi-wet
D2-RAR15	Dense 1	15% RAR	PG64-22	Semi-wet
G1	Gap 1	-	PG64-22	-
G1-CR15	Gap 1	15% CRM	PG64-22-CR	Wet
G1-RAR25	Gap 1	25% RAR	PG64-22	Semi-wet
G2-RAR25	Gap 1	25% RAR	PG64-22	Semi-wet
[1] CR modified bitumen				

RAR composition consists of 58% of crumb rubber the rest being bitumen to pre-swell the rubber and also fillers. So once 25% of RAR is incorporated in the mix actually only 15% of crumb rubber is present. Similarly in a 15% RAR incorporation only 9% of actual crumb rubber is present.

Superpave mix design was performed for dense-graded asphalts according to AASHTO R35. The bitumen content corresponding to 96 percent relative density at N_d was considered as Optimum Bitumen Content. For a traffic level of 3 to 10 million ESALs, $N_{initial}$, N_{design} and N_{max} were selected as 8, 100 and 160. Cylindrical specimens 150 mm in diameter were compacted by Superpave gyratory compactor following AASHTO T312. Two specimens were prepared at different bitumen contents and all specimens were compacted to N_{design}. The bitumen content at the target air void of 4% was selected as the OBC. Two specimens were prepared at the OBC and compacted to N_{max}. Volumetric properties, dust proportion, and compaction density at $N_{initial}$ and $N_{maximum}$ were determined and verified regarding whether they are met at the OBC. For gap graded asphalts, volumetric mix design was performed based on AASHTO R46 using the gyratory compactor at 100 gyrations. Cylindrical specimens 150 mm in diameter were compacted at different bitumen contents and the volumetric properties were determined. The OBC was selected to provide the desired air void of 4% considering that the minimum content is specified as 6.0% and to satisfy the criteria specified in AASHTO M325. Bitumen film thickness is the ratio of bitumen volume (not absorbed into the aggregate) to the surface area of the aggregate and calculated for all asphalts. The surface area is determined by multiplying the surface area factors by the percentage passing the various sieves. Table 5 presents the volumetric properties, dust proportion and film thickness.

Table 5. Mixes design parameters and film thickness

Mix designation	OBC (%)	Density (kg/m^3)	Air voids (%)	VMA (%)	VFB (%)	Dust/Bitumen ratio	Film Thickness (μm)
D1	4.3	2.392	4.3	13.8	68.5	1.25	8.7
D1-CR10	4.5	2.402	4.1	13.6	69.8	1.23	7.1
D1-RAR15	4.8	2.388	4.1	14.4	71.3	1.15	7.6
D2-RAR15	5.5	2.376	4.1	15.0	72.9	0.59	10.3
G1	6.0	2.348	4.2	17.0	75.0	1.47	10.2
G1-CR15	6.0	2.346	4.3	17.1	74.7	1.44	7.9
G1-RAR25	6.0	2.348	3.9	17.0	77.0	1.45	6.6
G2-RAR25	6.7	2.343	4.2	17.5	75.9	0.648	11.0

It is suggested that rather than specifying a minimum VMA requirement for dense-graded asphalts, a better approach would be to specify a minimum bitumen film thickness of 8 μm [16]. RAR acts as a dry filler and it is important to determine the film thickness and to incorporate it in the mix design. A minimum film thickness of 12 microns is recommended for gap graded asphalts based on some previous RAR paving projects and also a surface factor of 10 for RAR [3]. Although the G1-RAR25 mix didn't satisfy the 12 microns of film thickness level, it was selected for evaluation in performance testing. The G1 and G2 gradations where selected to have about 17% VMA and about 6% OBC. These mixes are not to be confused with the Arizona gap graded asphalts that require a minimum of 19% VMA and usually have about 8.5 to 9% OBC and more than 18-micron film thickness.

4.4. Test methods

Wheel Tracking Test

Wheel tracking test is widely used to evaluate the rutting performance of asphalts. For rutting evaluation of unmodified and rubber modified asphalts, the wheel tracking test was conducted on core specimens according to EN12697-22 method with the small-size device shown in Figure 1. The device consists of a loaded wheel that moves on the test specimen back and forth and the rut depth in the surface of specimen is monitored. The wheel load is about 700 N which travels with a frequency of 26.5 cycles per minute. Cylindrical specimens, 150 mm in diameter with a thickness of 60 mm, were compacted by gyratory compactor to a target air void of 6%. All specimens were tested under dry condition at 55ºC and the rut depth versus number of loading cycles were recorded up to 10000 cycles.

Figure 1. Wheel tracking device and control unit

Uniaxial Cyclic Compression Test (Dynamic Creep)

Dynamic creep test was also performed for rutting evaluation. A full creep behavior consists of three stages. In the preliminary stage, there is a decrease in the strain rate with time. At a constant stress and temperature, creep rate is approximately constant during the second stage. Finally, the material undergoes tertiary flow stage where the creep rate increases and fracture occurs. Flow number is the initiation of tertiary stage or the minimum point of the strain rate curve [17]. The dynamic creep test was carried out according to EN12697-25, method A. In the test, a cylindrical specimen 150 mm in diameter and 60 mm in height, maintained at elevated temperature, is placed between two parallel loading platens. The lower platen stretches at least 5 mm outside the specimen and the upper platen has a diameter of 100 mm. The specimen is subjected to a cyclic axial block-pulse pressure and no lateral confinement pressure is applied. The change in height of the specimen is measured and the cumulative axial strain is determined as a function of load cycles. The test was conducted at 55 °C using a 300 kPa and a 200 kPa square pulse load for dense-graded and gap-graded asphalts with a loading time of 1 s at 0.5 Hz frequency and continued until 7% permanent strain. Gyratory specimens with an air void of 6% were tested. UTM test device and dynamic creep loading frame are shown in Figure 2.

Figure 2. UTM apparatus and dynamic creep loading frame

Beam Fatigue Test

The flexural bending four-point beam fatigue test was conducted consistent with ASTM D7460. The test consists of applying a repeated constant vertical strain to a beam specimen in flexural tension mode until failure. A servo electric-pneumatic controlled device shown in Figure 3 applied the input strain waveform. The fatigue life is defined as the point at which the product of the specimen stiffness and loading cycles (S×N) is a maximum. The test was conducted at 20ºC and at two strain levels of 700 and 1000 micro for dense-graded asphalts and strain levels of 900 and 1200 micro for gap-graded ones. The strain waveform was haversine shaped and applied at a frequency of 10 Hz. Asphalts were compacted to slabs using a roller compactor to the average air void of 4% measured from beam specimens and the beam specimens (380×63×50 mm) were cut from slabs.

Figure 3. Four-point beam fatigue test device

Illinois flexibility index test

The Illinois Flexibility Index Test (I-FIT) is used to determine fracture resistance parameters of asphalts at an intermediate temperature. The I-FIT test determines the fracture energy (Gf) and post-peak slope (m) of asphalts using a semicircular specimen based on AASHTO TP124 method. The fracture parameters are used to calculate the Flexibility Index (FI) of asphalts. The FI is calculated from the Gf and post-peak slope of the load-displacement curve. It helps to identify brittle asphalts that are prone to premature cracking. Test specimen is a half disc with a notch cut parallel to the loading. Asphalt core or gyratory specimen is trimmed and cut in half to create a semicircular shaped specimen. Gyratory specimens shall be 150 mm in diameter and 160 mm in height with a target air void of 7%. The thickness of test specimen shall be 50 mm which is tested at 25°C. A load is applied along the vertical radius of specimen and the loads and Load Line Displacement are measured during the test. The load is applied at a constant LLD rate of 50 mm/min. Test fixture and specimen are shown in Figure 4. Fracture energy (Gf) represents the energy dissipated by the crack propagation and is calculated as the area under the load-displacement curve divided by the ligament area of the crack that propagates during testing. The FI is developed based on calculations of the measured fracture energy and load-displacement curve post-peak slope (m) values as shown in Figure 5 and is calculated using Equation 1. Gyratory specimens were cut to obtain two 50 mm thick disc from the middle and each disk was cut in half to create four test specimens. A 15-mm deep and 1.5-mm wide notch was sawn at the center in the flat side of the semicircular specimens.

Figure 4. I-FIT fixture and test specimen

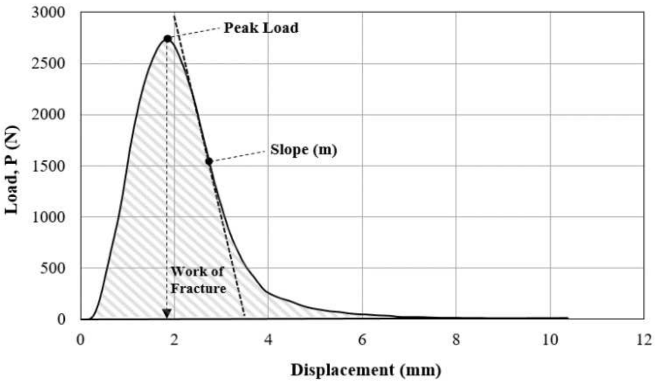

Figure 5. Typical load versus load-line displacement curve

$$FI = A \times \frac{Gf}{|m|} \quad (1)$$

Gf = fracture energy (J/m^2)
m = post-peak slope (kN/mm)
A= unit conversion and scaling coefficient taken as 0.01

5. RESULTS AND DISCUSSION

Wheel Tracking

The rut depth is plotted as a function of loading cycles in Figures 6 and 7 and the test data is summarized in Table 6. The data for Type1 dense and gap graded asphalts show that the rutting resistance of rubber modified asphalts is superior to that of unmodified asphalt, so that the rut depth of D1-CR10 and D1-RAR15 is 2.8 and 2.0 times lower than that of D1. The rut depth is also 1.9 and 2.0 times lower for G1-CR15 and G1-RAR25 compared to that of G1. The lower rut depth of D1-CR10 compared to D1-RAR15 with the same gradation type can be related to the slightly lower bitumen content and film thickness. On the other hand, the slightly lower rut depth of G1-RAR25 compared to G1-CR15 with the same binder content and mix gradation is attributed to the lower film thickness, 6.6 vs. 7.9 µm. It can be declared that the rutting performance of CR and RAR modified asphalts is nearly similar for the same gradation type, indicating RAR semi-wet process is as effective in rutting as the wet process CRM bitumen. The results of Type2 asphalts indicate that decreasing fine contents increased the rut depth of RAR mixes by a factor of 1.7 and 1.5 for dense and gap graded asphalts, but still less than unmodified asphalts. Type2 RAR modified asphalts with a higher film thickness and lower dust proportion exhibited enhanced rutting resistance compared to unmodified ones. RAR effectively improved permanent deformation behavior of asphalts of all gradation types as well as CRM does. As it is shown in Figures 6 and 7, Type2 asphalts experienced high initial rut depth as a result of pre-consolidation. But because of RAR modification effects on reduced rutting slope, the asphalts showed better performance than control asphalts.

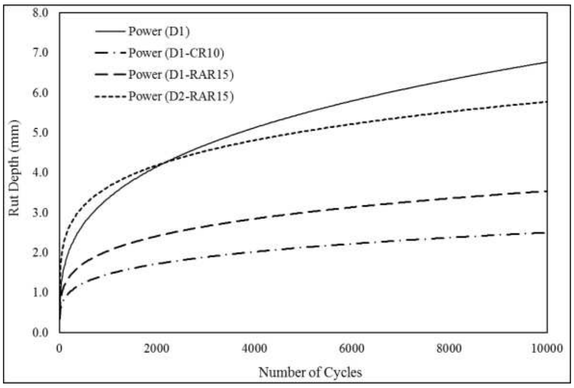

Figure 6. Rutting curves for dense graded asphalts

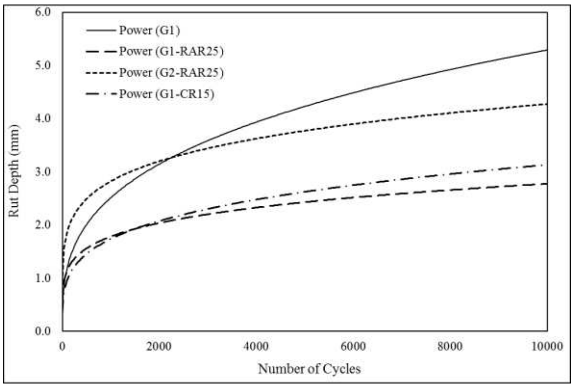

Figure 7. Rutting curves for gap graded asphalts

Table 6. Wheel tracking test results

Mix designation	Rut depth (mm)		Rutting slope (mm/cycle×10^3)
	5000 cycles	10000 cycles	
D1	5.46	6.80	0.268
D1-CR10	2.14	2.40	0.052
D1-RAR15	3.23	3.36	0.026
D2-RAR15	4.98	5.83	0.170
G1	4.03	5.61	0.316
G1-CR15	2.66	3.02	0.072
G1-RAR25	2.42	2.74	0.064
G2-RAR25	3.80	4.19	0.078

Dynamic creep

Dynamic creep test results are given in Table 7. Permanent strain is also plotted versus number of loading cycles in Figures 8 and 9. For dense graded asphalts, CRM asphalt showed better resistance to deformation compared to the others. The flow number is 4.9 and 2.0 times higher for D1-CR10 and D1-RAR15 compared to that of D1. For Type1 gap graded asphalts, CR and RAR showed similar effects. The flow number of G1-CR15 and G1-RAR25 is 10.6 and 12.2 times higher than that of G1. Similar to the rut depth of asphalts, a major part of the superiority in deformation resistance of D1-CR10 is given to the lower bitumen content and film thickness of that compared to D1-RAR15 with the same gradation type. Moreover, the higher flow number of G1-RAR25 compared to G1-CR15 with the same binder content and mix gradation can be related to the lower film thickness. It is concluded that CR and RAR enhance the deformation performance of asphalts to an equal extent. Type2 gap graded RAR modified asphalts, G2-RAR25, indicated better resistance to deformation compared to G1 control asphalt. The results confirm that RAR modification compensates for the high film thickness and low dust proportion. The flow number of D2-RAR15 and G2-RAR25 is 1.1 and 2.8 times more than that of D1 and G1. Moreover, rubber modification of gap graded asphalts is more effective than dense ones.

Table 7. Dynamic creep test results

Mix designation	Flow number (cycles)	Strain at flow (%)	Load cycles at 7% strain
D1	268	1.67	814
D1-CR10	1304	1.70	4088
D1-RAR15	540	2.52	1525

D2-RAR15	281	2.58	718
G1	190	2.01	643
G1-CR15	2008	1.88	6923
G1-RAR25	2320	2.17	7333
G2-RAR25	528	2.19	1725

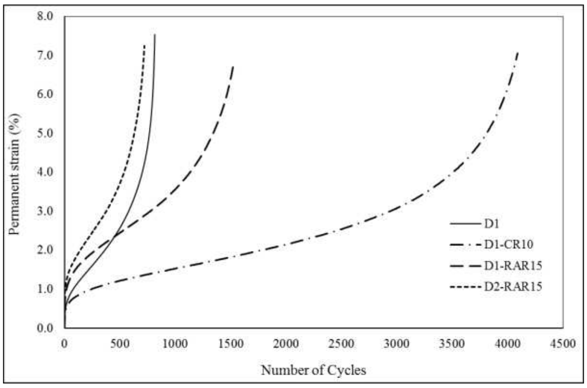

Figure 8. Creep curves for dense graded asphalts

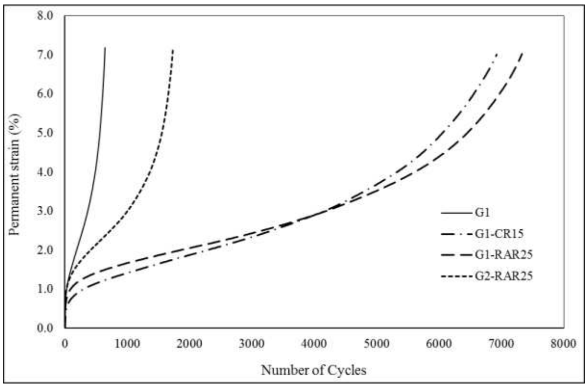

Figure 9. Creep curves for gap graded asphalts

Beam Fatigue

Test results are provided in Table 8 and typical fatigue curves are shown in Figure 10. For both dense and gap graded asphalts, CR modified ones showed enhanced fatigue performance compared to control asphalts. Comparing the results of CR and RAR modified dense graded asphalts with the same gradations, whereas D1-CR10 has lower bitumen content and film thickness compared to D1-RAR15, it is concluded that CR is superior for equal rubber, equal binder content and equal film thickness. The fatigue life of RAR modified asphalts was found to be sensitive to mix gradation, so that Type2 dense mix, D2-RAR15, showed high fatigue resistance, a minor enhancement was seen for Type2 gap mix, G2-RAR25, and Type1 RAR mixes, D1-RAR15 and G1-RAR25, showed no improvement in fatigue. The fatigue life at 700×10^{-6} strain was 4.5 and 2.5 times more for D1-CR10 and D2-RAR15 in comparison to D1. At the higher strain level of 1000×10^{-6}, the D2-RAR15 mix had a better performance so that the fatigue life was 31% and 64% more for D1-CR10 and D2-RAR15. The results reveal that modification effect on fatigue life of dense graded asphalts is prevalent at lower strain levels and the effects will be minimal at higher levels. The low film thickness of G1-RAR25 compared to G1-CR15 with the same bitumen content had a detrimental effect on fatigue life of the mix and can partly justify the much difference between fatigue performance of these rubber modified asphalts. It also explain the diminished fatigue life of G1-RAR25 comparing to the unmodified asphalt.

Table 8. Results of beam fatigue test

Mix designation	Strain ($\times10^{-6}$)	Initial stiffness (MPa)	Fatigue life (cycles)	Strain ($\times10^{-6}$)	Initial stiffness (MPa)	Fatigue life (cycles)
D1	700	2273	117340	1000	1862	26800
D1-CR10		2914	532550		2427	35240
D1-RAR15		2481	164830		2066	24570
D2-RAR15		1962	312580		1617	43950
G1	900	1845	106830	1200	1682	46240
G1-CR15		2118	510080		2125	219240
G1-RAR25		2420	83830		2352	12120
G2-RAR25		2179	136490		1841	54510

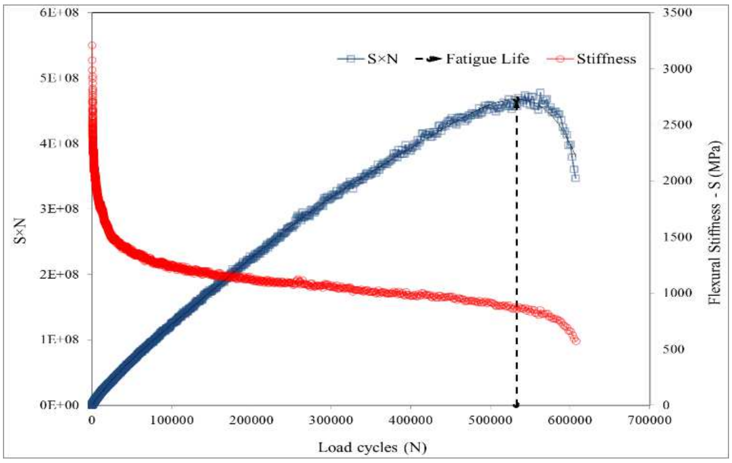

Figure 10. Typical beam fatigue test curves

Illinois flexibility index test

I-FIT test was conducted to determine the effects of RAR modification on the fracture properties of asphalts in terms of Flexibility Index (FI). Test results in Figure 11 highlights the effect of rubber modification on cracking resistance of asphalts with varying dust proportion and film thickness. Higher FI values indicate better cracking resistance. For dense gradation, D2-RAR15 with the highest FI and GF values performed the best. The FI of D2-RAR15 is 3.1 times more than that of D1. The results revealed that for dense gradations, RAR modification in conjunction with a low dust proportion leads to a highly crack resistant asphalt. Rubber modification in the form of CR and RAR considerably reduced the FI of Type1 dense graded asphalts. For gap graded asphalts, rubber modification resulted in relatively lower FI values compared to G1 control asphalt, with the G1-RAR25 having the worst performance. The results for G1-RAR25 show that for gap graded asphalts designed with about 6% binder content, RAR modification up to 25% would result in detrimental cracking effects. The lower FI value and the worse cracking resistance of G1-RAR25 in comparison to G1-CR15 with the same binder content is also attributed to the lower film thickness of RAR modified asphalt and it can be concluded that for equal binder content and film thickness the difference between RAR and CR would be minimal. G2-RAR25 exhibited a higher FI value relating to the low fines content and high film thickness.

Illinois DOT is considering a minimum FI of 8 for HMA surface mixes; however, D1 and D2-RAR15 met the requirement among dense-graded asphalts. It is also recommended that an FI value significantly greater than 8 be used for a level binder course to retard reflective cracking. All gap-graded asphalts exhibited high FI values showing a flexible behavior. Similarly, Type2 dense-graded and gap-graded asphalts showed high FI values because of the low dust proportion and high film thickness. G1-RAR25 with a low film thickness of 6.6 mm showed stiffest behavior among gap graded asphalts, as it contains 25% RAR.

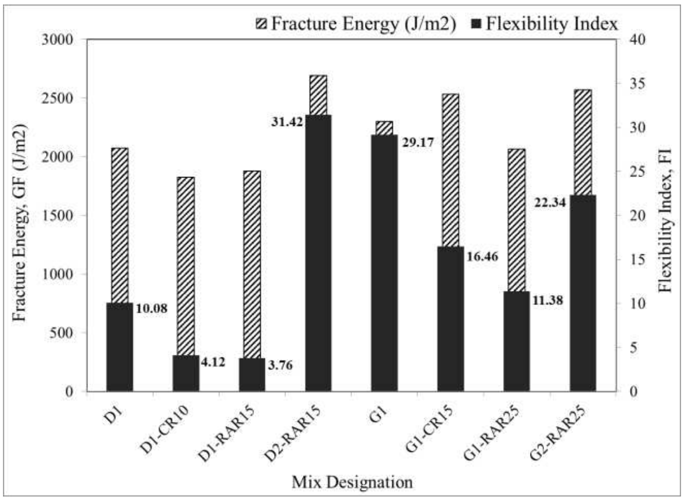

Figure 11. Flexibility index test results

6. CONCLUSIONS

A laboratory testing plan was completed to evaluate the performance characteristics of RAR modified asphalts, prepared through a semi-wet process comparing them to CRM asphalts prepared through the wet process and unmodified asphalts. Four mix gradations; two dense-graded and two gap-graded, with varying fine contents were tested. Performance tests were conducted and a short analysis was done on the bitumen film thickness. The findings are summarized below:

- Rutting resistance of rubber modified asphalts is superior to that of unmodified asphalt and the performance of CR and RAR modified asphalts is similar for the same gradation type, which indicate RAR semi-wet process is as effective in rutting as the wet process CRM bitumen.
- Decreasing the fines content in the mix gradation increases the rut depth. The rut depth increased for Type2 RAR asphalts, but still less than unmodified asphalts.
- According to dynamic creep test results, rubber modified asphalts show much better resistance to deformation compared to unmodified asphalts. Comparing the results of RAR and CR modified asphalts with the same gradation and analyzing the binder content and film thickness values revealed that CR and RAR enhance the deformation performance of asphalts to an equal extent.
- CR modified asphalts showed enhanced fatigue performance compared to unmodified ones and the fatigue life of RAR asphalts was found to be sensitive to mix gradation. Type2 dense-graded RAR asphalt showed high fatigue life and a minor enhancement was seen for Type2 gap-graded RAR asphalt. CR is superior to RAR in fatigue performance for equal rubber, equal binder content and equal film thickness.
- Rubber modification reduces the FI value and so the crack resistance of asphalts is decreased, but FI value for Type2 dense-graded RAR asphalt was determined 3.1 times higher compared to control asphalt. For dense-graded asphalts, rubber modification in the form of RAR in conjunction with a low fines content leads to a highly crack resistant asphalt relating to the high film thickness.

7. ACKNOWLEDGEMENT

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