Asphalt-Rubber Properties Indicative of Noise-Dampening Characteristics

Krishna Prapoorna Biligiri* – George B. Way – Ali Zareh*****

** Arizona State University, Tempe, Arizona, United States of America*
*** Consulpav International, Inc. United States of America*
*** Arizona Department of Transportation, Phoenix, United States of America*

krishna.biligiri@asu.edu; wayouta@cox.net; alizareh1356@yahoo.com

ABSTRACT. *The State of Arizona in the United States has been successful in utilizing variants of asphalt-rubber (AR) since the late 1980s for the purpose of not just alleviating pavement distresses but also in reducing tire/pavement noise. AR mixes have been successfully implemented as a "Quiet" pavement strategy worldwide. In particular, Arizona in the United States has been monitoring the noise reducing properties of AR open graded (ARFC) mixes since the last 14 years. Contemporaneously, in 1999, the ADOT placed five different asphalt wearing courses as test sections on Interstate 10 in southern Arizona. After a service life of about twelve years, the ARFC has experienced the least cracking and wear, and exhibited as the least noisy of the different pavement surfaces to date. The purpose of this paper was to present the theoretical laboratory studies conducted on the field cores to characterize the acoustical properties of the different pavement materials, including: Arizona I-10 asphalt wearing courses; several pavement mixtures from Arizona, Sweden, and California; and two different non-asphaltic mixtures for comparison purposes. Furthermore, the paper presents the concept of the development of a new and unique parameter to characterize acoustical properties of the different road materials; the parameter is referred to in this study as DAMP (Damping Acoustical Measurement Parameter). A standard ultrasonic pulse velocity (UPV) test methodology actually used to estimate cracks in concrete was modified and made suitable to obtain the various acoustical properties for the different materials. The outcome of the UPV experiment was the ultrasonic pulse time (UPT) taken for the acoustic wave to traverse from one end of the sample to the other. UPV and impedance (Z) values were estimated with the help of sample length, UPT, and material density. DAMP, an acoustic parametric index was estimated mathematically as a power expression, which also directly related to the impedance of a mix. Lower the value of DAMP, the lower the tire/pavement noise, which was confirmed from field noise measurements. Overall, the ARFC mix had the lowest DAMP compared to the other asphaltic mixtures, mainly due to the higher amount of binder than the other mixes and a higher porosity (air voids) in the mix matrix.*

KEYWORDS: *Asphalt-Rubber, Tire/Pavement Noise, Ultrasonic, Damping, Acoustical Parameter*

1. Introduction

Global urbanization has myriad benefits pertinent to infrastructure development such as design and construction of new structures, generation of new jobs, improvement in quality of life standards, and so forth; but, it also creates a host of effects on the environment. Of the many effects, traffic noise has become a growing problem in urban areas, especially, in the vicinity of the highways and arterial roads. More so, an increase in traffic volume will continue to add more noise pollution that affects human welfare in varying degrees (Tsunokawa and Hoban, 1997). Several studies have indicated that tire / pavement interaction noise contributes significantly to the overall roadway noise, mainly at vehicle speeds greater than 40 km/h (Sandberg and Ejsmont, 2002; Donavan and Rymer, 2003; Bernhard and Wayson, 2005). A multitude of factors have been listed to be of influencing tire / pavement noise such as pavement material type and property, friction, porosity, age, thickness, asphalt content, etc. (Rasmussen *et al*, 2007; Biligiri, 2008).

Construction of sound barrier walls along the city freeways has been one of the alternatives to reduce highway noise that affects the adjacent residential areas. But, typical noise barrier walls cost around US $1.25 Million/kilometer (Gibbs *et al*, 2005). Thus, the wider use of “quiet” roads has not only become a better strategy in reducing the overall noise exposure to counter the high cost of noise barriers but also as an important “quality of life & sustainability” concern.

The State of Arizona in the United States has been successful in utilizing variants of asphalt-rubber (AR) since the late 1980s for the purpose of not just alleviating pavement distresses but also in reducing tire/pavement noise. AR mixes have been successfully implemented as a “Quiet” pavement strategy worldwide. In particular, the Arizona Department of Transportation (ADOT) implemented a long-term Quiet Pavement Program to monitor the noise reducing properties of AR open graded (also AR Friction Course or ARFC) mixes in the Phoenix area. Contemporaneously, in 1999, the ADOT placed five different asphalt wearing courses as test sections on Interstate 10, a highly trafficked highway in Arizona. After a service life of twelve years, the ARFC has experienced the least cracking and wear, and exhibited as the quietest of the five pavement surfaces to date.

2. Objectives

The main purpose of this paper was to present the theoretical laboratory studies conducted on the field cores to characterize the acoustical properties of the different pavement materials, including: Arizona I-10 asphalt wearing courses; several pavement mixtures from Arizona, Sweden, and California; and two different non-asphaltic mixtures for comparison purposes.

Furthermore, the paper presents the concept of the development of a new and unique parameter to characterize acoustical properties of the different road materials; the parameter is referred to in this study as DAMP (Damping Acoustical Measurement Parameter).

3. Mixtures and Experimental Data

The database utilized in this study included 36 laboratory pavement specimens and 49 field cores obtained from national and international pavement sections. The samples represented the following agencies and countries that were cited in various studies conducted previously (Scofield, 2000; Kohler *et al*, 2007; Carlson *et al*, 2008; Biligiri and Kaloush, 2009).

- Arizona Department of Transportation (ADOT), USA
- Arizona State University (ASU), USA
- Swedish National Road and Transport Research Institute (VTI), Sweden
- Swedish Transport Administration (STA), Sweden
- University of California Pavement Research Center (UCPRC), USA
- California Department of Transportation (CALTRANS), USA

For the sake of completeness of the paper, although the descriptions of the various mixtures used for evaluation in this study are documented elsewhere, a brief account of those studies and mixtures is included next.

3.1 ADOT I-10 Wearing Course Experiment

The details of the wearing course experiment project are described in detail in the various previously published literature documents and also included in the AR2009 conference proceedings (Biligiri, 2008; Biligiri and Kaloush, 2009; Carlson *et al*, 2009). A brief description of the project is presented here. The ADOT I-10 wearing course experimental sections were part of a preventative maintenance pavement preservation project constructed during 1999 (Scofield, 2000). As part of this experiment, 32 test sections, with replicate cells, were constructed constituting five asphalt concrete pavement wearing courses types:

- ADOT I-10 – PEM: Permeable European Mixture
- ADOT I-10 – SMA: Stone Matrix Asphalt
- ADOT I-10 – ARFC: Asphalt Rubber Open Graded Friction Course
- ADOT I-10 – P-ACFC: Polymer Modified Open Graded Friction Course
- ADOT I-10 – ACFC: Standard Open Graded Friction Course

Some of the salient features of the different wearing courses are:

- Highest bitumen content used was for the ARFC mixture (~9.2%)

- Polymer type used in the P-ACFC mix was: Styrene-Butadiene (SB) or Styrene-Butadiene-Styrene (SBS)
- Wearing courses thickness were 19 mm for four mix types except for the PEM whose surface thickness was 32 mm
- Design life for each mix: 12 – 15 years

Noise measurements on the five different wearing courses comprising of 32 test sections were conducted using On-Board Sound Intensity (OBSI) method during the fall of 2002 by ADOT as part of the Arizona's Quiet Pavement Program (Scofield and Donavan, 2003). In late 2007, ADOT in conjunction with the Rubber Pavement Association (RPA) and ASU performed spot check highway noise measurements on these 32 test sections using a handheld noise meter attached to the running board of a van, in such a way that the noise meter was in close proximity to the tire / pavement interface (Carlson *et al*, 2009). Four runs were performed at three different speeds, namely, 100, 120 and 135 km/h, and the readings were recorded simultaneously. In addition, Dynatest Inc. measured noise levels on these sections using the OBSI technique during March 2008 at 100 km/h (Kohler *et al*, 2007).

Figure 1 shows a comparison of noise readings on these test sections for the years: 2002, 2007 and 2008. As can be observed, the least noise observed for all years and measurements is for the ARFC surface. This difference agreed with the visual distress observations made in 2007. Several sections that exhibited higher noise had greater amount of raveling and cracking. In general, the noise level of each test section appeared to be related to the degree of surface deterioration.

In February 2011, the authors undertook a continuing effort to measure noise and wear of the same test sections to investigate the materials' surface characteristics after a service of 12 years. Noise readings at 100 km/h were taken using a handheld noise meter inside the car, which was basically a spot-check measurement method. Figure 2 presents the results of those measurements.

As observed in the Figure 2, the ARFC mix was the quietest amongst the five mixes even in 2011 and the trends of the noise values of the other surfaces was akin to the readings of the years 2007 and 2008. At the same time, a visual inspection of those surfaces revealed that ARFC experienced the least cracking and wear after more than a decade of service while the other test sections showed considerable cracking and wear.

It must be noted that the noise values are significantly different in terms of magnitude as the measurement method used in the 2011 spot check study was to use an un-calibrated handheld noise meter. Nevertheless, the basic noise trends are clearly visible for each mix even though the method used was just a verification using an unsophisticated instrument.

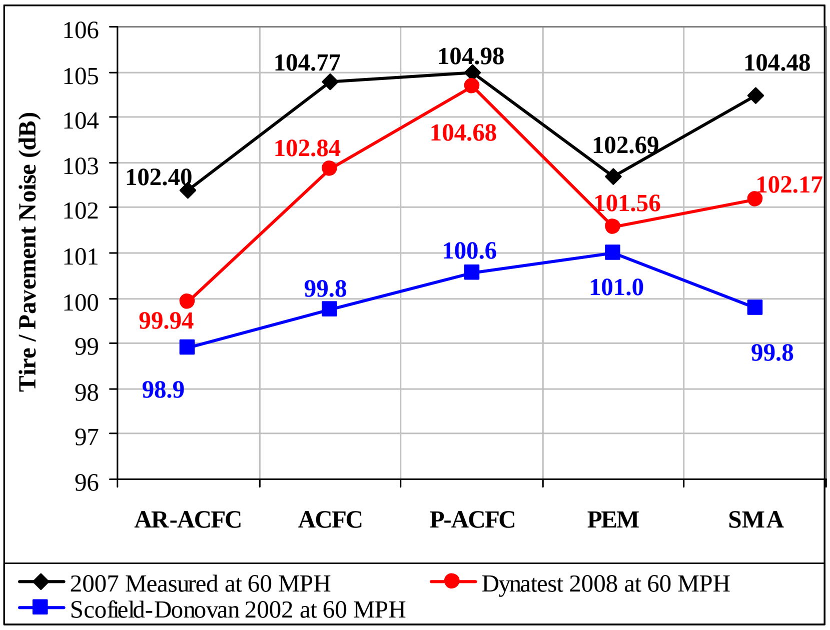

Figure 1. *Noise Measurement Comparison for Arizona I-10 Test Sections, Years 2002, 2007, and 2008*

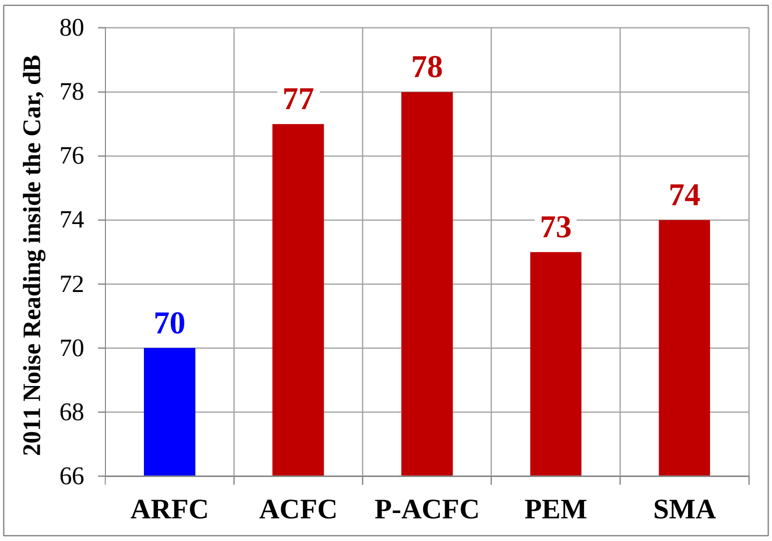

Figure 2. *Noise Values for Arizona I-10 Test Sections using Handheld Noise Meter inside of the Car, Year 2011*

3.2 ASU-ADOT Studies

ASU-ADOT database consisted of laboratory prepared mixtures from field samples obtained from different sites in Arizona. Three different asphalt mixtures were prepared for the acoustical evaluation whose mix volumetrics are provided later on in the paper, including air voids, asphalt content, and density:

- ADOT – DGAC: Conventional Dense Graded Asphalt Concrete
- ADOT – ARAC: Asphalt Rubber Asphalt Concrete (AR Gap Graded)
- ADOT – ARFC: Asphalt Rubber Friction Course (AR Open Graded)

3.3 ASU-Swedish Studies

ASU received gap graded and open graded mixtures, with and without rubber modification from two different Swedish research and transport agencies (Biligiri, 2008). One agency VTI-Swedish National Road and Transport Research Institute sent 13 laboratory-prepared gap and open graded mixtures to ASU for noise investigation. The second agency was the Swedish Transport Administration (STA) wherefrom two types of gap graded mixtures with and without rubber modification from an actual Swedish project E-06 site was obtained for laboratory noise evaluation studies apart from a full suite of mixture material characterization.

- VTI – OGAR1 and OGAR2: Open Graded Asphalt Rubber Types 1 and 2
- VTI – OGAC: Open Graded Asphalt Concrete (without rubber)
- VTI – GGAR1 and GGAR2: Gap Graded Asphalt Rubber Types 1 and 2
- VTI – GGAC1 and GGAC2: Gap Graded Asphalt Concrete Types 1 and 2 (without rubber)
- STA – E-06 – GGAC: Gap Graded Asphalt Concrete (without rubber)
- STA – E-06 – GGAR: Gap Graded Asphalt Rubber

3.4 ASU-California Studies

In fall 2007, UCPRC in conjunction with CALTRANS sent 19 asphalt concrete samples to ASU for laboratory noise evaluation (Kohler *et al*, 2007). The different mixtures used as part of this study are as follows.

- UCD – DGAC: Dense Graded Asphalt Concrete
- UCD – RAC-G: Rubber Asphalt Concrete, Gap Graded
- UCD – RAC-O-F-mix: Rubber Asphalt Concrete-Open Graded – F
- UCD – OGAC: Open Graded Asphalt Concrete
- UCD – EU Gap Graded: European Gap Graded
- UCD – RAC-O: Rubber Asphalt Concrete, Open Graded

4. Laboratory Noise Evaluation using Ultrasonic Pulse Velocity Test

All the samples as documented previously were subjected to laboratory noise evaluation using Ultrasonic Pulse Velocity (UPV) technique. The methodology and the theory of the experiment are published elsewhere (Biligiri and Kaloush, 2009). A brief description of the test procedure and analysis is provided here.

The nondestructive UPV technique is based on the measurement of wave velocities through material as described in ASTM C597-02: Standard Test Method for Measuring Pulse Velocity through Concrete (ASTM E494-05; ASTM C597-02). In the laboratory, the ultrasonic pulse velocity (UPV) is calculated as a ratio of the measured path length to the measured pulse time. That is,

$$v = \frac{L}{T} \qquad [1]$$

Where:

v = ultrasonic pulse velocity through the material (m/s)

L = Distance between centers of sample faces (m)

T = Ultrasonic Pulse Time (UPT) for transit (μs)

A standard ultrasonic pulse test methodology actually used to estimate cracks in concrete was modified and made suitable to obtain the various acoustical properties for the different materials. Ultrasonic testing of materials (sample cores) utilized mechanical acoustic waves transmitted from one end of the sample to the other using a transducer of resonant frequency of 25 kHz. The outcome of the experiment was the UPT taken for the acoustic wave to traverse from one end of the sample to the other. UPV and impedance values were estimated with the help of sample length, UPT, and material density as follows.

With the estimated UPV, one can calculate the impedance (Z) of the material:

$$Z = {}^\circ * v \qquad [2]$$

Where:

Z = Impedance (cgs Rayls)

ρ = density of the material (kg/m^3)

v = ultrasonic pulse velocity through the material (m/s)

5. Concept of Damping Acoustical Measurement Parameter (DAMP)

Damping Acoustical Measurement Parameter (DAMP), an acoustic parametric index was estimated mathematically as a power expression, which also directly related to the acoustic flow resistivity (or impedance) of a mix. It is important to note that volumetric mix properties of the pavement materials are correlated to the noise dampening properties of the different mixes, which was also the basis for developing the DAMP indices. Thus, DAMP is given by:

$$DAMP = \left(\frac{Z}{100}\right)^{0.4} \qquad [3]$$

It must be noted that $1 \leq DAMP \leq 10$

5.1 DAMP of Pavement Materials

DAMP values were calculated for all the different pavement materials presented previously in Section 3. Table 1 presents the DAMP values of all the different pavement mixtures. The table also presents mixtures' air voids (AV %), bitumen content (AC %), material density ρ, and the estimated UPV and impedance, Z. Furthermore, two non-asphaltic mixtures that were not reported previously are also included in the table. One material is the Poroelastic Road Surface (PERS) mix which is currently under development as part of the European Union PERSUADE project. PERS mix presented in this study has about 9% (ground tyre) rubber content by weight of the mix, high porosity in the order of 37% and is bound by a non-asphaltic binder (Biligiri *et al*, 2011). Portland Cement Concrete (PCC), another non-asphaltic material was also compared for its acoustical properties with respect to the other mixtures under investigation. Figure 3 presents a pictorial representation of the average DAMP values for the different mixtures, including the minimum and maximum values (shown as error bars) as applicable.

As observed (from Table 1 and Figure 3), PERS mix provided the lowest DAMP value while PCC had the highest DAMP. In the group of asphaltic mixtures, ARFC had the lowest DAMP compared to all the other mixtures. This is indicative of the finding that ARFC provides highest damping to acoustic wave propagation through the material in comparison to the other asphalt mixtures such as gap graded, dense graded, and other materials. Overall, ARFC is the quietest pavement material, also confirming the various past field studies. Since impedance and DAMP are directly related; lower the value of Z, lower is the value of DAMP. Although one can distinguish noise characteristics of the different materials using just the impedance values, it is much easier to compare mathematically when the noise dampening parameter is of the order between a definitive and comparable value such as 1 and 10. Thus, in this study, impedance of the different materials was simplified using a unique mathematical parameter that is comprehensibly easier. In addition, when DAMP and air voids were correlated for each mix type, the reverse trend was observed as shown in Figure 4. It confirms one of the experts' opinions that air pockets in the materials aid in noise absorption / attenuation / dampening.

Table 1. *DAMP Estimations, All Mixtures*

Mix	AV (%)	AC (%)	UPV (m/s)	ρ (kg/m^3)	Z (cgs Rayls)	DAMP
PERS	37.08	0	898	1.34	1184	2.68
ARFC	17.44	8.48	2818	2.11	5832	5.09
P-ACFC	20.96	6.00	2988	2.01	5891	5.11
PEM	17.14	6.00	3316	2.07	6738	5.39
OGAC	17.52	7.75	3576	2.03	7088	5.48
ACFC	13.80	6.00	3391	2.19	7339	5.58
SMA	9.65	6.50	3566	2.13	7452	5.61
ARAC	9.04	7.47	3544	2.24	7786	5.70
GGAC	7.25	6.67	3786	2.29	8494	5.91
DGAC	5.19	4.96	3941	2.32	8963	6.04
PCC	1.85	0	7721	2.65	20052	8.33

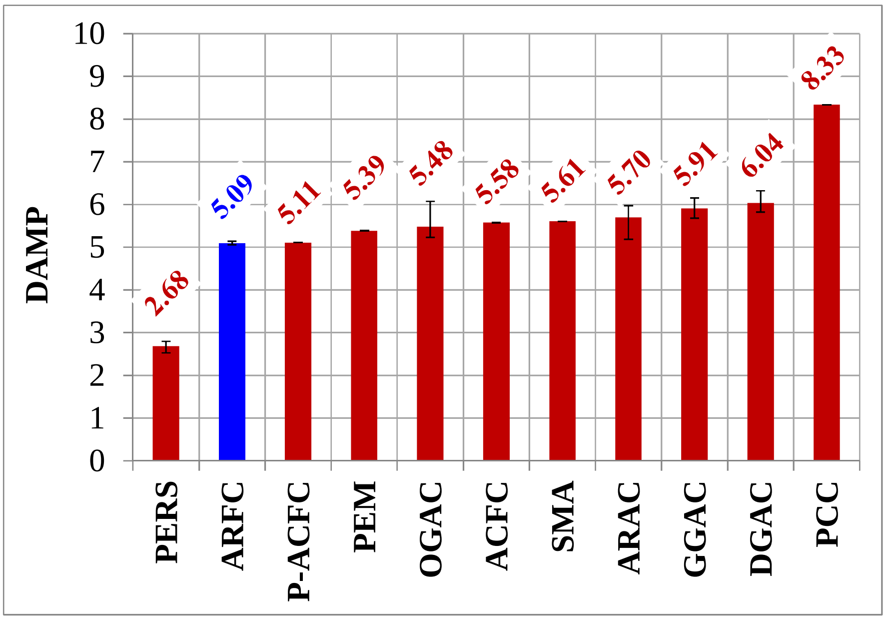

Figure 3. *Average DAMP Values for the Different Pavement Mixtures*

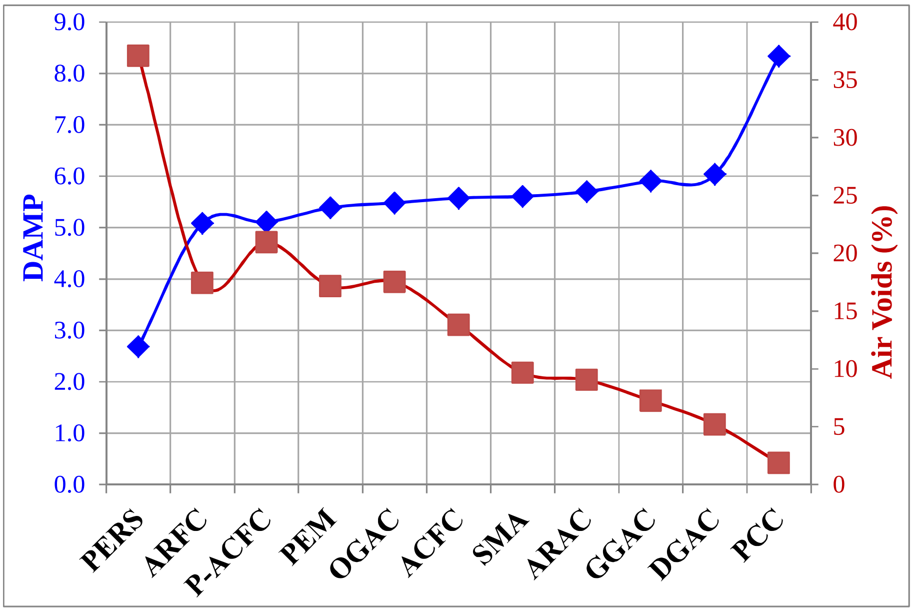

Figure 4. *Average DAMP versus Air Voids for the Different Pavement Mixtures*

5.2 Effect of Temperature on DAMP

Since DAMP indices for the different materials are directly related to the mixture properties, another effort was undertaken to understand the influence of temperature on the acoustical properties of the asphalt mixtures that are fundamentally viscoelastic in nature. To understand the effect of temperature on DAMP, the five different types of Arizona I-10 mixtures were subjected to UPV technique at three different temperatures: 4, 21, and 38 ^{o}C. Table 2 shows the estimated DAMP for the five different wearing courses at three temperatures. The table also includes air voids, bitumen content, density and impedance estimations for each sample and each mix type. A comprehensive scrutiny of the DAMP values indicated that with increase in temperature, there was a decrease in DAMP. This was confirmatory of the fact that asphalt mixtures exhibited a clear viscoelastic nature at higher temperatures where binder effect dominates the aggregate skeleton and a mobilization of the aggregate matrix takes place. Thus, the role of the binder (along with the air voids) in the matrix plays a vital role in noise attenuation as well. Furthermore, the observations revealed that ARFC had the lowest DAMP compared to the other mixtures at all temperatures, mainly due to high amount of binder (3% higher than other mixes) and a high porosity (air voids) in the mix matrix.

Figure 5 shows DAMP for the five different Arizona I-10 wearing courses at three different temperatures. The figure also shows the average DAMP lines for the mixtures at 21 ^{o}C (represented by black dashed line for each mix).

Table 2. *DAMP Estimations, Arizona I-10 Wearing Courses*

Mix Type	Sample ID	AV (%)	AC (%)	ρ (kg/m^3)	4 °C		21 °C		38 °C	
					Z (cgs Rayls)	DAMP	Z (cgs Rayls)	DAMP	Z (cgs Rayls)	DAMP
ARFC	7A	20.44	9.1	2.096	5340	4.909	4778	4.696	4669	4.653
	7B	21.10	9.1	2.078	6402	5.279	5649	5.021	5462	4.954
	8A	19.99	9.1	2.108	6015	5.149	5913	5.114	5627	5.013
	8B	20.87	9.1	2.085	7443	5.607	5770	5.064	5575	4.995
	9A	18.68	9.1	2.142	7272	5.555	5778	5.066	5407	4.934
	9B	20.04	9.1	2.106	7146	5.516	6635	5.355	5283	4.888
P-ACFC	2A	15.81	6	2.071	6871	5.430	6401	5.279	6241	5.225
	2B	15.50	6	2.079	6885	5.434	6622	5.351	6560	5.330
	4A	20.21	6	1.963	5569	4.993	5055	4.803	4672	4.654
	4B	19.50	6	1.980	6230	5.222	5791	5.071	5633	5.015
	6A	18.90	6	1.995	7011	5.474	6244	5.226	6148	5.194
	6B	20.06	6	1.967	5735	5.051	5234	4.870	5183	4.851
PEM	3A	15.41	6	2.078	7773	5.705	6446	5.293	6318	5.251
	3B	14.85	6	2.092	6544	5.325	6544	5.325	6544	5.325
	1A	16.35	6	2.056	7367	5.584	6581	5.337	5983	5.138
	1B	12.73	6	2.145	7917	5.747	7488	5.620	7076	5.494
	5A	17.04	6	2.039	6590	5.340	5958	5.129	5877	5.101
	5B	17.44	6	2.029	7933	5.751	7411	5.597	6144	5.193
ACFC	10A	7.34	6	2.277	8772	5.987	7017	5.476	6865	5.428
	10B	10.06	6	2.210	9334	6.138	8349	5.870	8212	5.832
	11A	3.75	6	2.365	10712	6.486	9756	6.247	8956	6.037
	11B	6.52	6	2.297	9162	6.093	8159	5.816	7932	5.751
	12A	17.42	6	2.029	7851	5.727	5447	4.949	4801	4.705
	12B	20.52	6	1.953	7110	5.505	5308	4.897	4958	4.766
SMA	13A	11.98	6.5	2.080	8764	5.985	8100	5.799	7529	5.632
	13B	8.66	6.5	2.158	8785	5.991	7342	5.576	6929	5.448
	14A	7.29	6.5	2.190	9624	6.214	8567	5.931	7874	5.734
	14B	8.00	6.5	2.174	6245	5.227	5498	4.967	5084	4.814
	15A	11.13	6.5	2.100	8299	5.856	7786	5.709	7884	5.737
	15B	10.85	6.5	2.106	8557	5.928	7416	5.599	7302	5.564

As observed in the Figure 5, on average, the DAMP for ARFC, P-ACFC, PEM, ACFC, and SMA were 5.05, 5.1, 5.4, 5.6, and 5.65, respectively. It is noteworthy that since DAMP is a power expression, 1/10th of DAMP is equivalent to about 10% acoustical change between any two materials.

Figure 6 presents DAMP noise distinguishing bands for all the different pavement materials used in this study. As observed, three DAMP bands were created which represented three unique noise characteristics. ARFC material was placed in the “Quiet” band since both laboratory and field noise investigations proved it to be the quietest pavement material to date. Since asphalt mixtures are viscoelastic, the rest of the different asphaltic materials were placed in the zone of noise lessening or “Perturbed” band, meaning, the materials are not as quiet as ARFC. The PCC mix type, which has shown to be highly annoying to the human ear, was placed in the “Noisy” band that also had highest DAMP values. The characteristics of the material mixtures properties are also shown in the figure for complete understanding of the DAMP bands.

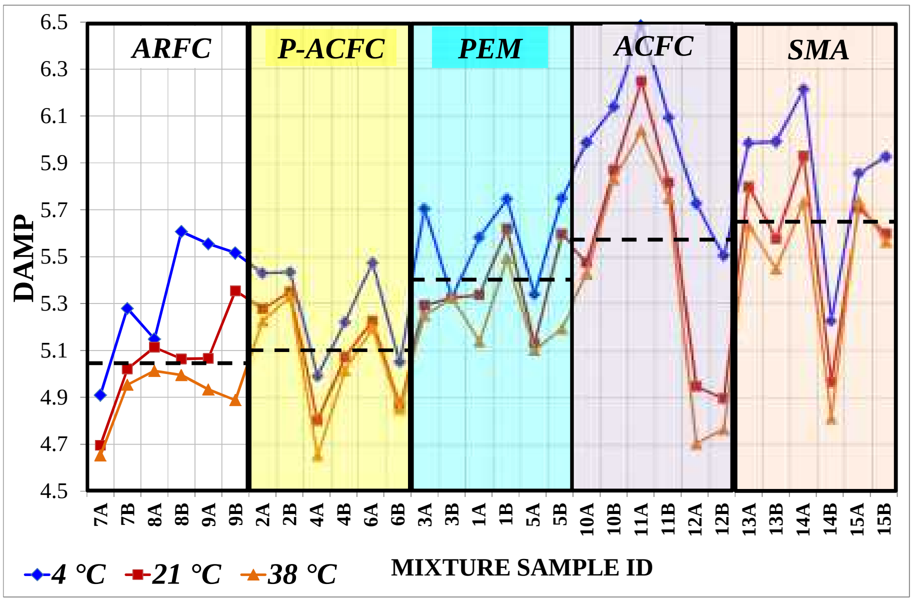

Figure 5. *DAMP for the Arizona I-10 Wearing Course at Three Temperatures*

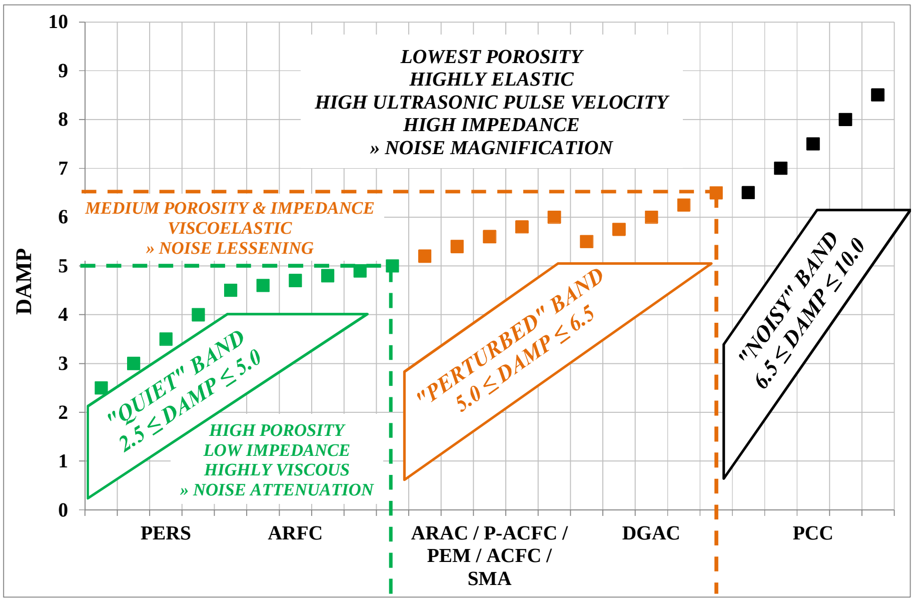

Figure 6. *DAMP Noise Distinguishing Bands for the Different Pavement Materials*

6. Conclusions

The State of Arizona in the United States has been successful in utilizing variants of asphalt-rubber (AR) since the late 1980s for the purpose of not just alleviating pavement distresses but also in reducing tire/pavement noise. AR mixes have been successfully implemented as a "Quiet" pavement strategy worldwide. In particular, Arizona in the United States has been implementing and monitoring the noise reducing properties of AR open graded (also AR Friction Course or ARFC) mixes. Contemporaneously, in 1999, the Arizona Department of Transportation placed five different asphalt wearing courses as test sections on a highly trafficked Interstate 10 in southern Arizona. After a service life of twelve years, the ARFC has experienced the least cracking and wear, and exhibited as the quietest of the different pavement surfaces to date.

The purpose of this paper was to present the theoretical laboratory studies conducted on the field cores to characterize the acoustical properties of the different pavement materials, including: Arizona I-10 asphalt wearing courses; several pavement mixtures from Arizona, Sweden, and California; and two different non-asphaltic mixtures for comparison purposes.

Furthermore, the paper presents the concept of the development of a new and unique parameter to characterize acoustical properties of the different road materials; the parameter is referred to in this study as DAMP (Damping Acoustical Measurement Parameter).

The database utilized in this study included 36 laboratory pavement specimens and 49 field cores obtained from national and international pavement sections. A standard ultrasonic pulse velocity (UPV) test methodology actually used to estimate cracks in concrete was modified and made suitable to obtain the various acoustical properties for the different materials. The outcome of the UPV experiment was the ultrasonic pulse time (UPT) taken for the acoustic wave to traverse from one end of the sample to the other. UPV and impedance (Z) values were estimated with the help of sample length, UPT, and material density.

Damping Acoustical Measurement Parameter (DAMP), an acoustic parametric index was estimated mathematically as a power expression, which also directly related to the Z of a mix. It is important to note that volumetric mix properties of the pavement materials are correlated to the noise dampening properties of the different mixes, which was also the basis for developing the DAMP indices. DAMP values were calculated for all the different pavement materials under investigation.

ARFC had the lowest DAMP compared to all the other asphaltic mixtures. This was indicative of the finding that ARFC provided highest damping to acoustic wave propagation through the material in comparison to the other asphalt mixtures such as gap graded, dense graded, and other materials. Since Z and DAMP are directly related; lower the value of Z, lower is the value of DAMP. Although one can distinguish noise characteristics of the different materials using just the Z values, it is much easier to compare mathematically when the noise dampening parameter is of the order between a definitive and comparable value such as 1 and 10. Thus, in this study, impedance of the different materials was simplified using a unique mathematical parameter that is comprehensibly easier. In addition, when DAMP and air voids were correlated for each mix type, the reverse trend was observed, confirming one of the experts' opinions that air pockets in the materials aid in noise absorption / attenuation / dampening.

Another effort was undertaken to understand the influence of temperature on the acoustical properties of the asphalt mixtures. The Arizona I-10 mixtures were subjected to UPV technique at three different temperatures. A comprehensive scrutiny of the DAMP values indicated that with increase in temperature, there was a decrease in DAMP. This was confirmatory of the fact that asphalt mixtures exhibited a clear viscoelastic nature at higher temperatures. Thus, it was inferred that the role of the binder (along with the air voids) in the matrix plays a vital role in noise attenuation.

Overall, it was clear that ARFC had the lowest DAMP compared to the other mixtures, mainly due to the higher amount of binder than the other mixes and higher porosity (air voids) in the mix matrix.

Finally, three DAMP bands were created to represent each mix's unique noise characteristics. ARFC material was placed in the "Quiet" band since both laboratory and field noise investigations proved it to be the quietest pavement material to date. Since asphalt mixtures are viscoelastic, the rest of the different asphaltic materials that were not as quiet as ARFC were placed in the zone of noise lessening or "Perturbed" band. The PCC mix type, which has shown to be highly annoying to the human ear, was placed in the "Noisy" band that also had the highest DAMP values.

7. Bibliography

ASTM C597-02. Standard Test Method for Pulse Velocity through Concrete, 2002.

ASTM E494-05. Standard Practice for Measuring Ultrasonic Velocity in Materials, 2005.

Bernhard, R. J., and Wayson, R. L. (2005). "An Introduction To Tire/Pavement Noise", Final Report, SQDH 2005-1 HL 2005-2, Institute for Safe, Quiet, and Durable Highways, Purdue University, West Lafayette, IN, January 2005.

Biligiri, K. P. (2008). "Asphalt Mixtures' Properties Indicative of Tire / Pavement Noise", Ph.D. Dissertation, Department of Civil and Environmental Engineering, Arizona State University, December 2008.

Biligiri, K. P., and Kaloush, K. E. (2009). "Prediction of Pavement Materials' Impedance Using Ultrasonic Pulse Velocity", Journal of Road Materials and Pavement Design, Hermes Science Publications, France, Volume 10, Issue 4, 2009, pp. 767-787.

Biligiri, K. P., Kalman, B., and Samuelsson, A. (2011). “Understanding the Fundamental Material Properties of Low-Noise Poroelastic Road Surfaces”, International Journal of Pavement Engineering, Taylor & Francis (online: DOI:10.1080/10298436.2011.608798).

Carlson, D. D., Way, G. B., Zareh, A., Kaloush, K. E., and Biligiri, K. P. (2009). “Noise Characteristics and Field Performance of Five Different Wearing Courses in Arizona”, Asphalt Rubber 2009 Conference, Nanjing, China, 2-4 November 2009 (Conference Proceedings).

Donavan, P., and Rymer, B. (2003). “Measurement of tire pavement noise sound intensity methodology”, Asphalt Rubber 2003 Conference, Brasilia, Brazil, December 2003 (Conference Proceedings).

Gibbs, D., Iwasaki, R., Bernhard, R., Bledsoe, J., Carlson, D., Corbisier, C., Fults, K., Hearne, T., McMullen, K., Newcomb, D., Roberts, J., Rochat, J., Scofield, L and Swanlund, M. (2005). Quiet Pavement Systems in Europe, Report No. FHWA-PL-05-011, Submitted by American Trade Initiatives, Virginia, Sponsored by Federal Highway Administration, American Association of State Highway and Transportation Officials, USA, May 2005.

Kohler, E., Ongel, A., Harvey, J., and Rymer, B. (2007) OBSI Measurements at the UC Pavement Research Center, Presentation made at the Transportation Research Board Summer Meeting, San Luis Obispo, California, USA, July 22-25, 2007.

Rasmussen, R. O., R. J. Bernhard., U. Sandberg., and E. P. Mun. (2007). The Little Book of Quieter Pavements, Final Report, FHWA-IF-07-XXX, Federal Highway Administration and the Transtec Group, July 2007.

Sandberg, U and J. A. Ejsmont. (2002). “Tyre / Road Noise Reference Book”, INFORMEX, 2002.

Scofield, L (2000) Arizona’s Pavement Preservation Experiment, Arizona Department of Transportation, 2000.

Scofield, L. and P. Donavan (2003). Development of Arizona’s Quiet Pavement Research Program, Proceedings of Asphalt Rubber 2003, Brasilia, Brazil, December 2003 (Conference Proceedings).

Tsunokawa, K., and C. Hoban (1997). World Bank Technical Paper No. 376, Roads and the Environment, A Handbook, The World Bank, Washington, D. C., 1997.