New Advancements in Rubberized Asphalt Using an Elastomeric Asphalt Extender – Three Case Studies

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ABSTRACT: A new frontier in rubberized asphalt technology has been achieved with the new innovative product called Reacted and Activated Rubber (RAR). As introduced in AR2012 international conference and in the 2013 TRB annual meeting, RAR is composed of neat soft bitumen, fine grinded crumb tire rubber, and a siliceous Activated Mineral Binder Stabilizer (AMBS), at optimized proportions. RAR is produced by a simple low-energy process to form a dried granulated activated rubber. It can be added, directly to the pugmill, for producing any type of Hot Mix Asphalt (HMA) – Dense, Open Graded, Gap graded, SMA, etc., for replacing part of the asphalt cement (bitumen) at different proportions.

As reported, RAR modifies the neat bitumen by increasing its PG grading, while modifying also the resilience, and recovery properties. When added to HMA mixes, RAR showed much better Stability, Rutting & Fatigue resistance and low draindown in SMA mixes (without the fibers), under attractive cost/benefit and environmental conditions.

This paper summarized further successful R&D effort in the laboratory and in the field, where actual three Road Tests were performed and monitored in Israel, using RAR HMA mixes under hot climatic conditions. The RAR HMA mixes (Dense and Superpave "S" graded) were produced in conventional batch asphalt plants with the use of the regular SMA fiber-feeder for feeding the RAR directly to the pugmill without any additional heating or setting. The road tests included a residential street and highly trafficked industrial road in the city of Tel Aviv, and an access road to a very busy aggregate quarry. The performance and results so far (after more than two years of service from the first road test) have clearly strengthen the advantages of RAR Asphalt Rubber mixes achieved in the first phase of the research, leading to actual paving jobs, and new modified specifications for asphalt rubber in Israel.

KEYWORDS: Rubberized Asphalt, Elastomeric Asphalt Extender, Reacted and Activated Rubber, Laboratory and Field Tests, Cost/benefit and Environmental Advantages .

1. Background

Despite the proven advantages of Asphalt Rubber (AR) hot mix asphalts, there is still no breakthrough or significant development in the global practical use and implementation of this technology. Some reasons of this stagnation can be listed as**:** The tedious wet process of producing the Asphalt Rubber Binder, involving very high temperature and long blending and reaction time; The complexity and cost of the blending unit that must be installed in every asphalt mixing plant; The necessity to re-heat the hot asphalt rubber binder after longer rest periods; And the high cost of the Asphalt Rubber paving mixes as compared to conventional HMAs. One solution to these disadvantages, that was found to provide a basis for an innovating and improving Asphalt Rubber, is the new "Reacted and Activated Rubber" – RAR,

The new RAR, as an **Asphalt Rubber Binder**, is composed of neat soft asphalt cement (bitumen), fine crumb rubber from scrap tires, and an Activated Mineral Binder Stabilizer (AMBS) at optimized proportions. RAR is produced by a short time hot blending and activation in a specially designed industrial process to form a dried granulated reacted and activated rubber. RAR can be added to any type of Hot Mix Asphalt (HMA) – Dense, Open Graded, Gap-graded, SMA, etc., for replacing part of the bitumen at different proportions. In the mixing plant, RAR is added directly to the pugmill or dryer drum, right after the bitumen spraying, using existing feeders (i.e. fiber feeders for SMA mixes, etc.).

Extensive R&D Research has shown that Asphalt Rubber HMA, produced with RAR, outperforms conventional HMA and even common modified and asphalt rubber mixes. In general, RAR is an **elastomeric asphalt extender** that modifies the plain bitumen by increasing its PG grading, resilience, and recovery properties. Different types of HMA produced with RAR showed much better Stability, Rutting and Fatigue resistance under attractive cost/benefit conditions (Sousa *et al*. 2012, 2013).

2. RAR Composition and Properties

As seen in Figure 1, RAR is composed of soft asphalt cement (bitumen), fine crumb tire rubber (usually #30 mesh) and an Activated Mineral Binder Stabilizer (AMBS) at optimized proportions. A brief description of the ingredient is as follows:

<u>The asphalt cement</u> can be straight run neat soft bitumen. Asphalt cements or bitumens graded as Pen 100-200 to Pen 35/50, or AC 20, or PG 52 to PG 70, are used. The use of the softer bitumen enable to produce HMA's at common mixing and laying temperatures without losing the proper workability, despite the addition of the crumb rubber.

Bitumen **Crumb Rubber** **AMBS**

Figure 1. *RAR ingredients: Asphalt Cement (Bitumen), Crumb Tire Rubber and AMBS*

<u>The Crumb Rubber</u> is usually consisting of scrap tires that are processed and finely ground by any proven industrial method. The scrap tires consist of combination of automobile tires and truck tires, and should be free of steel, fabric or fibers before grinding. For the production of RAR, the crumb rubber particles should be finer than 1.0 mm. A #30-mesh maximum particle size is preferred. Cryogenic or ambient ground crumb rubber can be used.

<u>The Activated Mineral Binder Stabilizer (AMBS)</u> is a new micro-scale binder stabilizer that was developed to prevent excessive drainage of the bitumen in SMA mixes during mix haulage, storage and laying. This stabilizer is an activated micro-ground raw silica mineral (40 μm and finer), which is a waste by-product of Phosphate Industries mining. The activation, made by Nano monomolecular particle coating. It was aimed at obtaining Thixotropic and Shear-Thickening properties for the bitumen, since the mastic in the mix should possess high viscosity at rest (haulage, storage and after laying) - for reducing draindown, and low viscosity in motion (mixing and laying) - for maintaining the proper workability (Ishai *et al*., 2011, Watson and Moore., 2011, Svechinsky *et al*., 2011, Ishai *et al*., 2012, Wu *et al*. 2012).

The presence of the active AMBS in the RAR provides a unique and enhanced mechanism of joining the bitumen to the rubber particles to form an extended elastomeric binder, which is more stable and flexible for creating stronger and more durable bituminous mixtures. This means better Stability, Rutting & Fatigue resistance and low draindown in SMA mixes (without the fibers), under attractive cost/benefit and environmental conditions (Sousa *et al*. 2012, 2013).

A typical example of the modification effect of RAR, when added to a soft plain bitumen to form a combined binder is illustrated in Figure 2. As can be seen, the addition of RAR to non-modified bitumen upgrades significantly the rheological behavior of the bitumen. This is reflected by the increase of the positive PG grading indicator as a function of increasing the RAR proportion in the combined binder. This effect is similar to the addition of polymer modifiers to the neat bitumen to get modified asphalt binders. It should be stressed that with the addition of the RAR to the neat bitumen, the presence of the crumb rubber and the enhancing network created by the AMBS, provide combined bitumen with much better elastic properties.

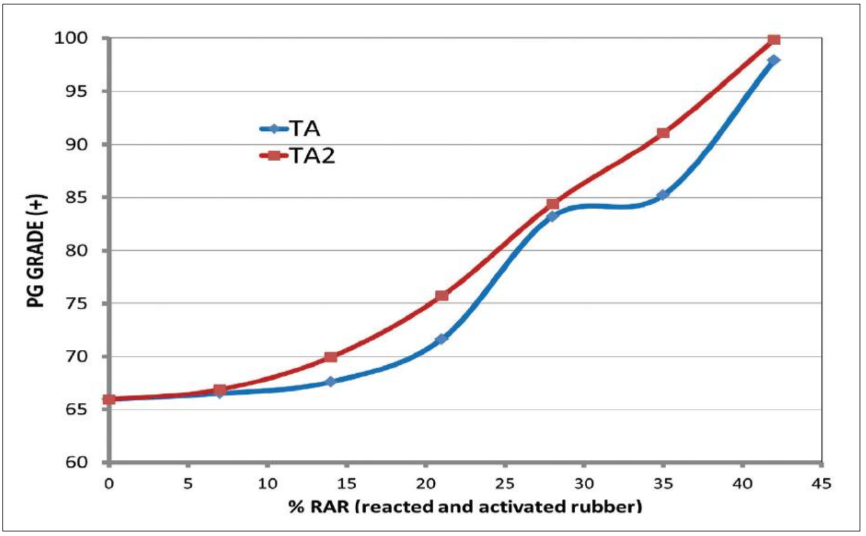

Figure 2: *Effect of RAR content on the PG grading of the combined binder (positive indicator)*

3. RAR Production

The Reacted and Activated Rubber is produced in a specially designed plant by a unique and fully controlled industrial process. After several pilot of machinery equipment, a large-scale industrial plant have been designed and manufactured in the USA. This plant was imported to Israel, and it is now installed in the yard of Dimona Silica Industries (see Figures 3 and 4). This is a batch system, which produces up to two batches of one metric ton RAR per hour. The production system operates semi-automatically, where the feeding and discharge stages are controlled manually and the heating and cooling stages – automatically.

RAR is generally produced by a short term heating and activation process. This is done in the following stages:

1. Feeding the fine crumb rubber into a heating mixer, and heating to a target temperature.
2. Pumping the hot bitumen through a heating exchanger into a metering container and heating to the target temperature and above. After heating the bitumen, the Activated Mineral Binder Stabilizer (AMBS) is fed into the container and mixed with the bitumen while heating back to the same temperature. This stage is performed parallel to stage one.

3. Transferring the heated crumb rubber into a mixing reactor while keeping the target temperature.
4. Transferring the bitumen-AMBS mix by pumping it into the mixing reactor.
5. Mixing all three components in the reactor while elevating the heat up to a higher target temperature.
6. Transferring the heated mix into a cooling mixer operated by circulation of cold water. Reducing the heat down to 50^{o}C.
7. Transferring the cool mix into a coating mixer and coating it with additional AMBS and a special mineral filler. The final product is the Reacted and Activated Rubber - RAR, in the form of dried granulated particles.
8. Feeding and packing the dried granulated RAR in to plastic big-bags for storage or direct delivery.

Figure 3: *RAR production plant installed and operated in the Dimona Isreal*

Figure 4: *The control panel for the semi-automatic operation of the RAR production plant*

4. Case Study 1: Access Road to an Aggregate Quarry

4.1 *Site and Work Description*

The first actual road test construction in Israel, using RAR modified asphalt-rubber mixes, was performed in October 2012 on an access road to a heavily operated regional aggregate quarry in the Bait She'an Valley. The traffic in the road composed of about 500 loaded heavy trucks daily, moving back and forth. The test section was 150 m. length and 7 m. wide, with 5 cm thick layer, at 6% road slope. Air ambient temperature range during mid-day construction time was 31-33^{o}C. The total mix quantity in the road test section was about 120 metric tons.

The RAR HMA was produced by batch type mixing plant with a 5 tons batch capacity, using fully computerized monitoring. Actual production for the test - 3 tons batches. Conventional paving equipment were used, including a new VOIGELE paver, a steel tandem roller and a heavy pneumatic roller. The RAR, in the form of of dried granulated particles, was fed directly to the mixer by the conventional fiber feeder as used for producing SMA mixes. An asphalt emulsion tack-coat was sprayed on the cleaned existing road surface prior the construction (see photographs in Figure 5).

Figure 5: *Photographs describing the application of Tack-coat, laying and compaction, and RAR feeder during the October 12th 2012 road test*

4.2. ***Mix Design and Characteristics***

The basic control conventional asphalt mix for the road test is a 19 mm. "S" graded (Superpave) HMA with PG 70-22 bitumen. Dolomite aggregates were used for the fine fractions and Basalt for the coarse ones (for skid resistance purpose). The gradation of the basic control mix is presented in Table 1:

Table 1. *Aggregate gradation of the basic control mix*

Sieve Size	in/# mm.	3/4" 19	1/2" 12.5	3/8" 9.5	#4 4.75	#10 2.0	#20 0.85	#40 0.425	#80 0.180	#200 0.075
% Passing		100	91	74	36	24	14	11	8	5.5

A standard Marshall mix design was performed on the basic mix. Mixing temperature was 165-170^{o}C and samples were compacted at 75 blows. According to the local asphalt mix design criteria, an Optimum Asphalt Content (OAC) of 4.5% was obtained for a median 6.0% air voids, as seen in Figure 6:

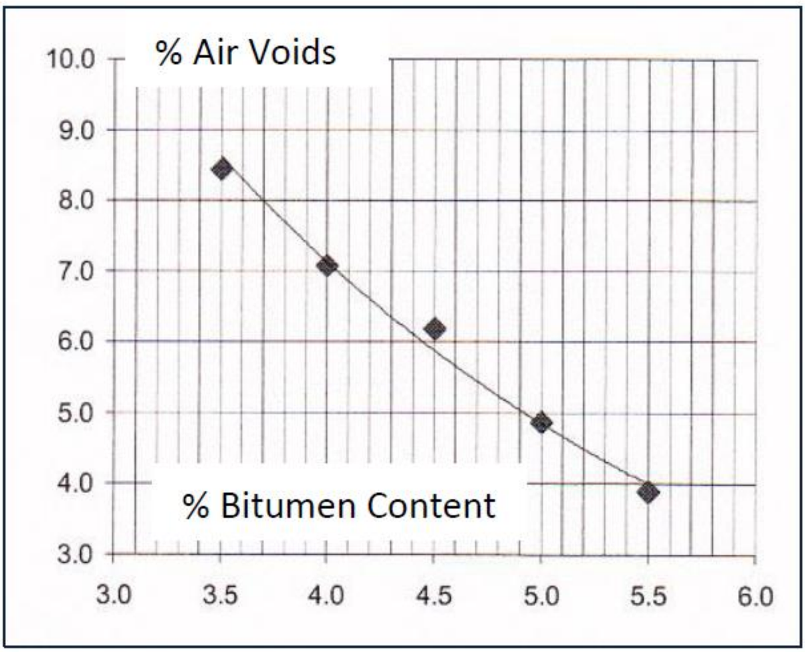

Figure 6. *An Optimum Bitumen Content (OAC) of 4.5% of the basic control mix obtained at a median 6.0% air voids*

The same aggregate gradation and bitumen type were used for the RAR Asphalt Rubber mix. In this mix, 15% percent of the bitumen were replaced by RAR, so the total binder contained 85% PG 70-22 neat bitumen and 15% RAR. The same Marshall mix design procedure was used, where between mixing and compaction, the samples were kept in the oven for one hour, in order to simulate plant storage and hauling time, which help the activation and further melting of the rubber. Keeping the same median air voids criterion, the mix design led to the same OAC of 4.5%. Table 2 presents the comparison of mix characteristics at OAC, for both the basic control mix and the RAR Asphalt Rubber:

Table 2. *A comparison of mix characteristics at OAC, between the basic control mix and the RAR Asphalt Rubber (average values):*

Mix Type	Basic Control Mix	RAR Asphalt Rubber
% Air Voids	6.0	6.0
% OAC (neat or with RAR)	4.5	4.7
% VMA	15.4	15.0
Bulk Density (kg/m^3)	2380	2420
Stability (lb)	2960	3810
Flow (1/100in)	10	15
% Retained stability (24hrs, 60^{o}C)	92	94

It can be seen that under identical air voids criterion, the RAR Asphalt Rubber mix possessed slightly higher OAC. The rubber mix is more flexible, denser and possess higher strength and slightly higher durability after 24 hours in hot water immersion. The road test involved the production and laying of the RAR Asphalt Rubber mix, as described in paragraph 4.1.

4.3 *Production Quality Control*

The Israeli Standard Institute (ISI) Roads and Soil Laboratory, using the asphalt plant laboratory, made the quality control of the RAR AR mix production. Four representative samples were taken during the 2 hours production period. Table 3 summarizes the average properties of the RAR AR mixes during production (see next page):

As can be seen, the production of the mix through the duration of the road test was uniform. This is reflected mainly by the density and stability values. The RAR AR plant mix possessed lower stability and density comparing to the laboratory made design mix, however the absolute stability values are much higher than the standard requirement. As typical for asphalt rubber mixes, higher air voids or lower densities were obtained for a given value of bitumen content. In general, the plant RAR AR mix fully complied with the local standard requirements.

Table 3. *Characteristics of the plant RAR Asphalt Rubber mixes as sampled and tested during production in the road test (average values)*

Sample No.	Temp. at Sampling (°C)	Air Voids (%)	Binder Content (%)	Bulk Density (kg/m^3)	Stability (lb)	Flow (1/100")	Retained Stability (%)
1	168	8.1	4.3	2352	2844	16	87.9
2	170	7.5	4.4	2364	3041	10	--
3	168	8.2	4.5	2347	2915	13	90.3
4	170	7.1	4.7	2376	2810	12	--
Aver.	**169**	**7.7**	**4.5**	**2360**	**2903**	**12.8**	**89.1**
Mix Design		6.0	4.7	2420	3810	15	94
Local ISI Standard		4.5-7.5	--	--	>2000	8-16	>80

4.3 ***Monitoring Pavement Condition***

The RAR AR road test section in the access road to the quarry was opened to traffic immediately after construction. Four months later, road cores were drilled at six locations for monitoring the asphaltic layer properties. They were of 100 and 150 mm diameter, as seen in Figure 7:

Figure 7. *Field core drillers of 100 and 150 mm diameter and drilling two 150 mm core pair at location A*

The field cores were tested for volumetric characteristics, as well as for stability & flow. Average results (for four cores at each location) are summarized in Table 4:

Table 4. *Volumetric and mechanical properties of 100 mm field cores drilled at the road test section four months after construction (average of 4 samples)*

Testing Location	Core Thick. (mm)	Bulk Density (kg/m^3)	Compaction Degree (%)	Stabi-Lity (lb)	Flow (0.01")	Gradation Compa-tibility	Binder Content (%)
A	50	2326	98.5	1048	19.5	yes	4.0
B	46	2310	97.9	1114	19.0	yes	4.2
C	56	2314	99.0	1283	27.0	yes	4.3
E	55	2356	99.9	1393	27.7	yes	4.3
F	49	2342	99.3	1128	23.5	yes	4.5
Aver.	**58**	**2330**	**98.9**	**1193**	**23.3**	**yes**	**4.3**
Control: Re-compacted Samples		2308	--	2074	21.7	--	4.7

It can be seen that after four months of intensive and heavy truck traffic operated back and forth to the quarry, all layer parameters indicate very good condition and performance: high degree of uniformity, high density and compaction degree. As for the stability, the low field values conform to the local relationship between the stabilities of field vs. laboratory samples, in this case at a ratio of 1.43 (Livneh et.al 1979). As for the relatively high flow values, they are related to longer effect of rubber assimilation and activation within the mix. In addition, the slightly lower binder content reflects the exposed core perimeter due to the drilling through the aggregate mass.

Visual inspection of the pavement condition was made after four months and after two years from construction date, as seen in Figures 8 and 9.

Figure 8. *Pavement and top RAR Asphalt Rubber layer after four months from construction date*

Figure 9. *Pavement and top RAR Asphalt Rubber layer after two years from construction date*

As can be seen, layer and pavement condition are sound and smooth. No pavement damages were observed over the entire road test section of the RAR Asphalt Rubber top layer.

5. Case Studies 2 & 3: Two streets in the City of Tel Aviv

5.1. *General*

The City of Tel Aviv have upgraded its transportation infrastructure system to include Sustainability and Value-Engineering considerations in the decision making process for the design and construction phases of the street network. In this process, "green" environmental-friendly technologies were adopted together with longer lasting products that conform to cost/benefit criteria.

Based on this practical philosophy, the application of RAR in asphaltic mixes was chosen for testing. RAR contains about 80% of recycled waste. That is: about 60% of ground scrap tires and 20% AMBS (which is a waste by-product of the phosphate industry). Also, the mechanical and durability advantages of RAR asphalt rubber mixes (as described in paragraph 2 above), has place this product within the front of the asphalt rubber paving technology.

Accordingly, the rehabilitation projects of two streets in the city, involving milling and asphalt laying, included also road test sections were RAR asphalt rubber was applied. The following streets included the road test sections:

- **Yeheskel Street**: A two-lane one-way street, 6 meters wide and 320 meters long, in a residential neighbourhood. Served as the "ability proof" road test section for the main road test.

- **Salame Street**: The main road test. A four-lane two-way street 12 meters wide and 600 meters long. A heavily trafficked arterial street in a commercial zone. Divided into three sub test sections.

5.2. *Mix Design and Characteristics*

The following three types of HMA were involved in the mix design and characterization stage of the Yeheskel and Salame Streets road tests:

- A 19 mm. "S" graded (Superpave) HMA with PG 70-22 bitumen and Dolomite aggregates. Used for both Wearing and Binder courses. Both RAR Asphalt Rubber and conventional (neat) mixes were used in the road tests. In this mix RAR replace 15% of the bitumen content.
- A 19 mm. dense graded HMA with PG 70-22 bitumen and Dolomite aggregates. Used for Wearing courses only. Both RAR Asphalt Rubber and conventional (neat) mixes were used in the road tests. In this mix RAR replace 20% of the bitumen content.
- A 12.5 mm. SMA (Stone Matrix Asphalt) mix with PG 70-22. Basalt aggregate was used for the coarse fraction and Dolomite for the fines and filler. In this mix RAR replace 25% of the bitumen content. This mix was a part of the mix design stage but not used in the road tests. Both RAR Asphalt Rubber and conventional (neat) mixes were used in the mix design testing. In the conventional SMA mix fibres were added for draindown prevention. There was no need for fibres in the rubber mixes since RAR was acted also for preventing draindown.

Tables 5 and 6 present the gradations and the properties of these mixes as obtained in the mix design procedure. The conventional (neat) mixes were served as control mixes in the Salame road test.

Table 5. *Aggregate gradations of the conventional and RAR HMA included in the road tests performed in the city of Tel Aviv*

Sieve Size	in/# mm.	3/4" 19	1/2" 12.5	3/8" 9.5	#4 4.75	#10 2.0	#20 0.85	#40 0.425	#80 0.180	#200 0.075
"S" Graded Mix – 19 mm		100	92	73	35	25	14	11	8	6.0
Dense graded Mix -19 mm		100	86	72	50	32	20	14	9	6.0
SMA – 12.5 mm		100	100	93	26	18	--	--	--	8.0

Table 6. *A comparison of mix characteristics at OAC, between the basic control (neat) mix and the RAR Asphalt Rubber for all type of mixes (average values):*

Mix Type	**"S" Graded**		**Dense Graded**		**SMA**	
# of Compaction Blows	**75**		**50**		**50**	
Rubber or Neat	**Control**	**RAR**	**Control**	**RAR**	**Control**	**RAR**
% RAR in the Binder	0	15	0	20	0	25
% Air Voids	6.0	6,0	4.5	4.5	7.2	7.2
% OAC (neat or with RAR)	4.3	4.8	4.9	5.3	5.9	6.5
% VMA	15.7	15.5	14.8	15.4	19.6	20.5
% Draindown in SMA	--	--	--	--	0.06	0.03
Bulk Density (kg/m^3)	2364	2355	2375	2365	2310	2320
Stability (lb)	2730	3100	3080	3350	1715	1729
Flow (1/100in)	11.2	10.8	12.2	13.0	--	--
Retained stability (24hrs, 60^{o}C)	89	92	91	93	94	94

By comparing the properties of the RAR Asphalt Rubber mixes with the neat control ones, it can be seen that at the identical air voids criterion the RAR AR mixes possessed higher total binder content in the range of 0.4-0.6% for the different types of mixes. This is mainly due to the thicker binder films on the aggregates obtained by the existence non-melted rubber particles and by the fine AMBS mineral particles in the RAR. Also it can be seen that the RAR "S" graded and dense graded mix are more stable and somewhat more durable as compare to the neat control mixes. By increasing the air voids criterion, a lower optimum binder content should be obtained in the rubber mixes. Further investigated in this respect should be performed.

As seen for the SMA mixes, by replacing part of the neat bitumen with RAR, the consistency effect of the Rubber and the activity of the AMBS on preventing draindown in very impressive. Despite the fact that the RAR AR mix possessed higher binder content, the draindown value is much lower without any fibres in the mix. As RAR and bitumen are in the same price scale, the omission of the necessity of fibres in SMA mixes creates a substantial saving.

5.3. *Case Study 2: Road test section in Yeheskel Street – Paving and Monitoring*

In this ability-proof project (performed in September 17, 2014) one layer of 19 mm. Dense Graded RAR asphalt rubber mix (see Tables 5 and 6) was implement in one a 5 cm. thick layer after milling and tack coating. A batch type mixing plant with a 4 tons batch capacity, and fully computerized monitoring, produced the mix. The RAR, in the form of of dried granulated particles, was fed directly to the mixer chamber by the conventional fiber feeder as used for producing SMA mixes Conventional paving equipment were used, including a VOIGELE paver, a steel tandem roller and a heavy pneumatic roller. Production temperature was 170-175^{o}C, laying temperature. - 150-160^{o}C, compaction temperature - 145-150^{o}C for the steel roller and 125-135^{o}C for the pneumatic roller. (See photographs in Figure 10).

Figure 10: *Photographs describing the production batch mixing plant, filling the SMA fibres bin with RAR, laying, and compaction with steel and pneumatic rollers. A day work on September 17, 2014 (an ability-proof road test)*

The quality control tests during production of the rubber mix led the following results that fully complied to the designed job mix formula and the Israeli standard for that mix (see Table 7).

Table 7. *Characteristics of the plant RAR Asphalt Rubber Dense mix as sampled and tested during production in the Yeheskel Street road test (average values)*

Sample No.	Temp. at Sampling (^{o}C)	Air Voids (%)	Binder Content (%)	Bulk Density (kg/m^3)	Stability (lb)	Flow (0.01")	Retained Stability (%)
1	170	5.2	5.3	2367	3434	11.5	92
2	168	5.4	5.4	2364	3306	11.0	--
Aver.	**169**	**5.3**	**5.35**	**2365**	**3370**	**11.2**	**92**
Mix Design (Table 6)		4.5	5.3	2365	3350	13.0	93
Local ISI Standard		3.0-6.0	--	--	>1800	8-16	>75

Yeheskel test section was opened to traffic one day after construction. One-month later, 100 mm. diameter cores were drilled at eight locations for monitoring the field density of the rubber-modified layer. The average compaction degree was found to be 0.6% below the general requirement, however due to the low traffic loads in this residential street (only private cars), this field density was approved.

Two months from the construction date, friction tests were performed using the British Pendulum Tester (according to ASTM E 303). Four friction measurements were made under wet conditions at five locations. The results are summarized in Table 8:

Table 8. *Results of friction measurements made by the British Pendulum Tester in Yeheskel Street (performed on November 11, 2014, Ambient Temperature 23^{o}C)*

Test Location	Measurement Number				Average BPN
	1	2	3	4	
A	66	65	65	65	65.2
B	68	68	67	68	67.7
C	67	68	68	68	67.8
D	67	67	68	68	67.5
E	68	67	67	68	67.5
Total Average					**67.1**

The British standard criteria, for "Light Sites" (low traffic, light slopes, straight lines, etc.) calls for a minimum friction value, as measured by the British Pendulum Tester - BPN, of 45 under wet condition. As seen in the table above, the friction number values measured in Yeheskel Street are far above, indication a very high skid resistance.

For summarizing the road test section in Yeheskel Street, as an "Ability Proof" project for the RAR Asphalt Rubber mixes, visual inspection of the street surface was made in the beginning of November 2014, prior to implementing this technology in Salame Street. As seen in the photographs of Figure 11, the top RAR asphaltic layer was found to be in a very good condition, without any visual damage.

Figure 11: *Photographs showing the surface condition of Yeheskel Street about two months after construction*

It was concluded that the very positive engineering indicators, related to the design, production, implementation and performance of the RAR Asphalt Rubber mix paved in Yeheskel Street, provided a "green-light" for the further and major actual road test in Salame Street.

5.4. *Case Study 3: Road test section in Salame Street – Paving and Monitoring*

The road test sections in Salame Street was considered as the main road test for the City of Tel Aviv in the decision making process to examine the adaptation of the Asphalt Rubber technology. The implementation of RAR asphalt rubber mixes was performed during six night jobs between November 10th and December 2nd, 2014.

Generally, the pavement rehabilitation involved 10 cm. depth surface milling, tack- coating, and laying of a binder and a wearing courses, 5 cm. thick each. Three sub-sections were defined and performed, each about 200m.long, as follows (see also Tables 5 and 6):

Section A: 19 mm. **"S" graded RAR Asphalt Rubber** mix for both the binder and wearing courses.

Section B: 19 mm. **"S" graded RAR Asphalt Rubber** mix for the binder course and 19 mm. **Dense graded RAR Asphalt Rubber** mix for the wearing courses.

Section C: The **control** section - 19 mm. **"S" graded conventional (neat)** mix for the binder course and 19 mm. **Dense graded conventional (neat)** mix for the wearing course.

The production and laying of the asphaltic mixes in Salame Street were made by the same contractor as in Yeheskel Street, using the same mixing plant, paving equipment and conditions (see paragraph 5.3 above). The photographs in Figure 12 present a typical night job at the mixing plant and construction site.

Figure 12: *Photographs describing the mixing plant control panel, tack coated surface after milling, laying, compaction with steel and pneumatic rollers, and milling the opposite direction lanes while loading an empty asphalt mix truck. A night work on sub-section A in Salame Street, November 10/11, 2014*

The visual inspection of section A on the day following construction, after applying the road paintings, is presented in the photographs of Figure 13:

Figure 13: *Photographs showing the surface condition of sub-section A in Salame Street on the day following construction (November 12, 2014)*

The quality control tests during production of the rubber and conventional mixes for Salame Street road test led the following results (see Tables 9 and 10):

Table 9. *Characteristics of the plant RAR Asphalt Rubber mixes ("S" graded and Dense graded mixes) as sampled and tested during production for the Salame Street road test (average values)*

Sample No.	Description	Air Voids (%)	Binder Content (%)	Bulk Density (kg/m³)	Stability (lb)	Flow (0.01")	Retained Stability (%)
		19 mm. "S" Graded Mixes					
1	**Sec. A, Binder**	5.4	4.8	2378	3398	13.0	96
2	**--"--**	5.7	4.8	2371	3283	12.0	--
1	**Sec. A, Wearing**	5.7	4.8	2373	3215	13.0	98
2	**--"--**	5.8	4.8	2370	3183	12.5	--
1	**Sec. B, Binder**	5.5	4.8	2380	3229	14.6	98
2	**--"--**	5.7	4.8	2375	3197	14.7	--
	Average	**5.63**	**4.80**	**2374**	**3251**	**13.3**	**97.3**
	Mix Design	6.0	4.80	2355	3100	10.8	92
		19 mm. Dense Graded Mixes					
1	**Sec. B, Wearing**	4.4	5.4	2381	3412	12.6	96
2	**--"--**	4.7	5.4	2376	3366	12.2	--
	Average	**4.55**	**5.40**	**2378**	**3389**	**12.4**	**96.0**
Mix Design (Table 6)		4.5	5.3	2365	3350	13.0	93

Table 10. *Characteristics of the plant* *Control Conventional* *("S" graded and Dense graded mixes) as sampled and tested during production for the Salame Street road test (average values)*

Sample No.	Description	Air Voids (%)	Binder Content (%)	Bulk Density (kg/m^3)	Stability (lb)	Flow (0.01")	Retained Stability (%)
		19 mm. "S" Graded Mixes					
1	**Sec. B, Binder**	5.9	4.4	2373	2996	15.2	95.0
2	**--"--**	5.5	4.3	2381	3072	14.9	--
	Average	**5.7**	**4.35**	**2377**	**3034**	**15.0**	**95.0**
Mix Design (Table 6)		6.0	4.3	2364	2730	11.2	89.0
		19 mm. Dense Graded Mixes					
1	**Sec. B, Wearing**	4.8	4.8	2372	3230	11.0	92.0
2	**--"--**	4.5	4.9	2380	3303	12.0	--
	Average	**4.65**	**4.85**	**2376**	**3266**	**11.5**	**92.0**
Mix Design (Table 6)		4.5	4.9	2375	3080	12.2	91

As compared to the rubber laboratory mixes used in the mix design stage, the results in Table 9 shows that the rubber plat mixes are more stable, but also possess substantial higher moisture resistance (durability), as express by the retained stability. The plant mixes also have higher air voids at identical values of binder content. Those differences in the strength and durability can be attributed to the longer period of rubber melting and AMBS activation that characterize the loose RAR AR mixes in actual plant production, storage, hauling and laying, as compare to the laboratory procedure.

When comparing the plant RAR AR mixes to the plant conventional control mixes (Table 9 vs. Table 10), it can be seen that the rubber mixes are more stable and more durable. This was obtain under identical air voids but with higher binder content in the rubber mixes (at a range of 4.5-5.5%). As shown before, similar trend was also obtained in the mix design stage for the laboratory mixes.

Two months after construction, 100 mm. diameter cores were drilled at eight locations in each sub-section for monitoring the field density and stability of each layer. The results are summarized in Table 11. As can be seen, high field density was obtained in each layer of each sub-section. The average compaction degree values of each layer ranges between 97.0-98.6% (based on bulk density), indicating relatively high field densities. No difference was recorded between the rubber sub-sections and the control one. As for the stability, relatively high field values were obtained for the entire road test (for comparison see Table 4), however, the stability of the RAR AR "S" graded layers were found to be much higher than that of the conventional "S" graded mixes in the control sub-section.

Table 11. *Field density and stability of 100 mm cores drilled at the Salame road test section two months after construction (average of 6 samples in each sub-section)*

RAR Asphalt Rubber or Conventional Mix	Rubber				Conventional (Control)	
Sub-Section	A		B		C	
Course	Binder	Wearing	Binder	Wearing	Binder	Wearing
Type of Mix	"S"	"S"	"S"	Dense	"S"	Dense
Construction Date, 2014	Nov. 10	Nov. 11	Nov. 12	Nov. 18	Nov. 17	Dec. 2
Relative Field Density (kg/m^3)	97.9	97.8	98.6	97.6	97.0	97.7
Field Stability (lb)	1512	2175	1570	1775	1461	1778
Average stability (lb)	1752			1775	1461	1778

Similar to the Yeheskel "ability-proof" road test, three months from the final construction date (on March 2nd, 2015), friction tests were also performed in Salame road test using the British Pendulum Tester (ASTM E 303). Four friction measurements were made under wet conditions at each of 24 locations. The results are summarized in Table 8:

Table 12. *Total average results of friction measurements made on top of the wearing course in Salame Street using the British Pendulum Tester (Ambient Temperature 19^{o}C)*

RAR Asphalt Rubber or Conventional Mix	Rubber		Conventional (Control)
Sub-Section	A	B	C
Construction Date, 2014	11.11.14	18,11,14	02.12.14
Type of Mix	"S" Graded	Dense Graded	
Course	Wearing		
Total Average BPN Friction Number	**60.25**	**60.87**	**59.50**

The British Standard criteria, for "Medium Sites" (Freeways, arterial roads, urban streets with heavy traffic) calls for a minimum friction value, as measured by the British Pendulum Tester - BPN, of 55 under wet condition. As seen in the table, the friction number values measured in Salame Street are above the minimum criterion, indication a good skid resistance. By comparing the dense graded wearing courses in sub-sections A and B, it can be seen that the rubber wearing course surface possesses higher skid resistance than that of the conventional wearing course in the control sub-section.

In addition, the friction results in Salame street road test are lower than that of Yeheskel street (see Table 8). This might be due to the much higher traffic volume, heavier vehicles, and the longer time from constriction to friction measurements that characterize the Salame road test.

For summarizing the road test sections in Salame Street, as the main project for the RAR Asphalt Rubber mixes, visual inspection of the street surface along the road test was made in the beginning of March 2015 (3-3½ months after the end of construction). As seen in the photographs of Figure 14, the top RAR asphaltic layers, as well as in the control sub-section, were found to be in a very good pavement condition, without any visual damages that might occur due to the intensive traffic or to the very rainy winter months of 2014/2015.

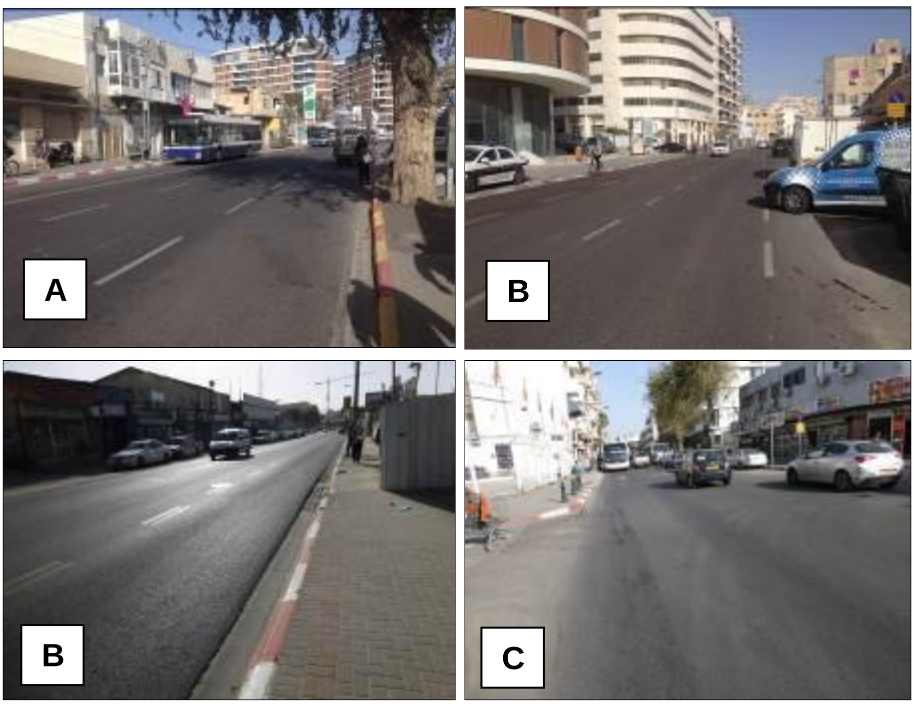

Figure 14: *Photographs showing the surface condition of Salame Street road test in sub-section A, B and C, 3-3½ months after construction*

It was concluded that the very positive engineering indicators, related to the design, production, implementation and performance of the RAR Asphalt Rubber mix paved in Salame Street road test, should provide an incentive for the further implementation of these rubber mixes when high performance, durable and green Hot Mix Asphalts are needed.

6. Summary

This paper summarized further successful R&D effort in the laboratory and in the field of asphalt rubber, where actual three Road Tests were performed and monitored in Israel, using RAR Asphalt Rubber mixes under hot climatic conditions. The RAR HMA mixes (Dense and Superpave "S" graded) were designed and produced in conventional batch asphalt plants with the use of the regular SMA fiber-feeder for feeding the RAR directly to the mixer without any additional heating or setting. The road tests included a residential street and highly trafficked industrial road in the city of Tel Aviv, and an access road to a very busy aggregate quarry. The performance and results so far (after more than two years of service from the first road test) have clearly strengthen the advantages of RAR asphalt rubber mixes achieved in the R&D phase of the research. This should lead to actual paving jobs, and modified specifications for asphalt rubber in Israel and elsewhere.

The following are the main advantages of RAR as an asphalt rubber binder in hot asphalt rubber mixes (as mainly compared to the common Asphalt Rubber technology):

- Easy and fast production. No need for Asphalt Rubber or modifier blenders.
- No more re-heat cycles in the asphalt mixing plant or job site.
- The RAR product is a dry granulated material – easy to handle, store and transport.
- Can be fed to any asphalt mixing plant directly to the pugmill or the dryer drum. RAR was successfully fed by the conventional fibers feeder used for SMA mixes
- When substituting part of the bitumen and blended with the rest neat bitumen in the mixing plant, a unique asphalt rubber binder is formed to provide better resilience & recovery and higher viscosity and softening point.
- With increasing RAR content in the combined binder (RAR + neat bitumen), any PG Grade binder can be formed (both positive and negative PG grade indicators).
- With the correct RAR content, any type of hot AR mix can be produced (Dense Graded, SMA, Open Graded, Gap Graded, etc.).
- Can make new improved hot AR mixes (with even more crumb rubber) that are stronger more resilient, and exhibit better Recovery, Rutting and Fatigue resistance.
- RAR most efficiency can substitutes the tedious cellulose fibers in SMA mixes to prevent draindown without any additional cost.

- Can create Warm Asphalt Mixes with the incorporation of proper warm mix additives.
- Environmental benefits: RAR contains 80% of recycled waste materials, with high proportions of crumb rubber (from recycling of scrap tires) and AMBS (as a waste of the phosphate industry). In addition to less energy spent during the production of Asphalt Rubber.
- Cost Effectiveness as compared to both conventional HMA and to regular Asphalt Rubber mixes.
- Now, an improved Asphalt Rubber can be produced and implemented in every job, in any country.

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