Quantifying the Mechanistic and Economic Impacts of Using Asphalt Rubber Mixtures

Mena Souliman[1(✉)], Ragaa Abd El-Hakim[2], Mark Davis[3], and Lubinda Walubita[4]

[1] Department of Civil Engineering, The University of Texas at Tyler, 3900 University Blvd, RBS 1008, Tyler, TX 75701, USA
msouliman@uttyler.edu

[2] Public Works Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt
ragaa.abdelhakim@f-eng.tanta.edu.eg

[3] Department of Civil Engineering, The University of Texas at Tyler, 3900 University Blvd, Tyler, TX 75701, USA

[4] TTI, The Texas A&M University System, 3135 TAMU, College Station TX 77843-3135, USA
L-Walubita@tti.tamu.edu

Abstract. As far as hot mix asphalt pavement goes, tension at the bottom layer of the HMA layer creates the most issues for pavement engineers. Adding rubber to asphalt mix has the ability to extend the life of a pavement and provide an end use to old tires that would otherwise end up in a landfill. It is already known that the initial construction cost of an asphalt rubber mix will be higher than that of a conventional mix, but the purpose of this paper is to see if the reduced layer thickness and improved fatigue life will offset the initial cost. After completing a mechanistic analysis using the FHWA software package named 3D Move, the pavement thickness required to last for 50,000,000 cycles (estimated endurance limit) is much less for the asphalt rubber mixes as opposed to the reference hot mix asphalt. The cost to construct one lane mile of the reference mix pavement designed for 70 mph traffic was $171,530.88 while the asphalt rubber mix at 70 mph came out to be $157,059.70. This is a $14,471.18 difference. Additionally, the cost to construct one lane mile of the reference mix pavement designed for 10 mph traffic was $231,932.76, while the asphalt rubber mix at 10 mph came out to be $200,162.55. This is a $31,770.21 price difference. Overall, analysis showed that AR modified asphalt mixtures exhibited significantly lower cost of pavement per 1000 cycles of fatigue life per mile compared to conventional HMA mixture.

1 Literature Review

To understand why there is an essential need for a more durable and tension resisting pavement material, it is important to understand what is already known about pavement distresses. Important parameters like pavement structure, load speed, load configuration, and bituminous material temperature need to be considered when selecting an appropriate pavement design for a certain geographical region. The bottom of the HMA

L. Struble and G. Tebaldi (eds.), *Materials for Sustainable Infrastructure*,
Sustainable Civil Infrastructures, DOI 10.1007/978-3-319-61633-9_2

layer and at the interface is referred to as the prime location where fatigue cracking will occur, and load magnitude and configuration is one of the main factors that can cause fatigue cracking. Ambassa et al. (2013) supports the Equivalency Factor as an important parameter to be taken into account when predicting pavement performance.

Moreno and Rubio (2012) specifically look at the grading curve of aggregates used in mix design along with the nature of the aggregate. Properties like absorption, specific gravity, bulk specific gravity, and saturated surface dry specific gravity can all be used to characterize aggregates. LTPP (Long Term Pavement Performance) provides soil classification data for base materials and subgrade of pavement structures in the United States and Canada, making it possible to look at similar parameters in studies, meaning that actual laboratory work and field samples does not necessarily need to be taken. Moreno and Rubio (2012) specifically site that the main cause of fatigue failure is from traffic loading and thermal related influences.

Adding rubber to asphalt has the ability to extend the life of a pavement and provide an end use to old tires that would otherwise end up in a landfill. As far as hot mix asphalt pavement goes, tension at the bottom layer of the HMA layer creates the most issues for pavement engineers. Although pavement performs poorly in tension, adding rubber to the asphalt mix has been proven to help in this area. Quoting Souliman and Eifert (2015), “results from the beam fatigue tests indicated that the AR gap graded mixtures would have much longer fatigue life compared with the reference (conventional) mixtures”. Souliman and Eifert (2015) proved that when evaluating asphalt rubber and conventional hot mix asphalt mixtures based on their performance and economic feasibility, the cost of using asphalt rubber mixtures was lower than hot mix asphalt for the entire life of the pavement. Only layers of 4 in and 8 in were considered in that study, but the groundwork was laid to do more in depth future studies. In that paper, it was also noted that as the vehicle speed decreases, the cost per 1000 miles increased.

When considering the performance of pavement, it is very important to look at what is called the endurance limit. “If the pavement thickness is controlled so that the strain at the bottom of the asphalt layer is kept below the endurance limit, the pavement would endure indefinite load repetitions and would not experience bottom-up fatigue cracking” Souliman et al. (2015). Additionally, Souliman et al. (2013) states that “A hyperbolic function between stress ratio and number of load cycles was developed. The asymptote of this curve parallel to the load cycle axis indicates that there is a stress level below which the number of cycles to failure does not proportionally increase with decreasing stress, thus the material tends to have unlimited fatigue live”. This is an important idea when considering pavement life, and provides much of the theory behind the study presented in this paper.

The basic principal of the current study is that if the strains are below the endurance limit at the bottom of the asphaltic layer, the pavement has the ability to possibly heal itself between cycles of loading and unloading according to Souliman et al. (2015). If a pavement possessed the ability to heal itself, it would stand to reason that it would last longer. When comparing conventional hot mix asphalt to rubberized asphalt, there is a potential that the thickness of the HMA layer will not need to be as high with the asphalt rubber mixes. It is already known that the initial construction cost of an asphalt rubber mix will be higher than that of a conventional mix, but the purpose of this paper in part is to see if the reduced layer thickness and improved fatigue life will offset the initial cost via a comprehensive mechanistic and cost analyses.

2 Background

In 2008, the cooperation between Arizona State University (ASU) and the Swedish Road Administration (SRA) started by testing conventional and Asphalt rubber-gap-graded mixtures placed on Malmo E6 External Ring Road in Sweden. In 2009, the cooperation between SRA and ASU continued to test three types of gap-graded mixtures: conventional, Asphalt Rubber-modified mixtures, as well as polymer modified asphalt mixtures placed on highway E18 between the interchanges JärvaKrog and Bergshamra in the Stockholm area of Sweden.

Rice specific gravities and beam specimens were prepared according to the Strategic Highway Research Program (SHRP) and the American Association of State Highway and Transportation Officials (AASHTO): SHRP M-009 and AASHTO T321-03 (equivalent European test standards are: EN12697-24 A to D). Air voids, thickness and bulk specific gravities were measured for each test specimen and the samples were stored in plastic bags in preparation for the testing program. The designated road section within the construction project had three asphalt mixtures: a Reference gap-graded mixture (designation: ABS 16 70/100) used as a control, a Rubber-modified mixture (designation: GAP 16) that contained approximately 20% ground tire rubber (crumb rubber) and another polymer modified asphalt mixtures which is out of the scope of this paper. Test sections were located in fast lanes on highway E18 between the Järva-Krog & Bergshamra interchanges. The Swedish Road Administration provided information stating that the field compaction/ air voids for the three mixtures was around 3.0% to reduce any potential for moisture damage. The original mix designs were done using the Marshall Mix design method.

Previous publications showed that asphalt rubber mixture had a superior fatigue resistance performance over the conventional HMA mixture as shown in Fig. 1 (Souliman and Kaloush 2010). In addition, asphalt rubber mixtures have been widely accepted by the pavement community as an alternative to conventional asphalt mixtures to reduce bottom-up fatigue cracking due to its flexibility especially at low temperatures (Mobasher et al. 1997; Kaloush et al. 2010; Zborowski and Kaloush 2011; Rodezno and Kaloush 2011). The fatigue-resistant nature of asphalt rubber allows the designer to use a thinner layer to reach the endurance limit as compared to conventional asphalt mixtures as shown from other studies (Xiao et al. 2009, 2011). This hypothesis was the motive for this study. The remaining unanswered question is: do AR mixtures represent a cost effective solution to resist fatigue cracking compared to conventional HMA mixtures?

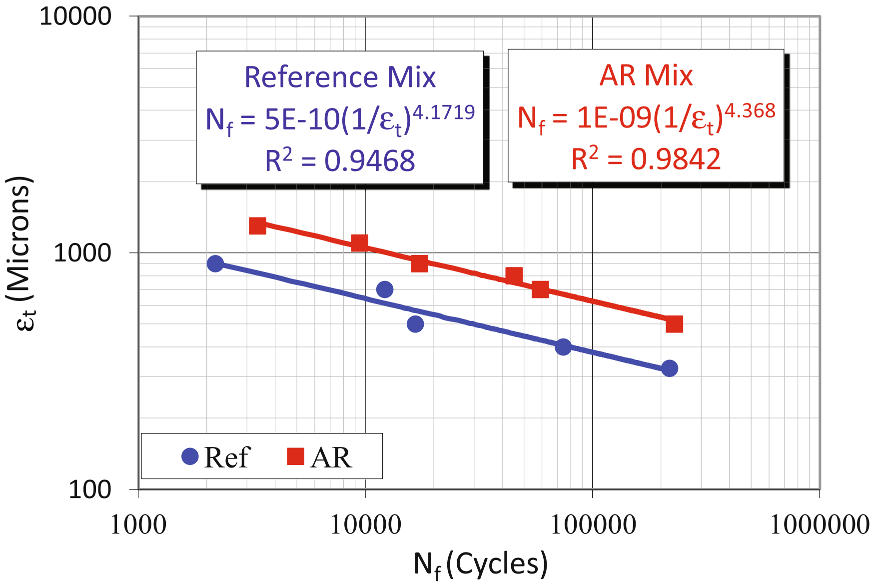

Fig. 1. Fatigue life comparison between reference conventional mixture and AR mixture at 21 °C using N_f at 50% of the initial stiffness (Souliman and Kaloush 2010)

3 Research Methodology

In this paper, the reference conventional mixture and the AR mixtures are compared in order to quantify the mechanistic and economic impacts of using asphalt rubber mixtures. Table 1 shows the reported average aggregate gradations for each mixture And the in-situ mixture properties of the Stockholm pavement test sections, which includes % binder content by mass of the mix, Marshall Percent void content by volume of the mix, and maximum theoretical specific gravity of the mixes estimated at ASU laboratories. The base bitumen used was Pen 70/100 and rubber was called GAP 16.

Table 1. Average aggregate gradations and mixture characteristics, Stockholm Highway

	Sieve size (mm)	Reference Conventional	AR
Gradation (% Passing by mass of each sieve)	22.4	100	100
	16	98	98
	11.2	65	68
	8	38	44
	4	23	24
	2	21	22
	0.063	10.5	7.5
Binder Content (%)		5.9	8.7
Air Voids (%)		2.6	2.4
G_{mm}		2.4642	2.3588

Using 3D Move, a mechanistic-empirical analysis was performed on the asphalt rubber and reference hot mix asphalt to evaluate the performance of each. Each iteration/run of the study involved changing dynamic modulus (depending on which mix was being evaluated), phase angle (only when the dynamic modulus changed), superpave binder grade (only changed from asphalt rubber to reference mix), speed, layer thickness, and finally the response points for each run. A summary of the process is displayed in the figure below.

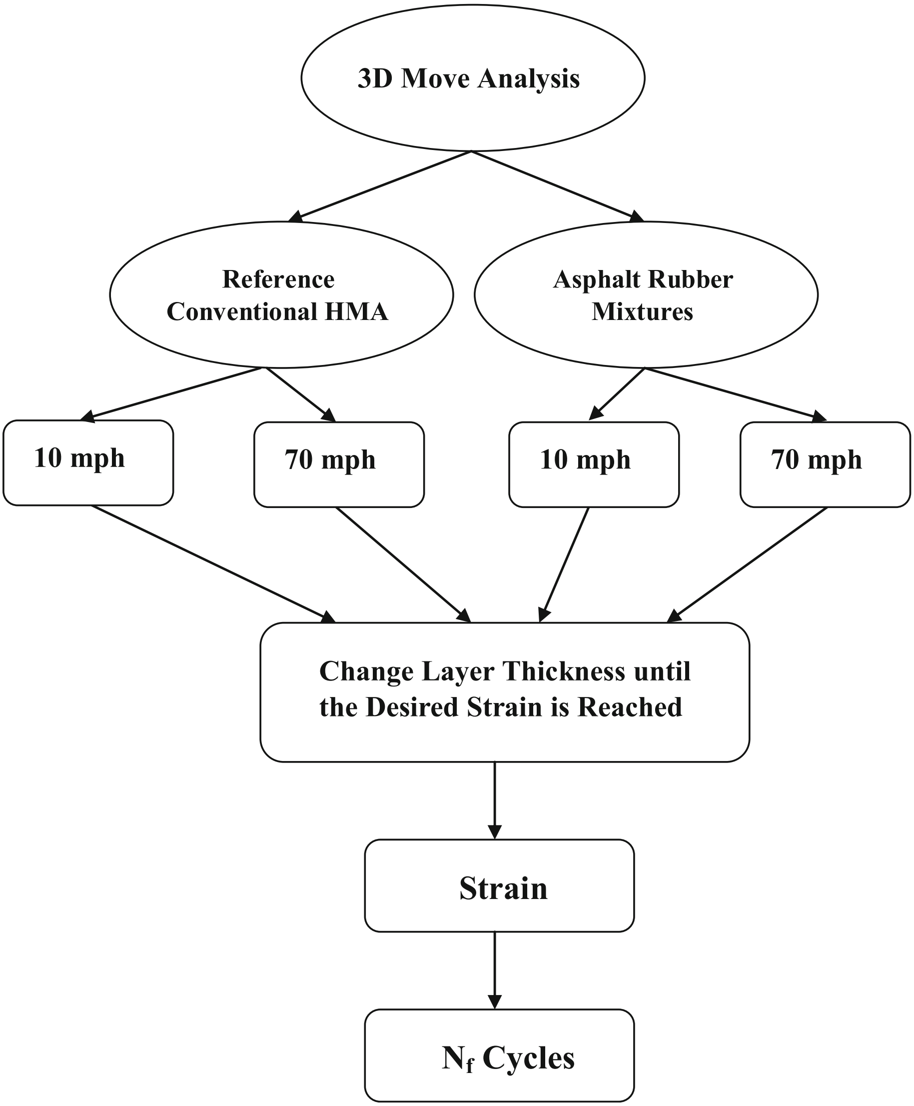

Fig. 2. Analysis flowchart

Figure 2 depicts the exact steps that were followed in the study for the 3D move analysis. The step where the pavement layer is changed was performed multiple times (10 times for some settings) until the desired strain in the pavement layer was achieved. In order to calculate the required strain for each asphalt mix, fatigue life prediction Eq. (1) was used.

$$N_f = k_1 \left(\frac{1}{e_t}\right)^{k_2} \quad (1)$$

where

N_f: The fatigue life, or number of load cycles to failure
e_t: Tensile strain
k_1 and k_2: Regression Coefficients

The k_1 and k_2 values were known from (Souliman and Kaloush 2010). For the asphalt rubber mix, $k_1 = 1 \times 10^{-9}$ and $k_2 = 4.37$. For the reference mix, $k_1 = 5 \times 10^{-10}$ and $k_2 = 4.17$. Since it was known that the desired fatigue life of the pavement was 50,000,000, the fatigue life of an asphalt concrete layer equation could be solved to find strain. The strain that was being looked for in the reference mix was 84 μ, while the strain in the asphalt rubber mix was 151 μ. When the appropriate pavement thicknesses have been selected based on the calculated strains, a cost analysis can be performed.

4 Mechanistic Analysis

3D move Mechanistic analysis was performed for the two investigated mixtures using different pavement thicknesses based on two speeds, 70 mph and 10 mph. The following figures represent the findings of the 3D move mechanistic analysis in the form of a relationship between pavement thickness, in. and number of load cycles to failure, N_f. The findings will be presented in the order of Reference hot mix asphalt at 70 mph, Reference hot mix asphalt at 10 mph, Asphalt rubber mix at 70 mph, and finally Asphalt rubber mix at 10 mph.

Above, the results for the Reference Mix at 70 mph are depicted in Fig. 3. Also on the graph, a horizontal line intersecting the N_f-Thick line has been plotted, and represents the exact pavement thickness at a life of 50,000,000 cycles. It can be noted that 5.4 in. is required to reach the endurance limit.

For the asphalt reference mix at 10 mph, the same type of analysis was performed. The main objective was to obtain a pavement thickness at 50,000,000 cycles. As demonstrated in Fig. 4, the pavement thickness required to last for that number of cycles was 7.3 in. This is about 1.9 in. in thickness difference, which is to be expected with lower speeds due to the increased strain at the bottom of the HMA layer (Fig. 5).

For the asphalt rubber mix at 70 mph, the pavement thickness would need to be 3.85 in. to last for 50,000,000 Load cycles. It's important to note again that the

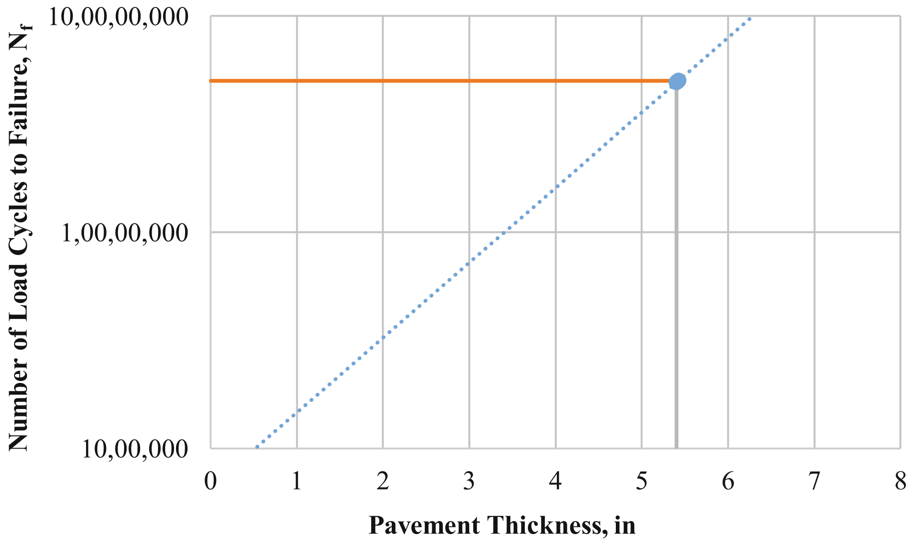

Fig. 3. Relationship between Pavement Thickness, in. and Number of Load Cycles to Failure, N_f, for Reference Mix at 70 mph

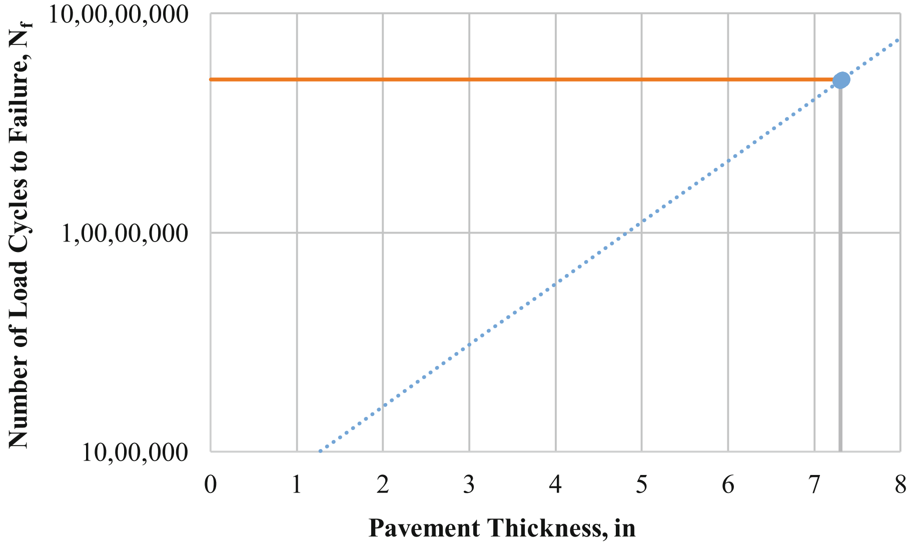

Fig. 4. Relationship between Pavement Thickness, in. and Number of Load Cycles to Failure, N_f, for Reference Mix at 10 mph

pavement thickness required for the reference mix at speed of 70 mph was 5.40 in. with a life of 50,000,000 Load cycles. The difference in required pavement thickness is 1.55 in. (Fig. 6).

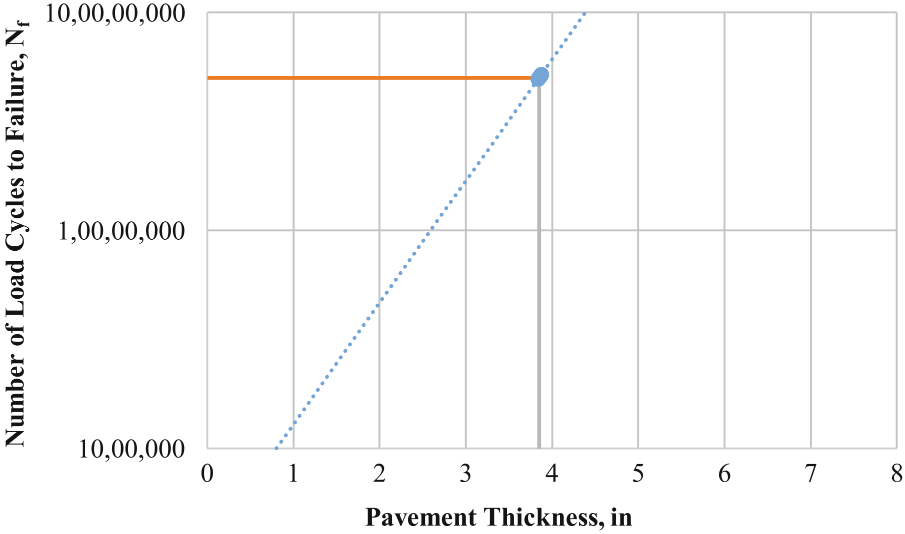

Fig. 5. Relationship between Pavement Thickness, in. and Number of Load Cycles to Failure, N_f, for Asphalt Rubber Mix at 70 mph

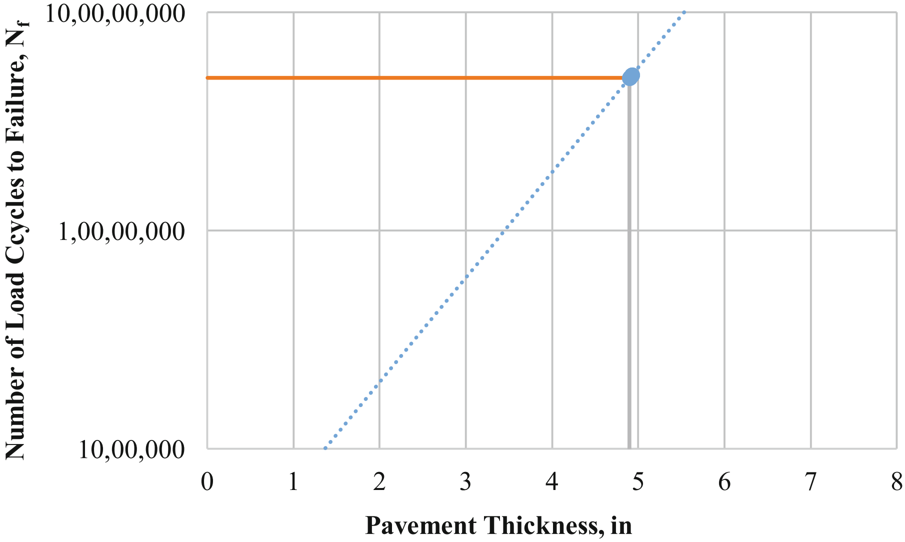

Fig. 6. Relationship between Pavement Thickness, in. and Number of Load Cycles to Failure, N_f, for Asphalt Rubber Mix at 10 mph

Finally, for the asphalt rubber mix at speed of 10 mph, the required pavement thickness is 4.90 in. in order to last for 50,000,000 cycles. Once again, this is 2.40 in. less required for the reference mix at speed of 10 mph. A final summary of the pavement thicknesses and the associated fatigue life is summarized in the table below (Table 2).

Table 2. Summary of pavement thickness results

Mix type	Thickness corresponding to endurance limit at 50 million cycles to failure (in)
RM at 70 mph	5.40
RM at 10 mph	7.30
AR at 70 mph	3.85
AR at 10 mph	4.90

5 Cost Comparison Based on Fatigue Performance

In order to evaluate the economic value of AR and reference HMA mixtures based on fatigue performances, a pavement section of 1.6 km (1 mile which is equal to 1760 yards) with 4.57 m (15 feet which is equal to 5 yards) wide single lane was considered. Based on the assumed density of 110 lb/sq-yd-in, the required quantities for paving the required pavement layer thickness for each case for the investigated mixtures are as follows:

- RM 70 mph: 5.421 in. $\times \frac{110lb}{\text{yd2in}} \times$ 1760 yd $\times$ 5 yd = (5,247,528 Ib) 2,624 tons
- RM 10 mph: 7.329 in. $\times \frac{110lb}{\text{yd2in}} \times$ 1760 yd $\times$ 5 yd = (7,094,472 Ib) 3,548 tons
- AR 70 mph: 3.847 in. $\times \frac{110lb}{\text{yd2in}} \times$ 1760 yd $\times$ 5 yd = (3,723,896 Ib) 1,862 tons
- AR 10 mph: 4.901 in. $\times \frac{110lb}{\text{yd2in}} \times$ 1760 yd $\times$ 5 yd = (4,744,168 Ib) 2,373 tons

The cost of production of 100 tons of HMA mixture can be calculated as follows:

- Optimum binder content in the mixture = 4.5% by total weight of mixture.
- Quantity of binder required = 4.5 tons
- Quantity of aggregates = 95.5 tons
- Total cost of binder @ $600/ton binder = 4.5 × 600 = $2,700
- Total cost of aggregates @ $14/ton aggregate = 95.5 × 14 = $ 1,337
- Cost of plant and equipment lump sum for 100 tons of HMA mixture = $2,500
- Total cost for the production of 100 tons of the HMA mixture =
- $2,700 + $1,337 + $2500 = $6,537
- Therefore, the cost of HMA per ton = $65.37

The additional cost for AR mixtures per ton was estimated to be around $18.98 based on the AASHTO Crumb Rubber Modified (CRM) 1993 cost survey conducted by Steiner (1993). Therefore, the estimated cost of one ton of asphalt rubber is $65.37 (Cost of HMA per ton) + $18.98 = $84.35 per ton. Knowing the cost of the HMA and

AR mixtures per ton, the required cost to pave 1.6 km (1 mile) of the pavement section with various mixtures were calculated as follows:

- RM 70 mph: \$65.37 × 2,624 tons = \$171,530.88
- RM 10 mph: \$65.37 × 3,548 tons = \$231,932.76
- AR 70 mph: \$84.35 × 1,862 tons = \$157,059.70
- AR 10 mph: \$84.35 × 2,373 tons = \$200,162.55

Combining the cost of the pavement per mile with the fatigue lives from the mechanistic-empirical analyses, the costs of 1000 cycles of fatigue life per pavement mile were calculated for the AR mixtures and their corresponding reference conventional HMA mixtures. This cost figure was derived by dividing the total cost of the 1-mile pavement section by the number of 1000 cycles to fatigue failure (i.e. N/1000 as summarized the next few lines). In other words, the cost of a 1.6 km (1-mile) pavement section for every 1000 cycles of fatigue life were determined as follows:

- RM 70 mph: \$171,530.88/(50,015,735/1,000) = \$3.43
- RM 10 mph: \$231,932.76/(50,018,958/1,000) = \$4.64
- AR 70 mph: \$157,059.70/(50,020,673/1,000) = \$3.14
- AR 10 mph: \$200,162.55/(50,021,863/1,000) = \$4.00

6 Summary and Conclusions

This paper investigated the mechanistic and economic impacts of using asphalt rubber mixtures. In order to quantify the economic value of using rubber, mechanistic analysis was performed using 3D move program on both reference and asphalt rubber mixtures for different thicknesses, and changed speed. From the results of 3D move, the required pavement thicknesses for asphalt rubber mixtures versus reference HMA mixtures for different speed rates were calculated. After the completion of the 3D move mechanistic analysis, the following conclusions were derived:

- The pavement thickness required to last for 50,000,000 cycles is much less for the asphalt rubber mixes as opposed to the reference hot mix asphalt.
- The cost to construct one lane mile of the reference mix pavement designed for 70 mph traffic was \$171,530.88 while the asphalt rubber mix at 70 mph came out to be \$157,059.70. This is a \$14,471.18 difference.
- Additionally, the cost to construct one lane mile of the reference mix pavement designed for 10 mph traffic was \$231,932.76, while the asphalt rubber mix at 10 mph came out to be \$200,162.55. This is a \$31,770.21 price difference.
- The cost for pavements constructed at 70 mph were at a lower cost per 1,000 cycles per mile was less than that of 10 mph.
- The cost for pavements constructed with asphalt rubber concrete mixtures were at a lower cost per 1,000 cycles per mile in comparison with that of reference conventional HMA (8.43% and 13.7% reduction in cost for speeds of 70 mph and 10 mph respectively).

Based off the results, the asphalt rubber not only adds fatigue resistance to the pavement, it also provides a more economical choice in the long term of the pavement mixture.

References

Ambassa, Z., Allou, F., Petit, C., Eko, R.M.: Fatigue Life Prediction of an asphalt pavement subjected to multiple axle loading with viscoelastic FEM. Constr. Build. Mater. **43**, 443–452 (2013). ScienceDirect. Web. 24 March 2015

Kaloush, K.E., Biligiri, K.P., Zeiada, W.A., Rodezno, M.C., Souliman, M.I., Reed, J.X., Stempihar, J.J.: Laboratory evaluation of rubber & polymer modified bituminous mixtures constructed in Stockholm. Final Report Submitted to Swedish Road Administration, Vägverket, 405 33 Göteborg, Kruthusgatan 17, Sweden (2010)

Mobasher, B., Mamlouk, M., Lin, H.: Evaluation of crack propagation properties of asphalt mixtures. J. Transp. Eng. ASCE **123**(5), 405–413 (1997). doi:10.1061/(ASCE)0733-947X(1997)123:5(405)

Moreno, F., Rubio, M.C.: Effect of aggregate nature on the fatigue-cracking behavior of halt mixes. Mater. Des. **47**, 61–67 (2012). ScienceDirect. Web. 24 March 2015

Rodezno, M.C., Kaloush, K.E.: Implementation of asphalt-rubber mixes into the mechanistic empirical pavement design guide. Road Mater. Pavement Design **12**(2), 423–439 (2011). doi:10.1080/14680629.2011.9695252. [Lavoisier.]

Souliman, M.I., Eifert, A.: Impact of Added Rubber on the Mechanical, Mechanistic, and Economical Attributes of Asphaltic Mixtures. Hardcopy, 1 November 2015

Souliman, M.I., Mamlouk, M., Kaloush, K.E.: Preliminary Prediction of Endurance Limit for Asphalt Rubber Mixtures Due to Healing. Copy. Accessed 31 Nov 2015

Souliman, M.I., Zeiada, W., Mamlouk, M., Kaloush, K.: Fatigue endurance limit for HMA based on healing. "Asphalt Pavement Technology" J. Assoc. Asphalt Paving Technol. **82**, 503 (2013)

Xiao, F., Amirkhanian, S., Juang, H.: Prediction of fatigue life of rubberized asphalt concrete mixtures containing reclaimed asphalt pavement using artificial neural networks. J. Mater. Civ. Eng. **21**(6), 253–261 (2009). doi:10.1061/(ASCE)0899-1561(2009)21:6(253)

Xiao, F., Zhao, W., Amirkhanian, S.: Laboratory investigation of fatigue characteristics of rubberized asphalt mixtures containing warm asphalt additives at a low temperature. J. Test. Eval. **39**(2), 290–295 (2011)

Zborowski, A., Kaloush, K.: A fracture energy approach to model the thermal cracking performance of asphalt rubber mixtures. Road Mater. Pavements Design J. **12**(2), 377–395 (2011). doi:10.3166/rmpd.12.377-395

Springer
http://www.springer.com/978-3-319-61632-2

Materials for Sustainable Infrastructure
Proceedings of the 1st GeoMEast International Congress and Exhibition, Egypt 2017 on Sustainable Civil Infrastructures
Struble, L.; Tebaldi, G. (Eds.)
2018, XII, 354 p. 206 illus., Softcover
ISBN: 978-3-319-61632-2