MECHANISTIC - EMPIRICAL PAVEMENT DESIGN GUIDE IMPLEMENTATION AND PAVEMENT PRESERVATION STRATEGIES WITH ASPHALT RUBBER

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ABSTRACT

Asphalt-Rubber (AR) mixtures, with their great field performance, have received great attention from many transportation agencies world-wide. Current pavement design procedures do not specifically address the unique engineering properties that these mixtures offer. For example, the Mechanistic-Empirical Pavement Design Guide (MEPDG) did not include asphalt-rubber mixes as part of its calibration and implementation in the USA. This paper addresses some issues on asphalt rubber mixtures implementation into the MEPDG. In addition, highlights of several studies conducted by the authors documenting benefits of the Asphalt Rubber Asphalt Concrete Friction Course (AR-ACFC) as a pavement preservation strategy. This includes results of laboratory material characterization tests, highway noise reduction, mitigation of daily thermal variances in Portland Cement Concrete pavements, improved skid resistance, reduced roughness, reduction of emission rates of tire wear per kilometer driven, and lower environmental impact by having lower CO2 emissions.

1 INTRODUCTION

The use of Asphalt Rubber (AR) mixtures has proof from field pavement performance with outstanding results. There are many studies in the literature on their unique properties that contribute to less permanent deformation and fatigue cracking (Kaloush et al 2002, Mohammad et al 2002, Way 2000). Several states in the U.S. and countries around the world have used, or are in the process of using asphalt rubber mixtures in new pavement designs or in pavement rehabilitation programs

In the USA, the new Mechanistic- Empirical Pavement Design Guide (MEPDG) developed by the National Cooperative Highway Research Program (NCHRP) utilizes material properties to predict distresses in pavement structures. This guide was calibrated and validated with a national performance data, and it is expected to replace the traditional design of pavement based on the AASHTO 1993. The national calibration process that was undertaken for the MEPDG did not include AR mixes.

Over the past 10 years, Arizona State University has developed a comprehensive testing program for AR mixtures that includes binder and mix characterization. Using this database and the experience developed over the years with AR mixtures, this paper addresses some important considerations that will aid in future implementation of these mixtures into the MEPDG.

The paper also discusses the AR-ACFC benefits as a pavement preservation strategy. The authors selected the following focus areas as the criteria for a good pavement preservation strategy: good mixture and binder characteristics through laboratory performance testing; reduced tire / pavement noise, improved thermal gradient characteristics and better interaction with the urban climate; good field frictional characteristics for safety; improved ride quality and comfort for users; less tire wear emissions and therefore better impact on air quality; and finally, lower environmental impacts by reducing CO2 emissions during the production and construction stage of the pavement system.

2 MEPDG MATERIAL INPUT AND IMPLEMENTATION FOR ASPHALT-RUBBER MIXTURES

In the MEPDG, there are basically three input steps for the asphalt concrete layer: mixture, asphalt cement (binder or bitumen), and a general asphalt category. The information required in each of these fields will vary according to the level of analysis to be used, as briefly described below.

Level 1: laboratory test data are required to develop the dynamic modulus master curve and shift factors. Dynamic modulus test results (AASHTO TP62-07) at different temperatures and frequencies must be input. Binder data at short term aging is also required. This can be either Superpave or conventional binder consistency tests. For the superpave binder test data, complex modulus and phase angle data are needed over a range of temperatures and loading rate of 1.59 Hz. For conventional binder test data, softening point, penetration, and viscosities are needed as input. These test results are used to determine the viscosity-temperature susceptibility parameters (Ai-VTSi) of the binder (ASTM D2493, 1998). The information required for the asphalt mixtures are the volumetric properties, which are also the same information required for Levels 2 and 3.

Level 2: the Witczak Dynamic Modulus predictive equation shown below is used. The same binder test data is needed as in the Level 1 analysis.

$$\boxed{\begin{aligned}\log E^* = {} & 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 \\ & - 0.058097V_a - 0.802208\left(\frac{V_{eff}}{V_{eff} + V_a}\right) + \\ & \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log(f) - 0.393532\log(\eta))}}\end{aligned}} \quad (1)$$

where:

E*=Dynamic Modulus, psi
η = Bitumen viscosity, 10^6 poise
f = Loading frequency, Hz
V_a= Air Voids Content, %

V_{eff} = Effective bitumen content, % by volume
ρ_{34}= Cumulative % retained on the 3/4 in sieve
ρ_{38}= Cumulative % retained on the 3/8 in sieve
ρ_{4}= Cumulative % retained on the # 4 sieve
ρ_{200}= % passing the # 200 sieve

Level 3: the Witczak's Dynamic Modulus predictive equation is also used to estimate the dynamic modulus. The binder information for Level 3 does not require laboratory test data. The binder viscosity information is estimated from typical temperature-viscosity relationships after the Rolling Thin Film Oven (RTFO) test results are established for different asphalt grades derived from various grading systems.

3 ASPHALT-RUBBER BINDER CHARACTERISTICS

Table 1 shows a summary of typical viscosity-temperature susceptibility parameters (Ai-VTSi) data for two binders with and without rubber. These results include original and RTFO aging levels. It is observed that the AR binders improve the performance grade of the virgin binder especially at high temperatures (lower VTSi values).

Table 1. Typical A_i and VTS_i Parameters for Binders with and without Asphalt-Rubber.

Binder Type	Aging	A_i	VTS_i
PG58-22	Original	11.164	-3.764
	RTFO	11.076	-3.722
PG58-22 AR	Original	8.3595	-2.726
	RTFO	8.0475	-2.598
PG64-16	Original	11.163	-3.755
	RTFO	11.116	-3.728
PG64-16 AR	Original	8.39	-2.738
	RTFO	8.543	-2.781

By using asphalt rubber as a binder, the film thickness is increased to a value of 19 - 36 micrometer compared to the typical dense-graded Hot Mix Asphalt (HMA) film thickness of about 9 micrometer [Way 2000]. In Arizona, the grade of asphalt binder used as a base to make AR is a PG58-22 (AC-10, Pen 85-100), in contrast to the typically stiffer grade of PG 64-16 (AC-20, Pen 60-70) used in the mountains. In the desert the AR base asphalt grade is PG 64-16 (AC-20, Pen 60-70) compared to the PG 70-10 (AC-40, Pen 40-50) typically used for dense graded mixes. The 20 percent ground tire crumb rubber particles change the AR temperature susceptibility, the VTSi of the rubber modified binders is better (flatter, lower slope) than the conventional (virgin) binder, both at high and low temperature conditions. At lower temperature conditions, the AR binders are softer than the virgin binder. Higher binder viscosities at high temperatures and lower viscosities at lower temperature are indicative of good overall mix performance characteristics. These characteristics also agree with observed field performance, where AR mixes are known to have better response against permanent deformation, and low-temperature cracking.

The results in Table 1 were used to provide approximate PG grading of the AR binders. Since no PG grading are established for AR binder in the MEPDG, one approach would be to find the PG grading that best match the A_i and VTS_i values obtained in Table 1. This approximate matching is demonstrated in Table 2. For example, a PG 70-40 is the PG grading that best represents the A_i and VTS_i values for the PG 58-22AR binder. Similarly, a PG 76-34 is the one that best matches the PG 64-16 AR binder. By using this approach, Levels 2 and 3 of the MEPDG can be implemented.

Table 2. Approximate PG Grading for AR Binders.

Binder Type	A_i	VTS_i
PG 58-22 AR	8.048	-2.598
PG 70-40	8.129	-2.648
PG 64 -16 AR	8.543	-2.781
PG 76-34	8.532	-2.785

4 DYNAMIC MODULUS CHARACTERISTICS OF ASPHALT RUBBER MIXTURES

The dynamic modulus testing program follows AASHTO TP 62-07, which basically is a test protocol for unconfined laboratory testing. However, unconfined and confined stress state conditions were conducted for AR mixtures at ASU over the past several years. The confined Dynamic Modulus E* test is especially important for the open graded mixes because it represents the true state of stress in the field (surface layer with high confinement stress under loading). The effect of confinement is clearly shown in Figure 1, where typical master curves for an AR-ACFC mixture test results are presented for unconfined and three levels of confinements: 69, 138, and 207 kPa. The confined test results yield much higher moduli and the difference among the level of confinements continue at high temperatures. Table 3 shows the complex modulus test results for several AR mixtures compared to conventional mixtures by means of a modular ratio comparison. The results show that the AR mixes have better moduli values compared to conventional mixes for several binder types.

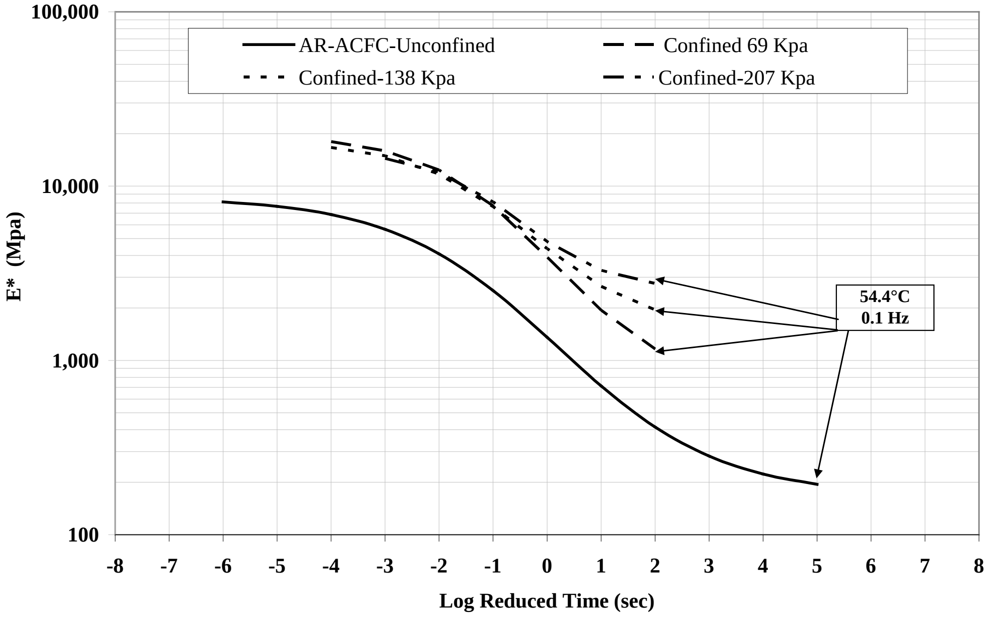


Figure 1. Comparison of E* Master Curves and Effect of Confinement for Typical AR Mixture.

Table 3. Modular Ratio at 37.8^{o}C / 10 Hz for AR and Conventional Mixes, Confined Testing.

Mix ID	Binder Type	AC %	Va %	Nom. Aggregate	Modular Ratio
ARAC (stiff)	64-16 (AR)	8.9	5.5	19.0-mm GG	1.08
AR-ACFC	58-22 (AR)	8.8	17.6	9.0-mm OG	1.02
ARAC[1]	58-22 (AR)	6.8	10.9	19.0-mm GG	1.00
Conventional	64-22	5.2	6.6	19.0-mm DGM	0.94
Conventional	AC-20	4.1	7.4	37.5-mm DGM	0.77
ARAC (Soft)	Pen 150-200 (AR)	8.9	9.7	19.0-mm GG	0.67

OG = Open Graded Mixture *GG = Gap Graded Mixture (SMA type of grading)*
DGM = Dense Graded Mixture [1] *Reference Mix*

Previous studies by the authors (Rodezno and Kaloush, 2009; Rodezno 2010) provided a new version of the Witczak's Dynamic Modulus predictive equation that is applicable specifically for asphalt rubber mixtures. The AR Dynamic Modulus predictive equation included unconfined and confined moduli consideration. The same variables and form of the predictive equation was used in this effort. Table 4 shows the new parameters for the modified predictive equations with excellent measures of model accuracy.

Table 4 New Coefficients for the Witczak Dynamic Modulus Equation Based on Unconfined and Confined AR Test Results

Coefficient		Current Equation	New Parameters Unconfined	New parameters Confined
Intercept 1		3.75	0.3461	4.0918
p_{200}		0.02932	0.72051	0.7084
p_{200}^{2}		-0.0018	-0.2661	-0.1802
p_{4}		-0.0028	0.068	0.0169
V_{a}		-0.0581	-0.04203	-0.0284
Vb_{eff}		-0.8022	-0.06702	-0.5883
Intercept 2		3.8719	4.8717	-0.6751
p_{4}		-0.0021	0.04564	0.03149
p_{38}		0.00396	0.03686	0.04937
p_{38}^{2}		1.7E-05	-0.001059	-0.001294
p_{34}		0.00547	0.00547	0.00547
K_{f}		-0.6033	-0.1753	0.23379
K_{v}		0.3134	-0.48033	-0.6026
b_{f}		-0.3953	-0.7411	-0.6419
Log	S_e/S_y	0.96	0.23	0.32
	R^2	0.08	0.95	0.9
Arithmetic	S_e/S_y	0.97	0.32	0.4
	R^2	0.08	0.9	0.84

5 TIRE / PAVEMENT NOISE CHARACTERISTICS

It has been well documented in the literature that the tire / pavement interaction is the dominant source of highway noise. Dominant factors that contribute to the tire / pavement noise include: air pumping, compression of tread block, friction, porosity, absorption, aggregate texture, thickness, age of the pavement and temperature (Biligiri et al, 2008). The authors believe that AR-ACFC mixes reduce tire/pavement noise because they act as an acoustic absorber due to the viscoelastic nature of the asphalt mix, and because air pushed through the layer voids (> 18%) avoiding the air compression under the tire. Furthermore, the smooth riding surface characteristics and small top size aggregate contribute to less tire deformation with travel and less squeezing of air between the tire and pavement. The viscoelastic characteristics of an AR-ACFC come from much higher asphalt binder content (9-10%) and inclusions of crumb rubber (20% by weight of the binder). In addition, the rubber particles in the AR-ACFC contribute to less noise due to the sound absorptive characteristic of rubber materials.

The Arizona Department of Transportation (ADOT) conducted a pavement preservation experiment on the Interstate – 10 (I-10) in 1999 (Scofield 2000). As part of this experiment, 32 replicate test sections were constructed constituting five asphalt concrete pavement wearing courses. The Annual Daily Traffic (ADT) for this highway is about 60,000 with 25% trucks. The five different pavement types included: Permeable European Mixture (PEM), Stone Matrix Asphalt (SMA), Asphalt Rubber Open Graded Friction Course (AR-ACFC), Polymer Modified Open Graded Friction Course (P-ACFC), and ADOT's Standard Open Graded Friction Course (ACFC). The AR-ACFC mix experienced the least cracking and wear after eight years of service with the other test sections showing considerable cracking and wear.

On-Board Sound Intensity (OBSI) noise measurements were taken during the Fall 2002 by ADOT as part of the Arizona's Quiet Pavement Program. In addition, Dynatest Inc. obtained new noise measurements in March 2008 as part of a larger California – Arizona highway noise study [Scofield 2000, 2003, CALTRANS 2006]. Figure 2 shows a comparison of average noise readings between the two measurement periods for the five pavement types. The least noise observed for both periods is for the AR-ACFC mixture. This difference agrees with visual distress observations where several sections that exhibited higher noise have greater amount of raveling and cracking.

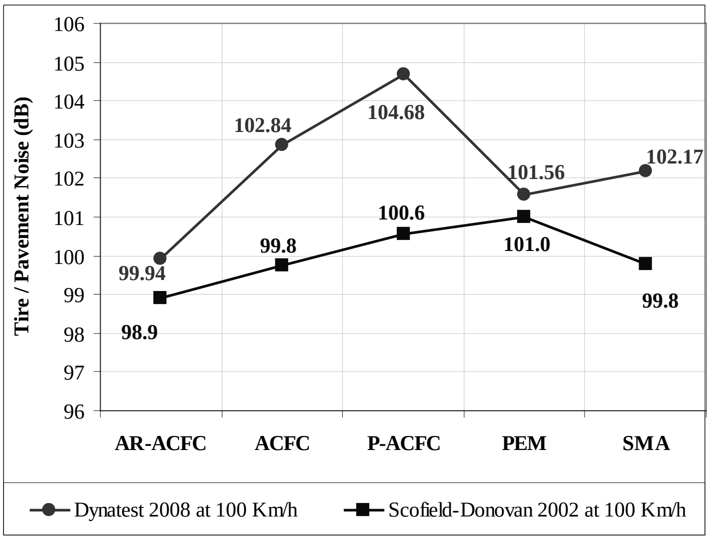


Figure 2. Comparison of Average Tire / Pavement Noise (dB) for Arizona I-10 Test Sections.

6 TEMPERATURE GRADIENT EFFECT ON PORTLAND CEMENT CONCRETE

Since 2003, ADOT has been placing AR-ACFC mixes over existing Portland Cement Concrete Pavements (PCCP) as part of the Quiet Pavement Program. An ASU study was conducted to evaluate the consequences of this paving strategy on the Urban Heat Island (UHI) effect, and the insulating effects of the AR-ACFC mix on PCCP.

Temperature data collection showed that the initial darker AR-ACFC surface color increases the surface temperatures of the pavement during daytime. However, the nighttime UHI effect showed a benefit of using the AR-ACFC overlay in reducing the pavement surface temperatures due to the porosity and lower thermal mass of the layer [Golden and Kaloush 2006]. An important consideration is subjecting these surfaces to traffic, which provides the necessary aeration effect. These findings are discussed below.

An Interstate 10 road experiment was conducted with the objective of quantifying the effects of AR-ACFC overlays on PCCP. The I-10 pavement sections had two adjacent test sites: one with the AR-ACFC overlay and one with only PCCP. Pavement temperature data were recorded for driving lanes as well as the shoulder areas, allowing a matrix that included data from areas with and without traffic. The existing PCCP was cored and sensors were placed using dowels to insure top to bottom spacing. Saw cut lines were then made from the cores to the shoulder so that future data collection could be made without impacting traffic. Data was recovered for the month of June, and the data were examined in depth.

Table 5 shows comparisons of the average temperature differentials (ΔT) measured for June 2006. Curling stresses for each respective section were calculated. The section with traffic and without the AR-ACFC overlay experiences daytime induced stresses on the magnitude of 25% greater than the section with traffic and with the AR-ACFC overlay. Night time values for the section without AR-ACFC were about 8% higher. When considering that a major portion of the damage to a PCCP structure results from thermal gradient induced stresses as opposed to traffic loadings, the service life of the PCCP can be significantly extended with the use of AR-ACFC overlays as a pavement preservation strategy.

Table 5. Comparison of Temperature Differentials

Overlay / Traffic Case	Max ΔT °C	Min ΔT °C	Range of ΔT °C
With AR-ACFC: Traffic vs. No Traffic	3.5	-2.5	6
Without AR-ACFC: Traffic vs. No Traffic	5	-1	6
With Traffic: AR-ACFC vs. No AR-ACFC	4	-3.5	7.5
Without Traffic: AR-ACFC vs. No AR-ACFC	4	0.5	4.5

7 ROUGHNESS AND FRICTION

Typical International Roughness Index (IRI) measurements before and after the AR-ACFC overlay on PCCP pavement sections in the Phoenix area are shown in Figure 3 It is observed that the AR-ACFC overlays provide a substantial improvement in ride quality by reducing roughness in half (on the average).

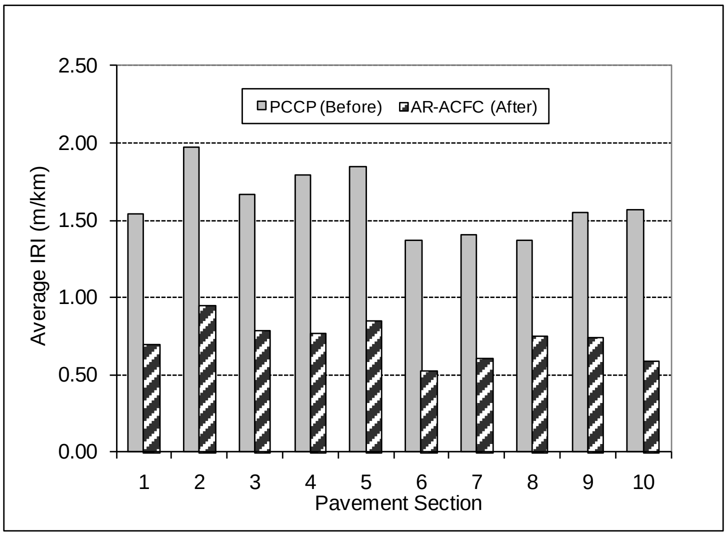


Figure 4. Comparison of IRI Before and After the AR-ACFC Overlay.

Typical average friction values (wet test), utilizing a MU Meter, before and after the AR-ACFC overlay on PCCP pavement sections in the Phoenix area are shown in Figure 5. Measurements are reported as a skid number. The data shows an improvement in the skid numbers after AR-ACFC overlays. In addition, the friction data after the overlay are more uniform as the overlay seems to correct polished surface problem that existed on the original PCCP pavement.

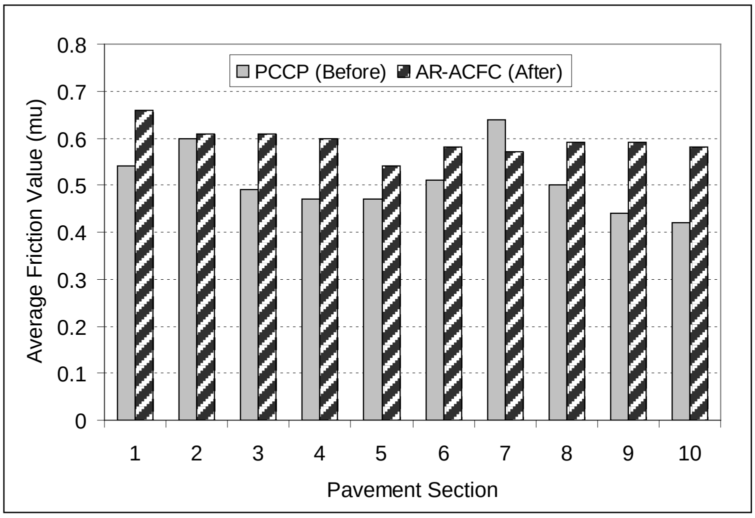


Figure 5. Comparison of Friction Measurements Before and After the AR-ACFC Overlay.

8 TIRE WEAR EMISSIONS

In a separate ASU study, aerosol measurement techniques were applied to evaluate tire wear emissions from the vehicle fleet using the Deck Park highway tunnel in the Phoenix area. The Deck Park Tunnel highway surface was PCCP, and was resurfaced with an AR-ACFC layer as part of the ADOT Quiet Pavements Program. This study took advantage of a rare opportunity to sample tire wear emissions at the tunnel before and after the AR-ACFC overlay [Alexandrova et al, 2007]. To ensure that no rubber from the pavement influences the results, the second sampling was done one year after the AR-ACFC overlay was constructed. This allowed for all of the initial surface wear that normally takes place on a newly constructed pavement. The emission rates of tire wear tracer compounds were calculated as shown in Table 6. Emission rates of tire wear tracers were found higher at the PCCP road surface than at AR-ACFC road surface. The emission rates of tire wear per kilometer driven at PCCP road surface were 1.4 to 2 times higher than emission rates of tire wear at AR-ACFC road surface. These findings provided ADOT with revised tire wear emission data for use in their federally-mandated air quality modeling for the Phoenix airshed.

Table 6. Tire Wear Emission Rates Measured in the Deck Park Tunnel, μg/km.

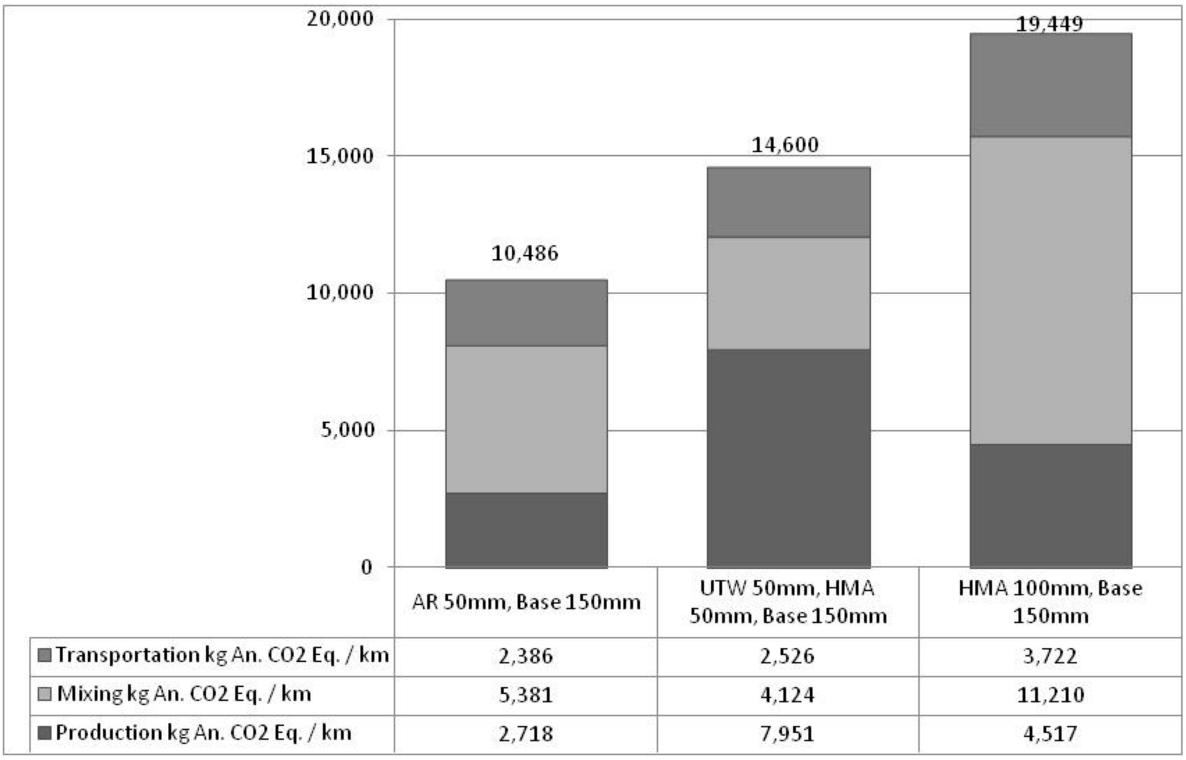
Tire wear emission based on	Experiment 1	Experiment 2
	(PCCP road surface)	(AR-ACFC road surface)
Compound # 3	354 ± 71	177 ± 35
Compound # 4	172 ± 34	120 ± 24

Compounds 3 and 4 are tire wear tracers.

9 ENVIRONMENTAL IMPACTS

Pavements impacts on climate change can be attributed to increased demands for additional pavement construction and rehabilitation. In a recent ASU study, effort was undertaken to introduce the process on how pavement production and construction contributes to direct CO2 emissions impacts [White et al., 2009]. The process employed variables and a model that can be modified by the user to customize for specific road configuration and materials type. By adjusting the model parameters, users can optimize a pavement design based on local resources, climatic conditions, traffic volumes, and energy needs.

In Arizona (and several other states), structural pavement layers are constructed at half thickness of those considered for conventional HMA pavements due to the improved engineering properties of AR mixtures. Figure 6 shows the annual kg. CO2 equivalent emissions per kilometer for three alternative pavement designs that would yield equal field performance under moderate traffic volume conditions. (UTW = Ultra-Thin Whitetopping PCC pavement). It is obvious that the AR road system offers substantial climate change reductions among the three alternatives.



	AR 50mm, Base 150mm	UTW 50mm, HMA 50mm, Base 150mm	HMA 100mm, Base 150mm
■ Transportation kg An. CO2 Eq. / km	2,386	2,526	3,722
■ Mixing kg An. CO2 Eq. / km	5,381	4,124	11,210
■ Production kg An. CO2 Eq. / km	2,718	7,951	4,517

Figure 6. Total Annual kg CO2 Eq. / km for Alternative Pavement Designs.

10 CONCLUSIONS

This paper discussed some important issues that need to be considered when asphalt rubber mixtures are being considered for implementation into the MEPDG. The paper also presented specific aspects on why AR-ACFC overlays are considered as good pavement preservation strategy. The focus areas summarized the outcome of several research studies conducted in Arizona, USA. Many benefits have been identified. The reduced permanent deformation and cracking have been confirmed through field observations and laboratory testing conducted on binders and mixtures. The restoration of a smoother ride and the increase in skid resistance were additional benefits identified through several pavement test sections. There is no doubt that AR-ACFC overlays provide the least tire/pavement noise compared to any other road surface type evaluated in these studies. In addition, AR-ACFC overlays have shown to have a significant impact on reducing the induced stresses in PCCP due to thermal gradients. A composite PCCP/AR-ACFC pavement design will be very long lasting. Emission rates of tire wear per kilometer driven on AR-ACFC overlays were reduced by half, having great impact on air quality and human health in urban areas. Due to reduced thickness design, CO2 emissions impacts are greatly reduced over the life cycle of the pavement.

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