REACTED AND ACTIVATED RUBBER FROM RECYCLED TIRES SUPERIOR ADVANCES IN ASPHALT RUBBER PERFORMANCE

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ABSTRACT

The asphalt rubber wet method technology of using crumb rubber from recycled tires as a modifier of asphalt (bitumen) binder has been successfully used in crack sealing, spray applications (chip seals) and hot mix asphalt for at least 50 years. The asphalt rubber wet method technology, which began in the late 1960's in Arizona and California, has been successfully used in a manner to benefit pavement performance and durability. The asphalt rubber wet process is a practical means of providing environmental, economic, sustainable, and safety of using crumb rubber from recycled tires using the wet method technology widely used in societal benefits. New imaginative and innovative engineering technology concepts have led to the development of a new asphalt rubber, crumb rubber semi wet method material. The new semi wet method employs reacted and activated rubber (RAR). The RAR semi-wet process has demonstrated a product capable of matching and surpassing the performance of traditional hot mix asphalt and the traditional asphalt rubber, crumb rubber method asphalt. Basically, RAR consists of pre-treated and pre-reacted crumb rubber that can be used directly in a hot mix plant just like a "filler" thus it is easy to handle and requires no special equipment for blending crumb rubber and asphalt and no additional heat source. The RAR dry filler when it meets hot asphalt amalgamates in such a way as to become like the traditional crumb rubber method asphalt rubber. The RAR is superior to the traditional asphalt rubber, crumb rubber method since it can be used at higher percentages. To ensure the quality and take advantage of the unique nature of RAR new specifications. These specifications encompass a broad range of quality measures to better enable wide use by road departments.

This paper introduces the concept and some experiences of using a RAR binder in asphalt thin gap mixtures applied with or without an RAR stress absorbing membrane interlayer (SAMI). The paper presents how the added flexible fatigue cracking resistance of these mixes leads to great environmental benefits. It introduces key concepts that can be the basis of specifications that can be used by road departments to ensure, not only that the crumb rubber is properly reacted and treated, but that the mixes have adequate bitumen and RAR to satisfy flexural/reflective fatigue cracking resistance.

Background – History

The idea of incorporating natural rubber (Latex) and vulcanized rubber into asphalt pavements has been investigated for over 100 years (1). Many researchers concluded that adding rubber to asphalt could enhance various properties of asphalt including but not limited to increase elasticity, decrease brittleness at low temperature, be less temperature susceptible, increase resistance to action of water and abrasion to traffic, reduce skidding, minimize maintenance, and be a beneficial recycling use of ground tire rubber. This keen interest in advocating for rubber in asphalt pavements stemmed to some degree in taking advantage of rubber's properties such as a Poisson ratio of 0.5 and rubber properties not temperature dependent like asphalt. It was not until 1970's when Charles McDonald developed the practical AR wet process asphalt rubber (AR) technique that AR could be routinely used in seal coating applications (2).

McDonald Wet Process Asphalt Rubber

Charles McDonald invented an asphalt rubber binder consisting of hot asphalt and at least 15 percent vulcanized ground tire rubber (crumb rubber). He invented this material primarily as a means of seal coating badly cracked pavement, thus reducing maintenance and extending the in-place pavement life until an overlay or reconstruction could be performed. He experimented with higher percentages of rubber up to 25 percent. He found, by albeit crude testing, that more rubber improved the fracture (cracking) resistance of the AR binder. However, mixing and applying a 25 percent rubber asphalt binder presented many practical problems, thus the use of 18 to 20 percent crumb rubber became the practical maximum.

From these early experiments and with the cooperation of the asphalt industry several patents were issued in the 1970's for asphalt rubber binder. The family of these patents is referred to as the McDonald wet process asphalt rubber. As more experience was obtained by use of wet process research was conducted to better characterize the properties of asphalt rubber binder. From this research it was determined that more rubber in asphalt rubber not only would improve the crack resistance, most likely due to the imparting of rubber properties in the binder which increased the amount of strain the asphalt rubber could sustain before cracking. Additionally, greater film thickness slows down the aging (oxidation) of the AR binder thus keeping it more pliable and less likely to crack.

During the late 1980's and into the early 1990's experiments and research was conducted to use AR binder in hot mix asphalt. This work led to development of the gap graded AR hot mix which consists of mixes with a higher VMA typically more than 19 percent. Following from this effort with gap graded AR an open graded mix was developed. The open graded mix typically has a VMA of 22 percent or more. Figure 1 shows as the VMA increases the amount of AR binder increases. The higher VMA is needed to accommodate the increase in binder required to allow enough space for the 15 percent of crumb rubber in AR binder (3).

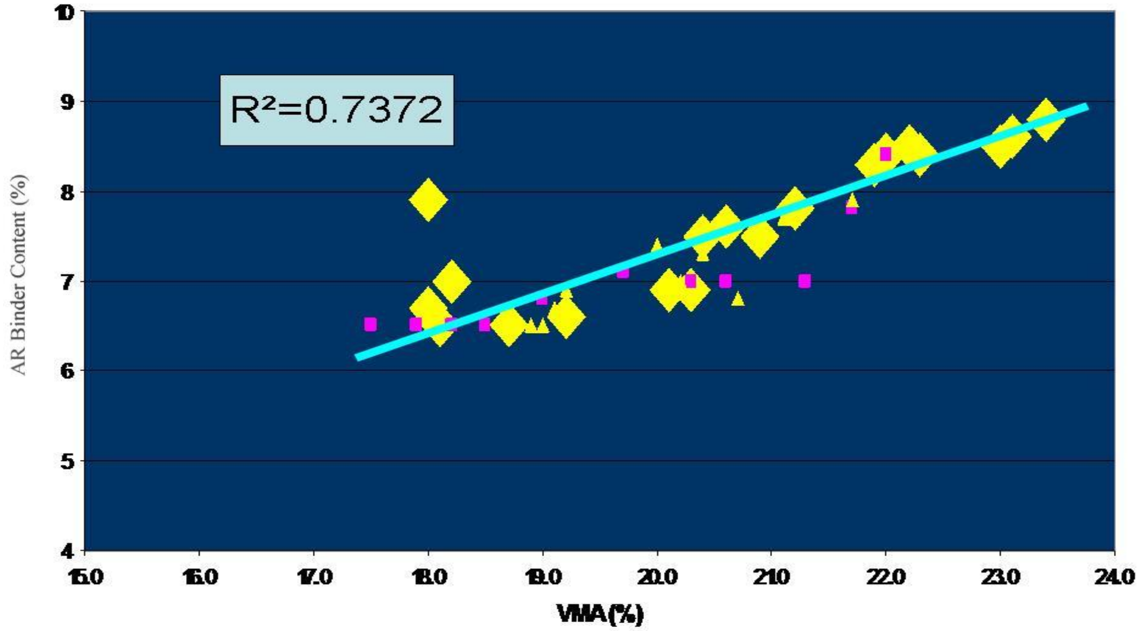

Figure 1 Asphalt Rubber Gap Graded Mixes VMA vs. Binder Content (3)

Asphalt Rubber Resilience

The origin of the significance of the 15 percent AR binder started with an Arizona Department of Transportation research report in 1977 (4). The researchers found that "asphalt rubber can undergo about five times the strain before rupture than can asphalt." Later research demonstrated that with a higher percentage of the crumb rubber AR binder becomes more viscous and has greater resilience (elasticity). The tests were conducted at that time at a practical maximum of about 21 percent crumb rubber. Figure 2 demonstrates an even higher percentages the AR binder would have even higher resilience (elasticity) (5).

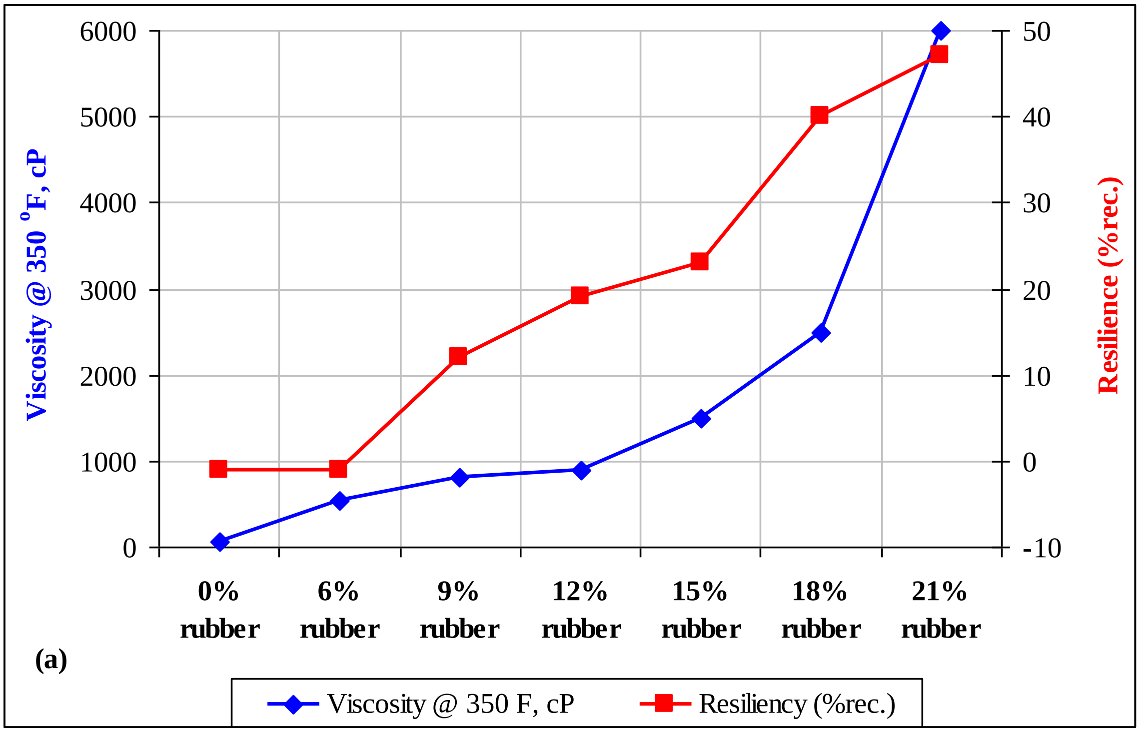

Figure 2 - Variations in AR physical properties, Viscosity and Resilience with increasing amounts of crumb rubber.

This clear trend of improved resilience with increased crumb rubber content has been recently reverified in 2023 as shown in Figures 3 for AR mixes with higher percentage crumb rubber content by weight of mix than previously possible. With reacted and activated rubber (RAR) 1.5 percent by weight of mix an AR binder with high resilience is achievable. Figure 4 shows the same trend for fatigue life from the four-point bending beam test which shows a substantial increase in fatigue life as percent rubber increases above 1.5 percent by weight of mix. The four-point bending beam test was developed as part of the Strategic Highway Research Program (SHRP) as a test to predict the fatigue cracking life of an asphalt hot mix. The combination of greater AR binder resilience (elasticity, can strain more before damage) from more crumb rubber in the binder and more AR binder in the hot mix now possible with RAR ensures greater fatigue life representing more traffic loadings before fatigue cracking occurs.

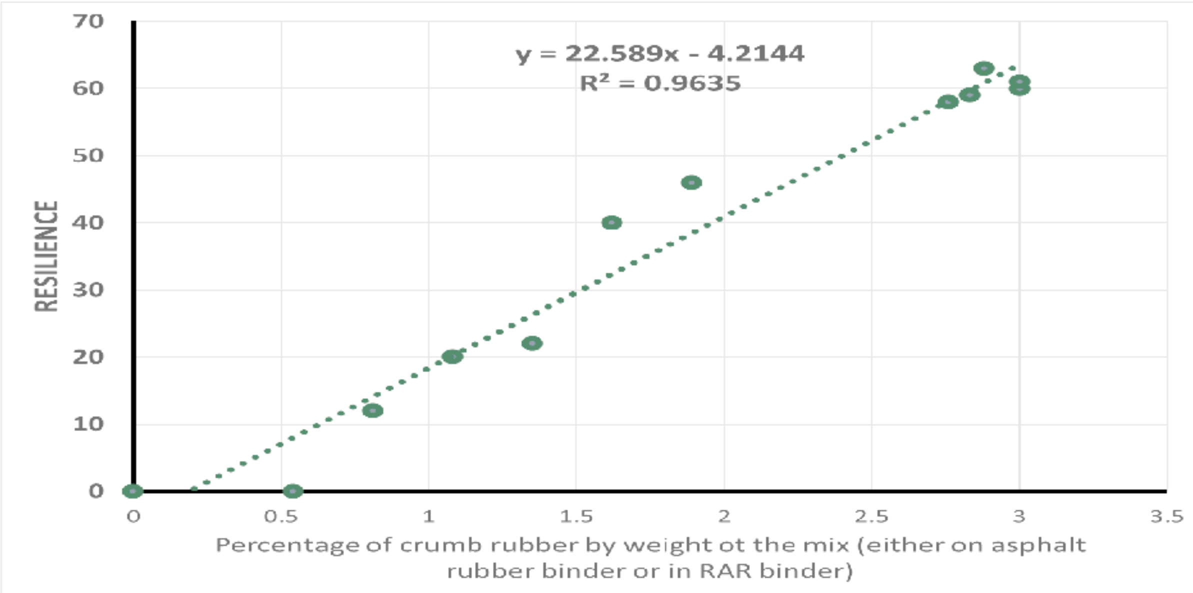

Figure 3 – Effect of percent of crumb rubber in the resilience of the binder.

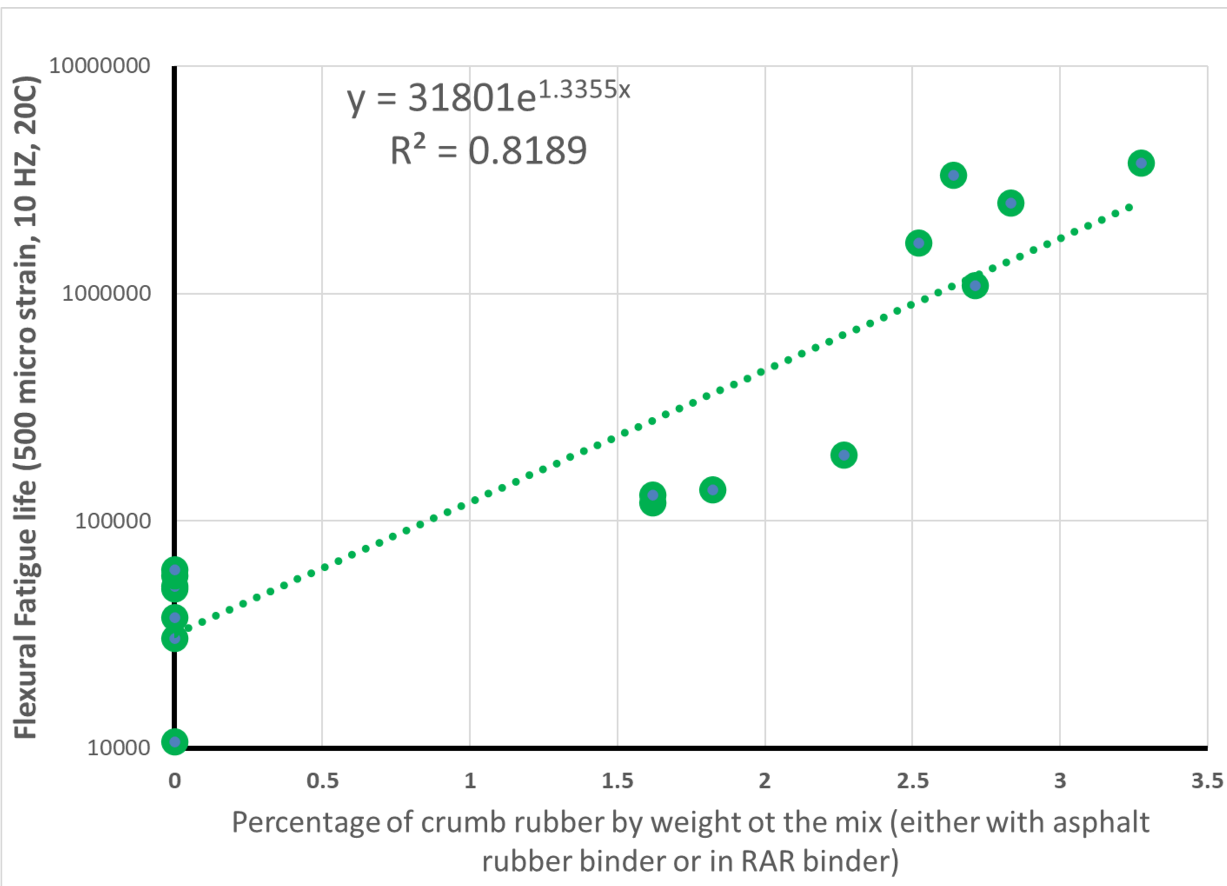

Figure 4 - Effect of percent of crumb rubber in the flexural fatigue of a mix.

Furthermore, in improved performance with the increase of asphalt rubber and RAR binder contents follows a trend that can be predicted by the fatigue SHELL formula (6).
Clearly the Shell equation demonstrates the reasonableness of the premise that as weight percent, i.e., volume percent, increases the fatigue life of the mix increases very dramatically as the four-point bending beam test results indicate.

Shell Equation:

$$\varepsilon_t = ((0{,}856 \times V_b + 1{,}08) \times E^{-0{,}36} \times N^{-0{,}2})$$

where:

$$V_b = \frac{P_b . G_t}{G_b}$$

ε_t – Tensile extension.
V_b – Non absorbed bitumen percentage by VOLUME of the mix.
E – Bituminous mixture deformability module (Pa).
N – Number of repetitions to failure, i.e. reach 50% moduli reduction.
P_b – Bitumen percentage by weight of the mix.
G_t – Bituminous mixture's specific gravity.
G_b – Bitumen specific gravity at 25ºC

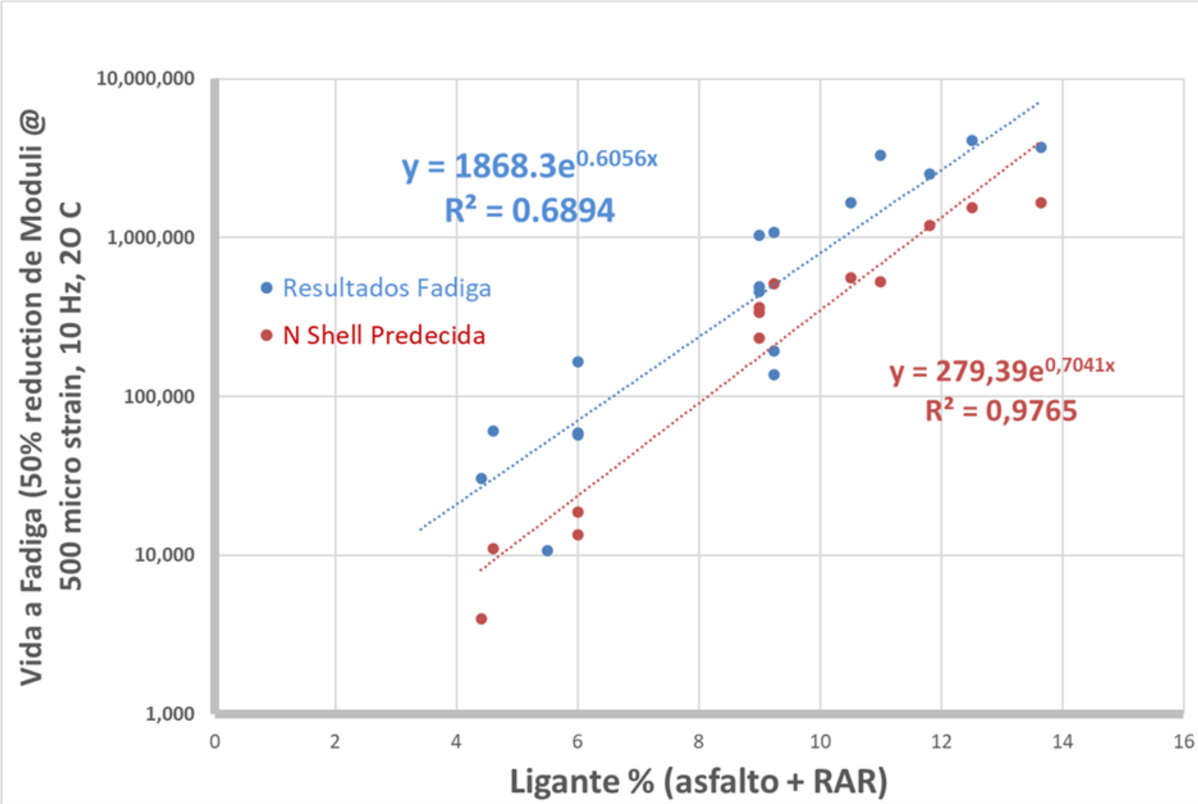

Figure 5 - Predicted by Shell equation and actual fatigue results in four-point bending testing function of binder %.

Asphalt Rubber Improved Fatigue Cracking Life

In the 1990s the US conducted a national Strategic Highway Research Program (SHRP) to improve asphalt tests and develop a mechanistic empirical pavement design program to improve pavement performance. From this research a four-point bending beam test was developed to predict fatigue cracking. With this test it was now possible to test various mixes at different asphalt binder and air void amounts to better select pavements that would resist fatigue cracking. The research was conducted on typical dense graded mixes with typical neat asphalt binders containing no polymer or rubber. From observation the beam damage during testing a 50 percent reduction in stiffness was selected as the end point or failure point of cycles to failure. Following this research many more tests have been done with AR gap graded and open graded mixes which demonstrate that AR mixes have longer fatigue life with greater amounts of rubber. Figure 3 shows as the percent crumb rubber increases the fatigue life increases the fatigue life from the four-point bending beam test number of cycles to failure increases. The advantage of more AR binder is very clear; however, it is even greater than Figure 5 shows. Figure 6 shows the fracture curve profile for a typical dense graded mix and a gap graded asphalt rubber mix. The asphalt rubber gap graded mix does not fail in the normal fracture mechanism but continues to absorb stress (strain) throughout the test. Similarly, the AR mixes tested by the four-point bending beam test do not fracture at the 50%

reduction in stiffness level thus the fatigue lives for the AR mixes on Figure 3 are considerably longer than shown. A more representative failure value for AR mixes is probably a 30% reduction of the stiffness. Arizona State University researched the mechanical properties of hot mix asphalt and asphalt rubber gap graded hot mix that that showed reduce cracking (7) by increasing the mixes fracture energy, Figure 7.

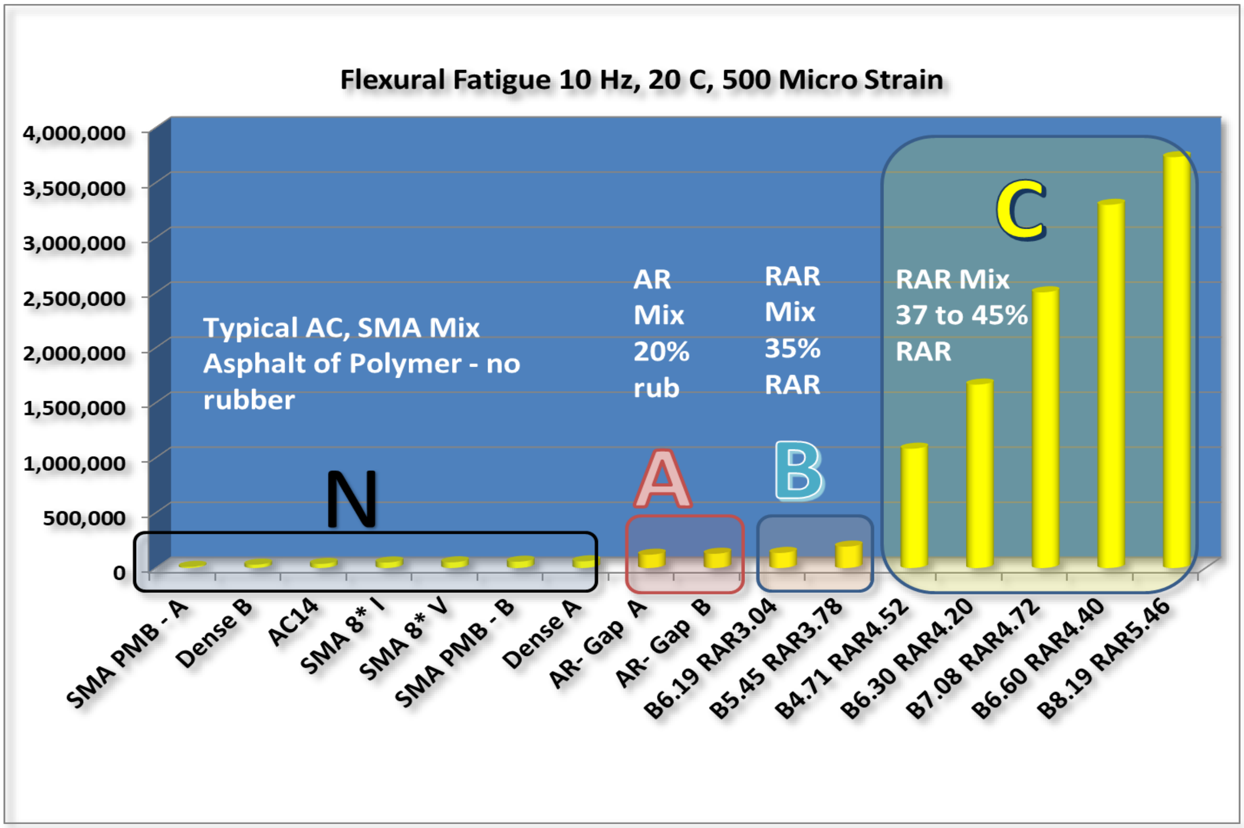

Figure 6 – Comparison of flexural fatigue life on four point bending at 20C, 10 Hz and 500 microstrain for several mixes, conventional, polymer modified, asphalt rubber and RAR modified mixes..

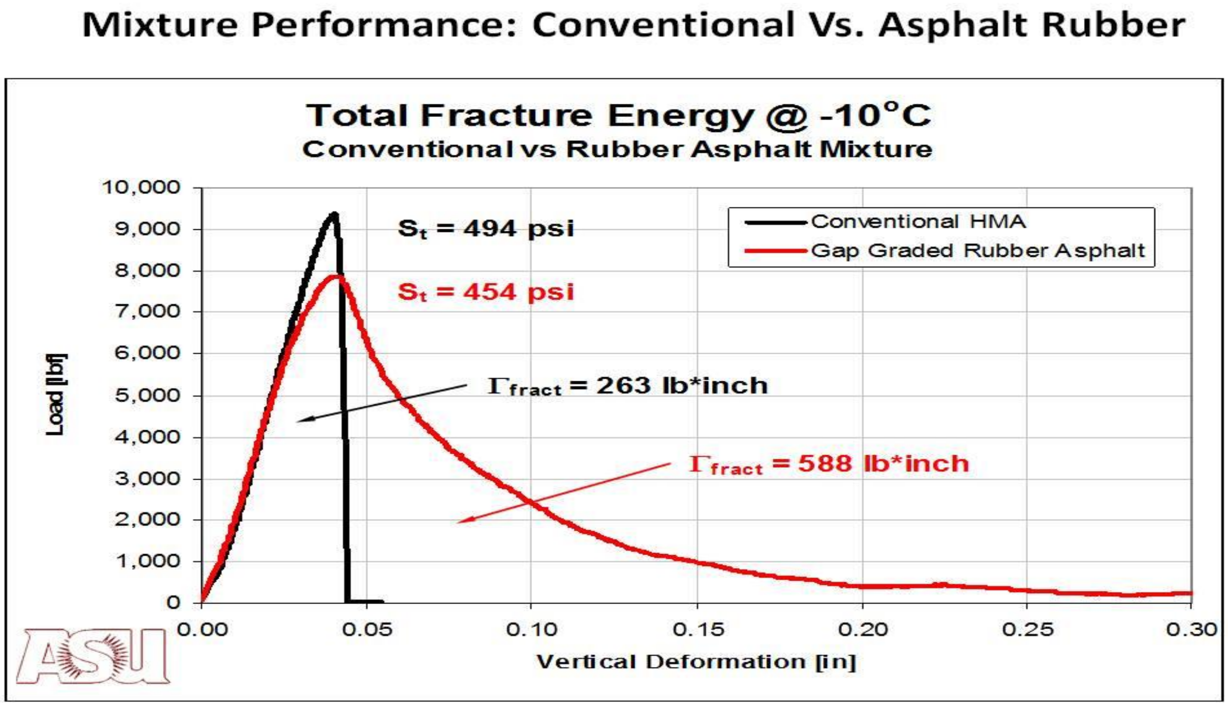

Figure 7 - Predicted greater fracture energy with asphalt rubber gap graded mix which reduces low temperature cracking (Zborowski, 2009).

The five times the strain finding in the 1977 research report was verified in a 2007 study (8) conducted in California and shown in Table 1. This study again shows that asphalt rubber with at least 15 percent of crumb rubber strain energy is at break 0f mixes is improved by a factor of five as shown in the 1977 report.

Table 1 - Results of Comparative Four-Point Bending Beam Test (TPC report for California)

Binder type	RATIO OF STRAIN ENERGY AT BREAK OF MIXES (OR BINDER)
Conventional	1
Polymer/Other Modified Binder	1.5
Asphalt Rubber 15% Crumb Rubber	5

The practical result of all these findings is that more AR binder with better resilience and more crumb rubber will be better able to resist fatigue cracking. This led to perfecting the RAR wet/dry, semi-wet process.

Wet/Dry, Semi-Wet Process RAR Asphalt Binder

It is now possible to make AR mixes with 24% or more of actual crumb rubber. On or about 2011 experiments were conducted that led to development of a wet/dry process or semi-wet process and development of a Reacted and Activated Rubber (RAR) shown in Figure 8. The process involves manufacturing a RAR powder that, when mixed with hot asphalt becomes an asphalt rubber binder and was patented in 2017. The mixing can be done in spray apply truck for seal coating or introduced into a batch or drum hot plant. The RAR is a powder so there is no need for any additional equipment or heat, thus saving on additional equipment costs and reducing energy costs and reducing CO_2 emissions. The RAR is a powder wherein higher percentages can be used, as Charles McDonald long ago envisioned.

Figure. 8 - Reacted and Activated Rubber Components and Product Powder

From the inspiration in 2011 to the present an amazing total of 4144 lane-km (lanes 1000 m long 3.5 m wide) have been constructed employing RAR in SMA, Gap Graded, Open graded and Thin Gap hot mixes. The RAR has been used in spray applications, seal coats and SAMI. It is beyond the scope of this paper to review in detail each project shown in Table 2 list of jobs constructed with RAR around the world. In 2019 a major resurfacing project was constructed in Mexico just outside of Mexico City. The project consisted of overlaying 80 kilometers of divided highway of a concrete pavement in poor condition with a 50 mm RAR-Thin Gap mix. This project was so successful that many other overlay projects have been recently constructed in Mexico. The successful use of the RAR binder is attributable to the improved properties of the binder and the hot mix. This success has led to the 2022 construction of a RARX manufacturing plant in Mexico, plants are also located in Spain and Portugal.

Table 2. List of jobs constructed with RAR around the world.

LUGAR DE LA OBRA	LOCALIZACION	PAIS	ANO
BULGARIA	Highways A-1 Lyubiments	BULGARIA	2013
CHILE	Ruta de la Fruta	CHILE	2019
Lefoll Contractor	Carreteras secundarias	FRANCIA	2014
ALEMANIA	BAVIERA	ALEMANIA	2018
ALEMANIA		ALEMANIA	2023
AUTOPISTA DE YAKARTA	YAKARTA	INDONESIA	2017
CARRETERAS DE CARBÓN		INDONESIA	2018
VARIAS CARRETERAS		INDONESIA	2018
CIRCUNVALACIÓN DE DUBLÍN	DUBLÍN	IRLANDA	2018
TEL AVIV	Camino de acceso a cantera	ISRAEL	2012
TEL AVIV	Calle Yeheskel	ISRAEL	2014
TEL AVIV	Calle Salame	ISRAEL	2014
Provincia de Trento	SS421	ITALIA	2013
Ciudad de Bussero	Via Primo Maggio	ITALIA	2013
Rho	Via Magenta	ITALIA	2013
Trento	SS 12 Freight terminal	ITALIA	2013
Venio	Viale Cavour Cemusco	ITALIA	2014
ITALIA	Carreteras secundarias	ITALIA	2017
ITALIA	Carreteras secundarias	ITALIA	2023
AUTOPISTA PIRÁMIDES	TULANCINGO	MÉXICO	2018-19
AVENIDA ACUEDUCTO	ZAPOPAN, JALISCO	MÉXICO	2020
CALLES DE RODAJE AEROPUERTO	GUADAJARA	MÉXICO	2020
AUTOPISTAS MICHOACAN TRAMO PATZCUARO	URUAPAN	MÉXICO	2020
PERIFÉRICO MORELIA	MORELIA	MÉXICO	2021
PISTA DE ATERRIZAJE AEROPUERTO TIJUANA	TIJUANA	MÉXICO	2021
AUTOPISTA MEXICO-TUXPAN	TRAMO NECAXA-TIHUATLAN	MÉXICO	2021-22
PUENTE COMANJILLA CARR. 45		MÉXICO	2023
PISTA ATERRIZAJE AEROPUERTO BJX	LEON	MÉXICO	2023
TRAMO PRUEBA CIRCUITO EXTERIOR MEXIQUENSE		MÉXICO	2023
REHABILITACION 200,000 M2 H. COLEGIO MILITAR		MÉXICO	2023
AUTOPISTA MERIDA-KANTUNIN SICT		MÉXICO	2023
TRAMO PRUEBA RCO LAGOS DE MORENO	AGUACALIENTES	MÉXICO	2023
BOMBARRAL	Plaza de peaje de autopista	PORTUGAL	2015
BRAGA	Rampas de acceso a autopista	PORTUGAL	2021
IC5 Vila Flor	Douro Litoral	PORTUGAL	2021
EN10	Setubal	PORTUGAL	2022
ALGARVE	Algar Barlavento	PORTUGAL	2023
ALGARVE	Algar Sotavento	PORTUGAL	2023
ALGARVE	EN 125	PORTUGAL	2023
SAN PETERSBURGO	Ringway South	RUSIA	2013
SAN PETERSBURGO	Puente	RUSIA	2018
Municipalidad de Al-Ain		EMIRATOS	2018
		REP CHECA	2022
Conception SACYR		BRAZIL	2023

LUGAR DE LA OBRA	LOCALIZACION	PAIS	ANO
CARRIL BICI TORREJÓN DE ARDOZ	TORREJÓN DE ARDOZ	ESPAÑA	2017
PLAN ASFALTO FUENLABRADA 2017	FUENLABRADA	ESPAÑA	2017
REFUERZO L-313 GUISSONA	LÉRIDA	ESPAÑA	2017
PLAN ASFALTO FUENLABRADA 2017	FUENLABRADA	ESPAÑA	2017
PLAN DE ASFALTO FUENLABRADA	FUENLABRADA	ESPAÑA	2018
A-42 PLAZA ELÍPTICA	MADRID	ESPAÑA	2018
SEGOVIA		ESPAÑA	2018
PRUEBAS	ORENSE	ESPAÑA	2018
PLAN ASFALTO DE COSLADA	COSLADA	ESPAÑA	2018
FUERTEVENTURA	FUERTEVENTURA	ESPAÑA	2019
ZAMORA		ESPAÑA	2019
PLAN ASFALTO DE COSLADA	COSLADA	ESPAÑA	2019
MALLORCA	MALLORCA	ESPAÑA	2019
GRANADA	GRANADA	ESPAÑA	2019
AEROPUERTO GRAN CANARIAS	GRAN CANARIAS	ESPAÑA	2019
AUTOVÍA A-4	VALDEPEÑAS	ESPAÑA	2019
OPERACIÓN ASFALTO MADRID	MADRID	ESPAÑA	2020
OPERACIÓN ASFALTO MADRID	MADRID	ESPAÑA	2020
AUTOVÍA A-68	ZARAGOZA	ESPAÑA	2020
OPERACIÓN ASFALTO MADRID	MADRID	ESPAÑA	2020
PUERTO DE HUELVA	HUELVA	ESPAÑA	2020
GRANADA	GRANADA	ESPAÑA	2020
LA GRANJA	SEGOVIA	ESPAÑA	2020
OPERACIÓN ASFALTO MADRID	MADRID	ESPAÑA	2020
AEROPUERTO DE FUERTEVENTURA	FUERTEVENTURA	ESPAÑA	2021
CV-35	VALENCIA	ESPAÑA	2021
PARKING ALEGRA		ESPAÑA	2021
LLANERA	OVIEDO	ESPAÑA	2021
PLAN DE ASFALTO DE MÁLAGA	MÁLAGA	ESPAÑA	2018-19
PLAN DE ASFALTO DE MÁLAGA	MÁLAGA	ESPAÑA	2018-20
ALICANTE	ALICANTE	ESPAÑA	2018-20
PLAN DE ASFALTO DE MÁLAGA	MÁLAGA	ESPAÑA	2019-20
OPERACIÓN ASFALTO MADRID	MADRID	ESPAÑA	2019-20
CONSERVACIÓN A-3	MADRID	ESPAÑA	2020-21
SEGOVIA		ESPAÑA	2020
SEGOVIA		ESPAÑA	2020
A-32 VILLACARRILLO-VILLANUEVA DEL ARZOBISPO	JAÉN (ANDALUCÍA)	ESPAÑA	2021
SUR DE SUECIA		SUECIA	2014
MICHIGAN	MICHIGAN	EEUU	2018
VIRGINIA-EEUU	VIRGINIA	EEUU	2019
14 obras		ESPAÑA	2022
15 obras ate Agosto		ESPAÑA	2023
		URUGUAI	2023
		CHILE	2023

AR Layer Thickness and Film Thickness Considerations

Charles McDonald's original asphalt rubber wet process material was used in a seal coat spray application of typically 2.4 l/m2. Later gap graded and open graded AR hot mixes were developed with 8 to 10 percent asphalt rubber binder. Comparing the film thickness of various mixes, routine dense graded mix with 5 percent asphalt has about a 9-micron film thickness, gap graded asphalt rubber can be as much as 18 micron and open graded 36 micron. The higher the film thickness the slower the aging. Gap graded and open graded mixes have been used as overlays over cracked pavements or as overlays on top of AR seal coat placed on a cracked pavement. In 1982 a research study was conducted to determine the relative merit of thin overlays with an asphalt rubber seal coat. The Arizona Department of Transportation had many miles of cracked and warped concrete pavements that were very rough riding and had low skid resistance. AR overlay using stress absorbing membrane interlayers were constructed over the concrete. The first layer placed over the concrete for leveling was an open graded mix, followed by an AR seal coat and then another open graded mix. At that time Open graded AR mixes did not exist, otherwise they would have been used. The research assessed the stress reducing capability of the three-layer SAMI system using finite element analysis. Results of the study (9) show that the three-layer system is equivalent to many inches of conventional overlay as shown in Figure 9. Years later AR gap graded, and open graded mixes were placed on thousands of miles of ADOT highways and the cracking consistent with the finite element findings as cracking is significantly reduced as shown in Figure 10. The conventional asphalt hot mix thickness was on the order of 115 mm whereas the gap graded is 40 mm to 50 mm and the open graded is 13 mm to 25 mm. The AR gap graded, and open graded mixes placed thinner than conventional mixes and performed better with less cracking (10).

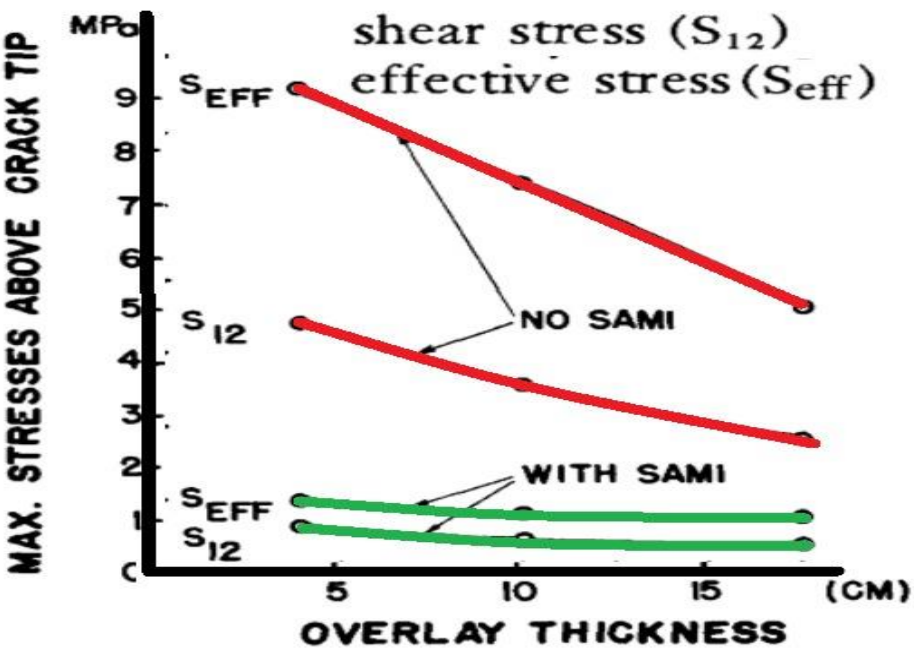

Figure 9 - Effect of a SAMI on the Shear and Effective Stresses in an overlay.

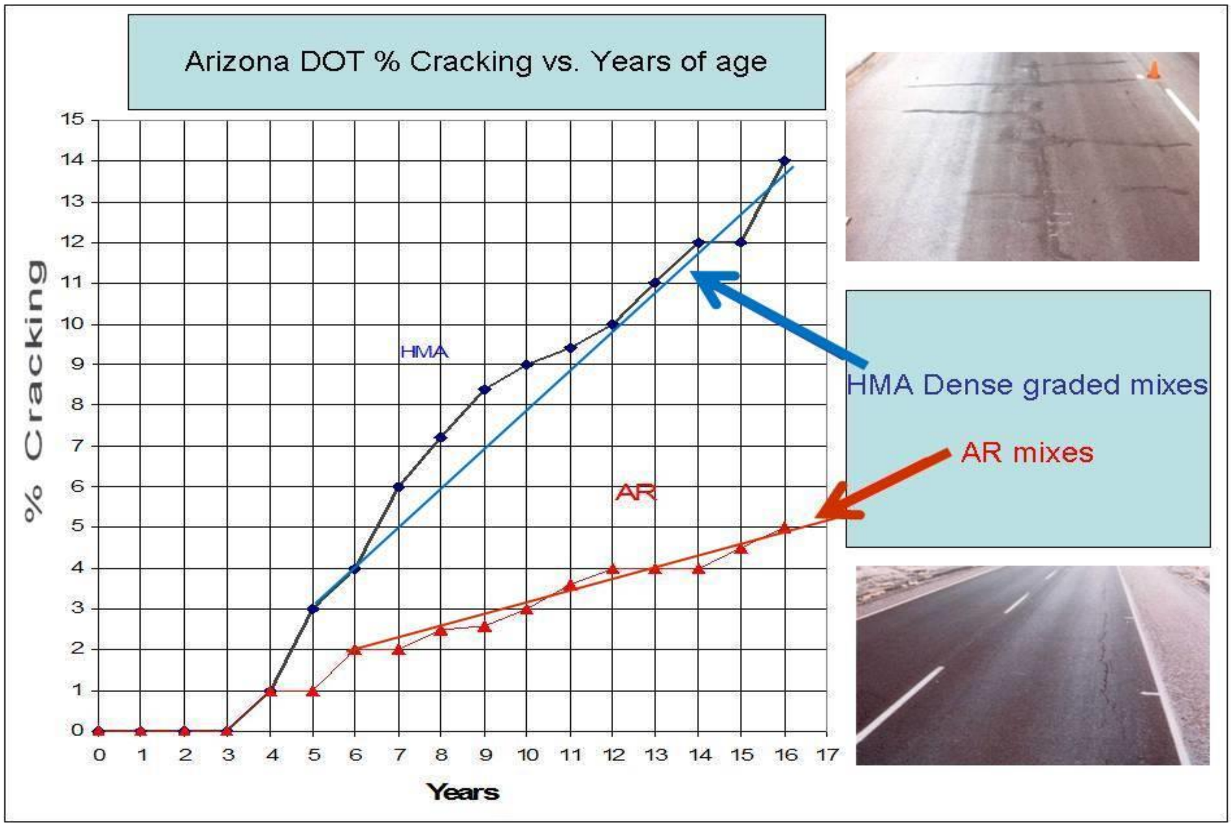

Figure 10 – Evolution of % cracking overtime – Asphalt rubber mixes as compared to dense grade mixes- data from ADOT.

RAR Projects with the highest crumb rubber contents

As shown above, since 2011 there have been many projects where RAR has been used. However, it is worth calling attention to a few jobs where the percentage of rubber in the mixes was probably the highest ever used in any mix. In these projects the attempt was to push the envelope to where the binder (i.e., bitumen and RAR) had a percentage of rubber vs bitumen that was very close to changing phases. Any more rubber percentage and the binder would not be a viscous liquid anymore.

At this high RAR content the binder has very high resilience and very high percentage recovery. Obviously to incorporate such high percentages of rubber as shown in Table 3 the aggregate gradations had to be adjusted and basically most fines were removed to create space for the high values of crumb rubber as shown in Figure 11. It is worth noting that having 5% by weight of RAR in the mix corresponds to about 12 % by volume. Furthermore, given the crumb rubber shape the surface is very high compared to that of regularly used aggregates. As such in these cases the surface area increases about 10-fold which requires higher binder contents to coat all particles of crumb rubber and of aggregate.

It is also clear that with the increased binder content there is increased film thickness around each particle which leads to increased durability as shown in a paper by Krishna, et. al. (11). All mixes where designed to about 4% air void content except A32-SPAIN mix which was design to achieve 18% air void thus reducing binder content and decreasing film thickness.

The projects selected were the pavements that had good structural capacity but were cracked. In this case a flexible mix was needed with great resistance to aging, great texture, and good skid resistance but also great reflective cracking capacity. In some projects where cracking was also too extensive and as such an RAR SAMI was also used.

Table 3 – General mix properties of successful overlays applied with high percentages of RAR.

	A4 - Madrid SPAIN + SAMI	IC5 - (SMA10S) PORTUGAL	Freeway PORTUGAL	EN10 - SETUBAL PORTUGAL	Mata do Duque - PORTUGAL	Michigan USA	A32 - SPAIN
Bitumen (% by weight of mixture)	7.2	7.5	7.08	6.9	7.5	7.2	4.64
RAR (% by weight of mixture)	4.8	5	4.72	4.6	5	4.8	1.36
Crumb rubber by weight of the	2.88	3	2.832	2.76	3	2.88	0.816
Film Thickness (micron)	**14.8**	**17.6**	**17.6**	**16.5**	**13.3**	**16.8**	**9.2**
VMA	23.5	27.5	29.8	26.7	27	26.6	27.5
Viscosity at 177 C (Poises)	10200	12200	8900	8600	9600	12800	-
Ring and Ball C	82	82	81	81	85	83	-
Resilience (%)		60	59	58	61	63	-
Fatigue life 10 Hz 20 C cicles to failure at (500µ)	3,700,000	4,076,667	2,200,000	1,200,000		3,300,000	-

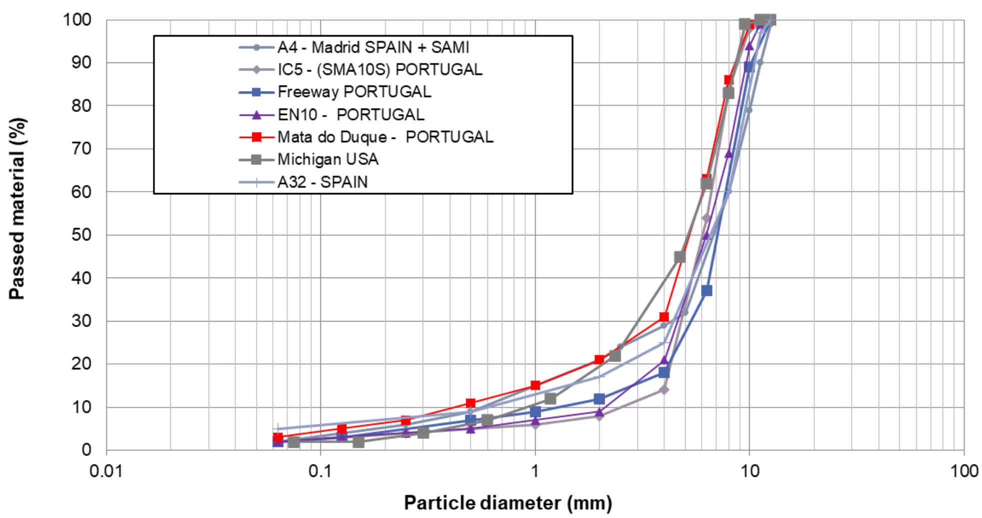

Figure 11 – Aggregate gradation of successfully applied mixes with high percentages of RAR.

The projects were and RAR-SAMI was used were A4-Madird SPAIN and Michigan USA. The RAR SAMI contained about 2.4 l/m2 with about 25to 30% RAR and about 14 kg/m2 of single size aggregate (between 19 and 16 mm).

All those projects after several years in the field are performing as expected demonstrating that high rubber content mixes really can have great environmental benefits because they are applied with very thin layers. In the cases above the thicknesses of the mixes varied between 2 to 4 cm thick.

The concept of reducing thickness when asphalt rubber or RAR mixes are used and more so if asphalt rubber SAMI-R are introduced to prevent reflective cracking is not new. They are part of Caltrans Pavement Design Guide (12) that strangely have not been widely implemented worldwide given how well these concepts and solutions have been performing. In Table 4 and Table 5 if is clear how effective asphalt rubber mixes Asphalt Rubber Hot Gix Gap Graded - ARHM-GG perform as compared to traditional mixes Hot Mix Asphalt HMA (DGCA – Dense Graded Asphalt Concrete) reaching 50% thickness reduction. It is also clear that with the introduction of a SAMI-R that reduction can reach 30% in some cases.

Table 4. *California Structural Equivalencies (mm)*

DGAC	ARHM-GG[1]	ARHM-GG/ SAMI
45	30[2]	-
60	30	-
75	45	30
90	45	30
105	60	45
120	60	45
135	45[3]	60
150	45[4]	60
165	60[3]	45[3]
180	60[4]	45[4]

Notes:
1. The maximum allowable non-experimental equivalency for ARHM-GG is 2:1.
2. The minimum allowable ARHM-GG lift thickness is 30 mm.
3. Place 45 mm of new DGAC first.
4. Place 60 mm of new DGAC first.

Table 5. *California Reflective Crack Retardation Equivalencies (mm)*

DGAC	ARHM-GG	ARHM-GG/SAMI
45	30[1]	-
60	30	-
75	45	-
90	45	-
105[2]	45[3]	30[4]

Notes:
1. The minimum allowable ARHM-GG lift thickness is 30 mm.
2. A DGAC thickness of 106 mm is the maximum thickness recommended by Caltrans for reflection cracking.
3. Use 45 mm if the crack width is less than 3 mm and 60 mm if the crack width is equal to or greater than 3 mm.
4. Use if the crack width is equal to or greater than 3 mm. If less than 3 mm, use another strategy.

The performance of all the projects in TABLE 2 confirms the validity of the concepts that underlines the creation of the guidelines in TABLE 4 and 5 - California Structural Equivalencies (mm)

Also, it has also been clearly corroborated by ALF - FHWA study (13) completed in 2012 that an asphalt rubber gap graded mix test section performed much better than all the other test sections as shown in Figure 12. Several sections were tested including a control section 10 cm thick constructed with the SHRP binder that was recommended after a 5-year SHRP research project for identification and selection of binder function of location, loading and environment against a 5 cm thick asphalt rubber over a 5 cm thick conventional mix (just like the one in the control section). The section with asphalt rubber (LANE 1) did not exhibit any cracking, see Figure 12, even after 350000 loading cycles while the control section started to crack and 20000 cycles.

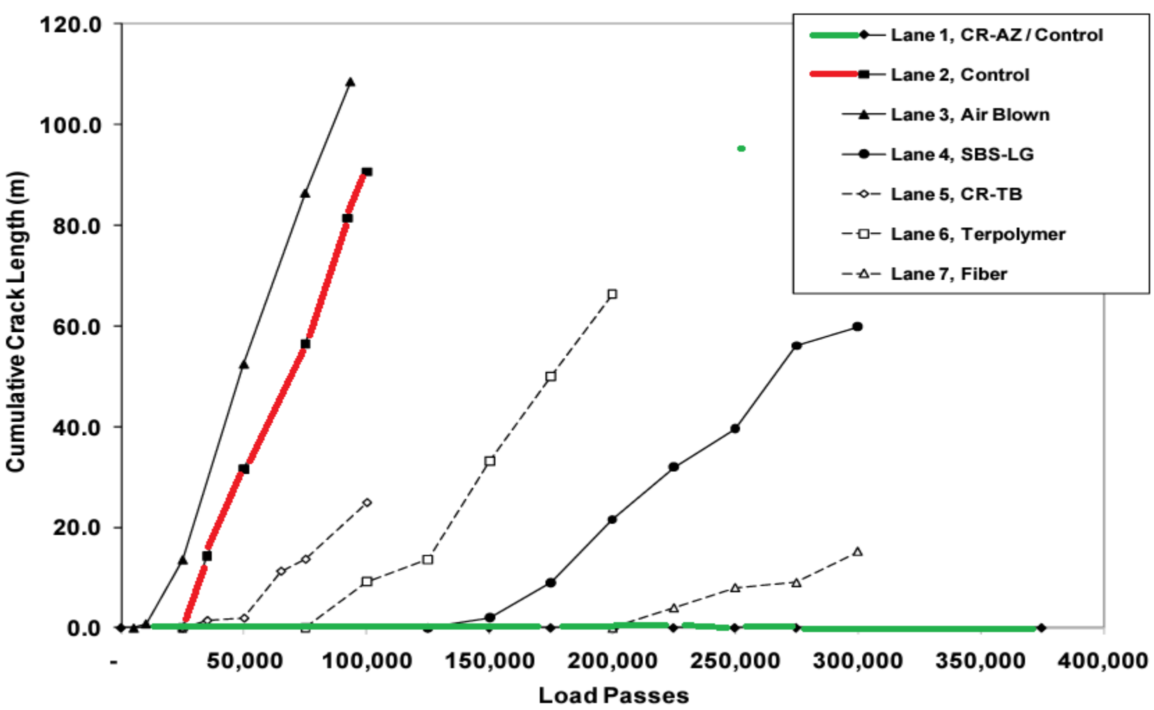

Figure 12 - Cumulative crack length versus ALF passes in 4-inch (100-mm) 66 °F (19 °C) fatigue loaded sections.

This overwhelming amount of data demonstrates the extent of the benefits derived by proper incorporation of crumb rubber in paving mixes suggest that it is a prime candidate to be extensively used in future sustainable asphalt paving strategies.

Sustainable Environment

As we need to create a more sustainable environment the importance of widely adopting mixes that properly incorporate asphalt rubber and RAR mixes become more relevant. With the increase in fatigue life (crack resistance) without compromising rutting or moisture damage these mixes can lead to the construction of thinner pavement and overlays directly leading to minimization of resources, namely of mining, transportation, and heating of aggregates.

A study was conducted to compare the energy savings by using asphalt rubber and RAR like mixes to other common uses of scrap tires, i.e., alternate daily cover and tire derived fuel (14). As shown in Figure 13 the use of asphalt rubber provided substantial energy savings as well CO_2 savings. This is primarily due to asphalt rubber and RAR mixes being placed in relatively thin layers which reduce the amount of aggregate that needs mining, transport of the aggregate and the amount of hot mix that needs to be heated. A similar finding was reported in an ASU report presented at AR2009. Figure 14 shows the nature of the CO_2 savings as reported by ASU (15).

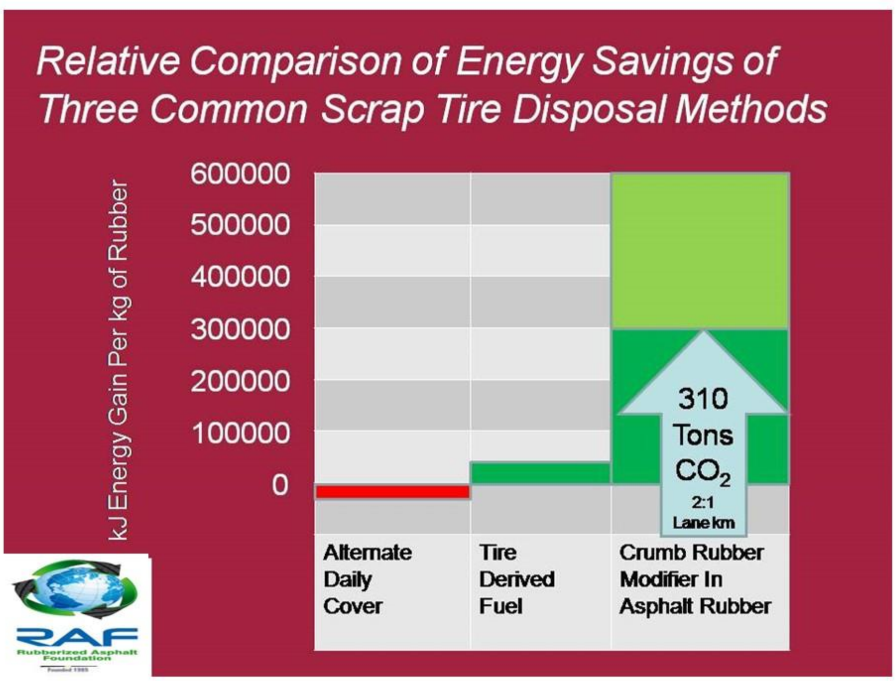

Figure 13- *Energy and CO_2 savings with asphalt-rubber*

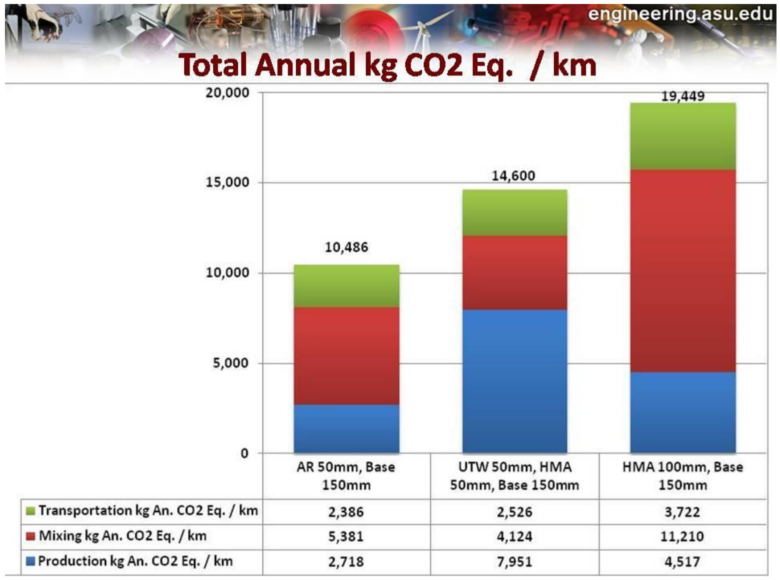

Figure 14 - *Total Annual kg CO_2 eq. / km for moderate traffic volume pavement designs*

The asphalt rubber and RAR mixes are more durable and have improved aging capability with less cracking which extends the service life of the pavement. The ASU study (15) demonstrated in Figure 15 the importance of increased service life to reducing CO_2. This Figure demonstrates that as the Asphalt Rubber and RAR service life increases the total annual CO_2 eq./km is significantly reduced. For pavements that last five years over a 25-year cycle will produce 500,000 Kg of CO_2 compared to pavements that last 25 years would produce 125,000 Kg of CO_2 a very substantial reduction. Such a reduction of CO_2 is very beneficial to the environment and a sustainable circular economy which is further expanded upon in a study which concluded that rubber-modified bitumen solutions provide an immediate benefit in terms of energy savings due to the reduction of raw materials and related processes required during the construction phase, as well as the advantage of longer pavement life (16).

Figure 15 – Change in Total Kg Annual CO_2 eq./km as a Function of Asphalt Rubber Pavement Service Life in Years.

The environmental benefits are further demonstrated in a paper presented at the RAR2022 Conference in Malaga, Spain (17). This paper, like the other two papers, concluded that after 20 years of operational life of an asphalt rubber/RAR pavement the environmental footprint and the carbon footprint are half that of a conventional asphalt mix.

Conclusions

The data presented in this paper supports the well demonstrated concept that the incorporation of properly designed binders and mixes with crumb rubber from recycled tires yields significant performance benefits in pavements.

Specifications exist in California for the usage of asphalt rubber considering reduction in thickness of some pavement layers and in conjunction with the usage of SAMI seals.

Newly formulated mixes that incorporate reacted and activate rubber (RAR) have demonstrated benefits that match and exceed those of asphalt rubber mixes simply because it is now possible to incorporate higher crumb rubber contents in the binder just like McDonald attempted to do when using regular asphalt rubber.

The formulation of several RAR mixes is presented with much higher binder contents than regular mixes, reaching 12.5%. Modeling, laboratory testing and field performance support the concept that the introduction of crumb rubber in mixes and SAMIs yield significantly better performance and that the performance increases with crumb rubber content. In part that increase in performance is due to the increase of film thickness around the aggregate.

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