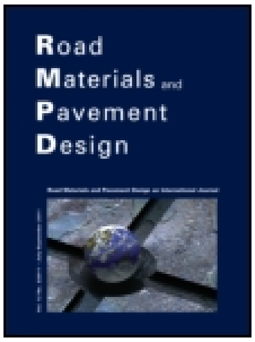

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Noise-damping characteristics of different pavement surface wearing courses

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The purpose of this research investigation was to conduct field and laboratory noise evaluation of 36 laboratory-blended and 49 field pavement cores encompassing 11 pavement types collected from Arizona and California in the USA and Sweden in Europe mainly to characterise their acoustical properties. Furthermore, a new and unique parameter referred to as damping acoustical measurement parameter (DAMP) was conceptualised and developed as part of this study to characterise noise-damping properties of the different road materials. Laboratory acoustical evaluation was performed on the samples covering nine conventional and modified asphalt and two non-asphaltic mixtures using the ultrasonic pulse velocity technique and Impedance (Z) was estimated. DAMP was established for the mixes which were inversely related to Z. Theoretically, lower Z and higher DAMP exemplified higher noise-damping capacity of the pavement. Amongst the asphaltic mixes, asphalt rubber friction course had the highest DAMP (~20%) compared to the other mixes indicative of being the quietest pavement material, also confirmative of the field noise measurement findings. Within the non-asphaltic mixtures, poroelastic road surface showed the highest DAMP (37%), while Portland cement concrete exhibited the lowest DAMP (12%).

Keywords: tyre/pavement noise; ultrasonic; damping; acoustical parameter; DAMP

1. Introduction

Global urbanisation has myriad benefits relevant to infrastructure such as design and building of new structures, generation of jobs, improvement in quality of life standards, and so forth; however, with all these developmental changes, it creates a necessity to focus on the environmental sustainability from materials and energy perspective. Amongst the many effects, one of them is the traffic noise that embodies both materials and environment aspects as related to quality of life issue. Traffic noise in urban areas, particularly, in the neighbourhoods of highways and arterial roads has become a growing problem for residents in the vicinity. Furthermore, a weighty increase in traffic volume will continue to add more noise pollution that can affect human welfare in varying degrees, both physiologically and psychologically (Tsunokawa & Hoban, 1997).

Construction of sound barrier walls along the city freeways has been one of the alternatives to reduce highway traffic noise. But, typical noise barrier walls cost around US$1–2 million/mile (Gibbs et al., 2005). Thus, the wider use of "quieter" roads (pavements) has not only become a better mitigation strategy in reducing the overall noise exposure to counter the high cost of noise barriers, but also as an important "quality of life interest" concern (Donavan, 2009).

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Several studies have indicated that tyre/pavement interaction noise contributes significantly to the overall roadway traffic noise, mainly at vehicle speeds greater than 40 km/h (Bernhard & Wayson, 2005; Donavan & Rymer, 2003). A multitude of factors influences tyre/pavement noise such as the pavement material type and property, age of the pavement, thickness, friction, porosity, etc. (Biligiri, 2008; Biligiri, Kaloush, & Uzan, 2010; Rasmussen, Bernhard, Sandberg, & Mun, 2007; Sandberg & Ejsmont, 2002; WRI, 2007). Furthermore, aggregate texture, which potentially illustrates unevenness in the pavement surface, has been found to affect noise generation (Ongel, Kohler, Lu, & Harvey, 2008a; Sandberg & Ejsmont, 2002); Sandberg and Ejsmont (2002) provide a comprehensive outlook as follows. The texture at wavelengths of about 10–500 mm affects the basic excitation of the tyre casing and the radiation of noise below 1000 Hz. In this range, increased texture will increase noise levels. In the next level of 0.5–10 mm, air pumping is predominant and the greater the texture wavelength, the lower the noise from air pumping. Very small wavelength texture will affect adhesion and friction but it is not clear whether this has more than a small to moderate effect on noise levels.

In the case of a flexible pavement such as an asphalt concrete mixture, the viscoelastic property has been found to be one of the main factors influencing tyre/pavement noise (Biligiri et al., 2010; Biligiri & Kaloush, 2010). The study also concluded that open-graded asphalt rubber friction course (ARFC) mixes reduce tyre/pavement noise in comparison with the other bituminous surfaces because they act as acoustic absorbers owing to the increased viscoelastic nature of the ARFC mix. The increased viscoelastic characteristics of an ARFC come from much higher bitumen content (9–10% by weight of the total mix) and, possibly, the inclusions of crumb rubber (20% by weight of the binder). Other studies in California, USA investigated the effects of a few other important pavement characteristics such as porosity, aggregate properties, rubber inclusions, texture, age, etc. on the measured field noise levels providing a relationship between those properties with frequency-related acoustic impact and shock mechanisms (Lu, Harvey, Kohler, Rymer, & Motumah, 2011; Ongel & Harvey, 2010; Ongel, Kohler, & Harvey, 2008b). As part of those studies, compared with conventional asphalt mixes of the same age, rubberised asphalt concrete surface courses had lower tyre/pavement noise levels by about 2–3 dB. Earlier studies by (Descornet & Sandberg, 1980; Morgan, Nelson, & Steven, 2003; Ongel et al., 2008b) have identified surface characteristics such as cracking as a major contributor to noise. Furthermore, Losa et al. developed the empirical models to relate texture levels of different low-noise asphalt pavement surfaces and their rolling noise levels (Losa, Leandri, & Bacci, 2010). The models were defined by the noise levels based on a reference tyre as a function of speed for dense and semi-porous asphalt surfaces. In a separate study, Wu, Lee, Du, & Shen (2010) considered many different material properties and developed a model to predict noise levels of asphalt mixes using the laboratory and field noise tests based on the grey system approach. The model predicted sound absorption coefficient and tyre/road noise, which was further evaluated using the statistical analyses. In an attempt to understand the changes of noise levels due to the durability of dense and porous asphalt surfaces from moisture-related properties, researchers from Portugal utilised the Statistical Pass-By field noise measurement technique and found that noise level increased considerably with the presence of water by about four decibels (Freitas, Pereira, Picado-Santos, & Santos, 2009). Also, the study concluded that very limited benefits are found with porous asphalt for heavy vehicular traffic.

The State of Arizona in the USA has been successful in utilising variants of asphalt rubber (AR) since the late 1980s for the purpose of not just alleviating pavement distresses but also in reducing tyre/pavement noise. Also, 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 Programme (QPP) to monitor the noise-reducing properties of AR open-graded (also ARFC) mixes in the Phoenix metropolitan area.

Concurrently, in 1999, the ADOT placed five different asphalt surface wearing courses as test sections on Interstate 10 (I-10), a highly trafficked highway in Arizona. After a service life of 13 years, the ARFC has experienced the least cracking and wear and has exhibited as the quietest of the five pavement surfaces to date.

However, understanding the theory behind the acoustical characteristics (or parameters) of the different pavement surface courses and its relationship to actual field noise-damping properties needs a scientific approach. The fundamental scientific noise-damping parameters that aid in noise generation and attenuation in the different pavement materials is not fully understood. A careful understanding of the basic noise-damping principles of the various road surfaces would lead to an analogy where the acoustic wave traversing the roadway surface and generating noise in a pavement system as a functional characteristic is associated with pavement structural characteristics such as distresses capable of storing (mass storage capacity) and dissipating (damping or magnifying capacity) acoustical energy.

The main purpose of this study was to conduct the field and laboratory noise evaluation of both laboratory-blended and field pavement cores covering 11 different pavement surface course materials. The different materials included: (i) field cores from Arizona I-10 asphalt wearing courses, (ii) several laboratory-blended sample mixes and field cores from Arizona and California in the USA, (iii) laboratory mixes from Sweden in Europe, and (iv) two different non-asphaltic mixtures for comparison purposes. Also, in this study, a new and unique parameter to characterise acoustical properties of the different road surface course materials was conceptualised and developed. The unique parameter was established based on the fundamental pavement material components inherently related to volumetrics of the mixes. The research scope of work included:

- Identify field test sections with a variety of road surfaces that could be used for the potential field noise evaluation and pavement surface characterisation assessment.
- Collect field core and laboratory-blended (prepared) samples of the different variants of pavement types, which are typical of those regions at national and international levels.
- Assemble and document the mixture material properties and field noise measurements of those pavement types acquired from both field and laboratory.
- Conduct a laboratory experimental programme to measure fundamental acoustical parameters for field and laboratory mixtures with known and/or measured field noise characteristics.
- Establish an acoustic parametric index unique to each pavement type using mathematical relationships, which are fundamentally based on the road mixture's volumetric properties.
- Understand the sensitivity of the established unique acoustic parametric index of each pavement type with respect to material properties influencing noise such as air voids and temperature.
- Create noise-distinguishing bands for the different pavement materials, which will categorise and quantify the road types based on their noise-damping capacities.

2. Mixtures and experimental programme

The database utilised in this study included 36 laboratory pavement specimens and 49 field cores obtained from national and international pavement sections as follows.

- ADOT, USA
- Arizona State University (ASU), USA
- University of California Pavement Research Center (UCPRC), USA
- California Department of Transportation (CALTRANS), USA

- Swedish National Road and Transport Research Institute (VTI), Sweden
- Swedish Transport Administration (STA), Sweden

The descriptions of the various pavement mixtures' databases used for the laboratory noise evaluation in this study are documented next.

2.1. *ADOT I-10 wearing course experiment database (2002–2011)*

ADOT conducted a preventative maintenance pavement preservation experiment on I-10 in Arizona during the year 1999 (Scofield, 2000). As part of this experiment, 32 test sections with replicate cells were constructed constituting five asphalt concrete pavement surface wearing courses' types. In 2008, the annual daily traffic was about 60,000 with 25% trucks and the total equivalent single axle loads was about 26 Million (Zareh, 2008). Pavement ride quality, friction numbers, rutting, and per cent cracking at each MP were also recorded in the pavement management system database. The five different pavement types under the study were:

- ADOT I-10 – permeable European mix (PEM)
- ADOT I-10 – stone matrix asphalt (SMA)
- ADOT I-10 – asphalt rubber open-graded friction course (ARFC or AR-ACFC)
- ADOT I-10 – polymer modified open-graded friction course (P-ACFC)
- ADOT I-10 – ADOT's standard open-graded friction course (ACFC)

Table 1 gives the surface wearing course material properties used in the study, including: aggregate size gradation, bitumen content, and type of bituminous binder Performance Grade. The salient features of the surface wearing courses of the I-10 experiment were as listed below.

- Highest bitumen content used was used in the ARFC mix (~9.2%)
- Polymer type used in the P-ACFC mix was Styrene-Butadiene-Styrene (SBS)
- Wearing course thicknesses were 19 mm for four mix types except for the PEM whose surface thickness was 32 mm
- Each wearing course was supported by three structural layers beneath it
- Design life for each pavement system: 12–15 years

Noise measurements on the five different wearing courses comprising of 32 test sections were conducted using the on-board sound intensity (OBSI) method during the fall of 2002 by the ADOT team as part of the Arizona's QPP (Scofield & Donavan, 2003). In late 2007, ADOT

Table 1. Binder and mixture properties of Arizona I-10 wearing course experiment test sections.

Size	ARFC	ACFC	P-ACFC	PEM	SMA
19 mm (3/4″)	100	100	100	100	100
12.5 mm (1/2″)	100	100	100	80–90	100
9.5 mm (3/8″)	100	100	100	35–60	70–90
4.75 mm (no. 4)	30–45	35–55	35–55	10–25	30–50
2.36 mm (no. 8)	4–8	9–14	9–14	5–10	20–30
0.075 mm (no. 200)	0–2.5	0–2.5	0–2.5	0–2.5	8–13
Bitumen content (%)	9.2	6.0	6.0	6.0	6.5
Performance grade binder	PG 76-22+	PG 64-16	PG 76-22+	PG 76-22+	PG 76-22+

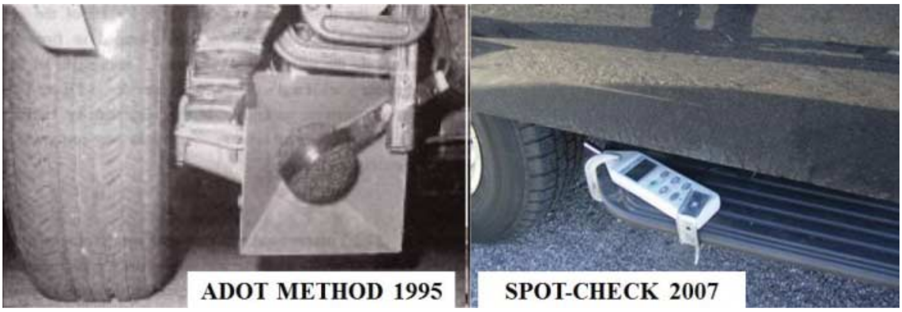

Figure 1. Tyre/pavement interface close-proximity noise measurement techniques: (a) ADOT in 1995 (left) and (b) ASU team using noise meter near the running board of the van on Arizona I-10 sections (right).

in conjunction with the Rubber Pavement Association and ASU performed spot check highway noise measurements on these 32 test sections (Carlson, Way, Zareh, Kaloush, & Biligiri, 2009). The 2007 noise measurements were not performed using the OBSI technique. Rather, a hand held noise meter was attached to the running board of a van, in such a way that the noise meter was in close proximity to the tyre/pavement interface as shown in Figure 1 (shown on right: SPOT-CHECK 2007). This was a similar technique that was used in Arizona in the early 1990s to measure the tyre/pavement noise as shown in the figure (shown on left: ADOT METHOD 1995). The sound meter was calibrated to measure the sound pressure in the range of 80–130 dB, which is an appropriate range of noise measurements in the field. A computer was connected to the sound meter to store the data. Stored data were transferred to a computer via an RS-232 interface and analysed using the system software. The total time taken for one full run on the 32 test sections depended on the speed of the test vehicle. Four runs were performed at three different speeds: 96, 116, and 120 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 96 km/h (Kohler, Ongel, Harvey, & Rymer, 2007). These measurements were part of a California–Arizona highway noise study indicated in (Caltrans, 2006).

Figure 2 shows a comparison of noise measurements performed by three different research teams on these test sections for the years: 2002, 2007, 2008, and 2011. As observed, the least noise observed at all time-scales and measurements is for the ARFC surface type. Furthermore, this noise-reading difference also contemporaneously agreed with the visual distress observations made in 2007 and 2011. Several sections that exhibited higher noise had greater amount of ravelling and cracking distresses. 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 96 km/h were taken using a handheld noise meter inside the car unlike the other measurement methods used previously only to get trends of the noise-damping properties of the different surfaces. As shown in 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 were 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 even after more than a decade of service, while the other test sections showed considerable to significant cracking and wear as shown in Figure 3.

It must be noted that the noise values in 2011 were significantly different in terms of magnitude in comparison with the other years as the measurement method used in 2011 was an un-calibrated

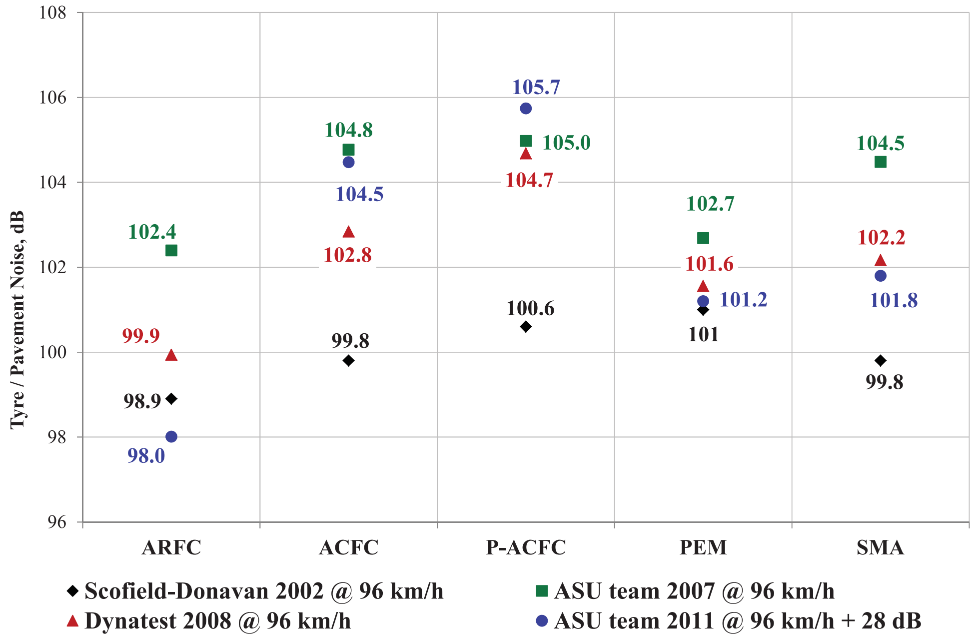

Figure 2. Noise measurements for Arizona I-10 test sections: 2002, 2007, 2008, and 2011.

handheld noise meter inside the car. Thus, the magnitude of noise readings in 2011 shown in Figure 2 reads ASU team 2011 96 km/h + 28 dB. The explanation of the shift in the noise values is described as follows. The original noise values were in the range of 70–78 dB measured using the handheld noise meter. For the five Arizona I-10 test sections, when a relationship between the readings of Dynatest 2008 (using OBSI) and ASU team 2011 (using handheld noise meter) was drawn, Figure 4 was obtained. A trend line relationship was obtained which is also shown on the figure with an excellent coefficient of determination, $R^2 = 94\%$. Furthermore, the average offset between the data was 28 dB, a value within the range of 27–29 dB for the second harmonic frequency range as indicated by (Donavan & Lodico, 2009), assuming that the frequency for the OBSI measurements was taken at around 800 Hz. In addition, a linear 1-1 fit line was also plotted with a slope equal to 1, which represents the best fit of the data relationship. It is also noteworthy that the standard deviation of the data points from the best 1-1 fit of the data is 0.72 dB, while the average deviation for actual data was 1.39 dB. The reason for this kind of change in the standard deviations between the 1-1 fit and actual data is that the slope of the regression indicates a more than 1-1 relationship. Regardless of the method used during the last 12 years, the noise measurement trends for each Arizona I-10 surface wearing course mix type were extracted and assembled in this study. Overall, the measured noise levels for each asphalt mix were related to the degree of surface deterioration.

2.2. *ASU–ADOT studies database (2004–2008)*

The ASU–ADOT database consisted of laboratory prepared samples from field mixtures obtained from different sites in Arizona. Three different asphalt mixes including one conventional and two types of crumb rubber modified mixtures were prepared for the acoustical evaluation. The three

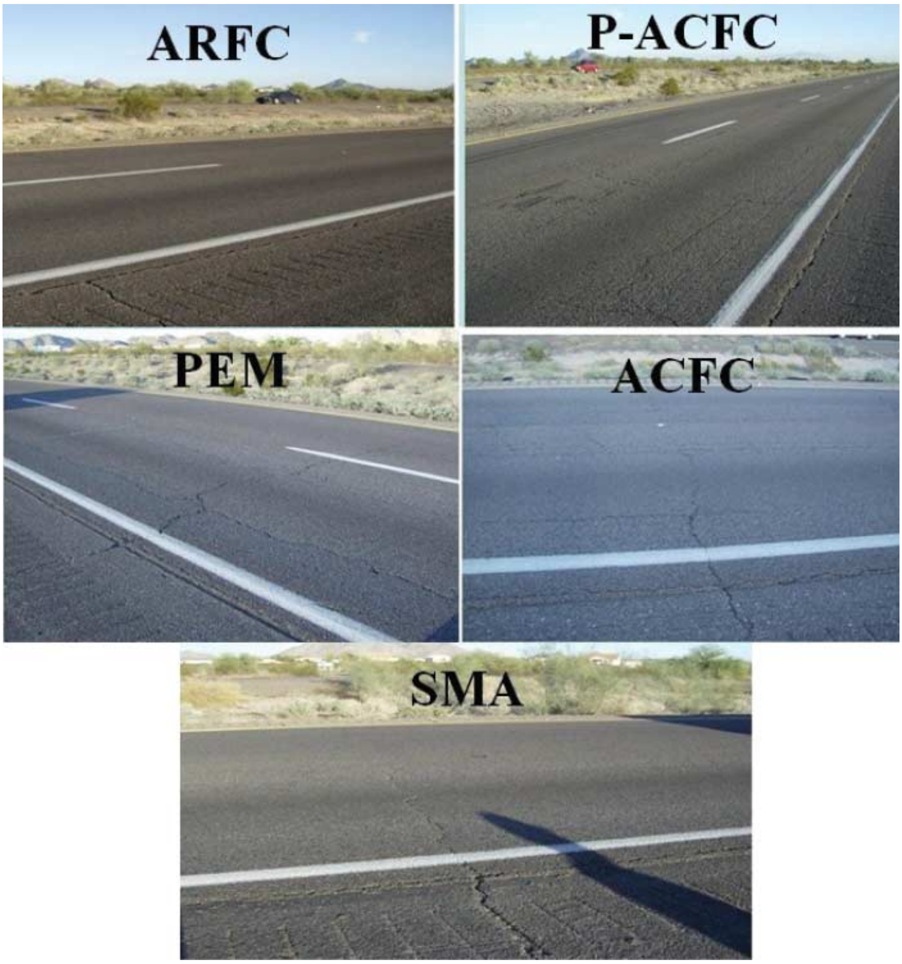

Figure 3. Illustration of 2011 pavement surface deterioration of Arizona I-10 wearing courses after 12 years of service.

asphalt mixtures under investigation included:

- ADOT – conventional dense graded asphalt concrete (DGAC)
- ADOT – asphalt rubber asphalt concrete (ARAC; AR gap graded)
- ADOT – ARFC (AR open graded)

2.3. *ASU – California studies database (2007–2008)*

In fall 2007, UCPRC in conjunction with CALTRANS sent 19 bituminous concrete samples to ASU covering six different asphalt pavement types for the laboratory noise evaluation study as listed below.

- UCD – DGAC
- UCD – rubberised asphalt concrete, gap graded (RAC-G)
- UCD – rubberised asphalt concrete-open graded F (RAC-O-F) mix

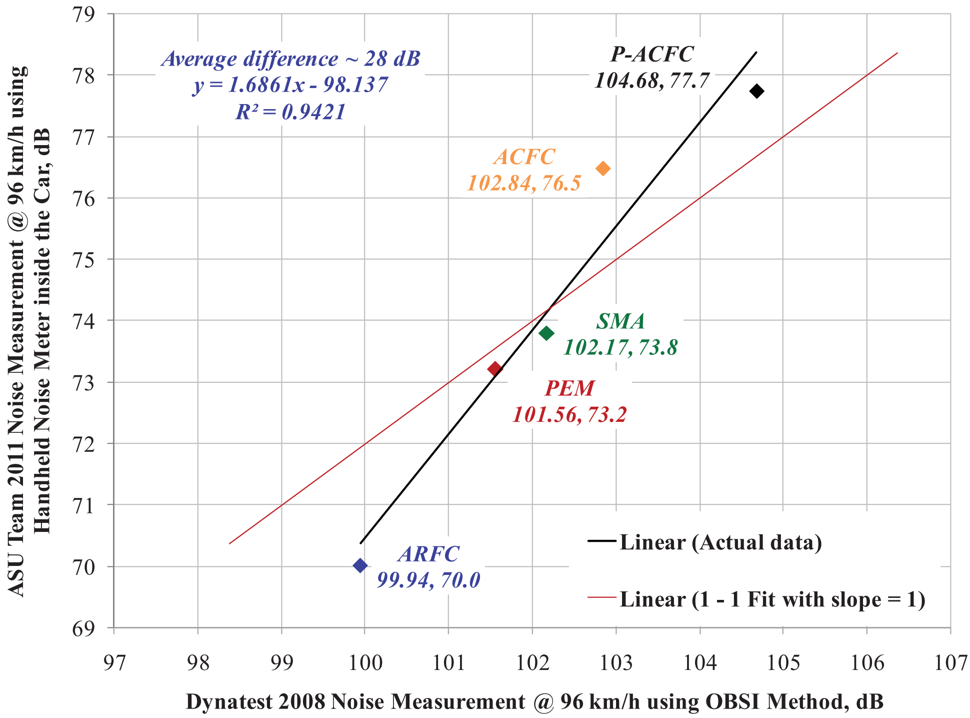

Figure 4. Relationship between ASU Team 2011 noise measurement using handheld noise meter inside the car and Dynatest 2008 noise measurement using the OBSI method, both at 96 km/h, dB.

- UCD – open-graded asphalt concrete (OGAC)
- UCD – EU gap graded: European gap graded
- UCD – RAC-O

2.4. *ASU – Swedish database (2007–2008)*

Along with the various mixes of Arizona and California in the USA, ASU received a variety of non-conventional bituminous mixtures from Sweden in Europe for the laboratory noise evaluation studies. In this study, the asphalt mix types included gap-graded and open-graded mixtures, with and without rubber modification from two different Swedish research and transport agencies. Thirteen laboratory-blended gap- and open-graded mixtures were part of VTI–ASU collaboration and two types of gap-graded mixtures with and without rubber modification from an actual Swedish project E-06 highway site were part of STA–ASU joint venture. Note that a full suite of advanced mixture characterisation laboratory tests along with the noise evaluation tests were performed on the STA–ASU gap-graded mixtures to understand the various material and damping properties. The various mix types used in this study for noise evaluation purposes included:

- VTI – open-graded asphalt rubber types 1 (OGAR1) and 2 (OGAR2)
- VTI – OGAC (without rubber)
- VTI – gap-graded asphalt rubber types 1 (GGAR1) and 2 (GGAR2)
- VTI – gap-graded asphalt concrete types 1 (GGAC1) and 2 (GGAC2) (without rubber)
- STA – E-06 – GGAC (without rubber)
- STA – E-06 – GGAR

3. Background to ultrasonic pulse velocity test

All the samples documented previously in Section 2 were subjected to the laboratory noise evaluation using ultrasonic pulse velocity (UPV) technique. The theory and methodology of the experimental technique are published elsewhere (Biligiri & Kaloush, 2009). Only a brief description of the test procedure and analysis is provided here. The non-destructive UPV technique is based on the measurement of wave velocities through the material as described in the American Society for Testing and Materials (ASTM) International standards (ASTM C597-02, 2002; ASTM E494-05, 2005). In the laboratory, the UPV is calculated as a ratio of the measured path length to the measured pulse time. That is,

$$v = \frac{L}{T}, \tag{1}$$

where v = UPV through the material (m/s), L = distance between centres 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 pavement surface materials. Ultrasonic testing of materials (sample cores) utilised 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. With the estimated UPV, one can calculate the impedance (Z) of the material:

$$Z = \rho^* v, \tag{2}$$

where Z = impedance (cgs Rayls), ρ = density of the material (kg/m^3), v = UPV through the material (m/s).

The sensitivity of the acoustical parameters obtained during the test and the mixture properties such as air voids, gradation type, and mix type have been published in (Biligiri, 2008; Biligiri & Kaloush, 2009). It is important to note that no literature exists that correlates mixture properties to impedance and/or other acoustical properties except the modest studies reported by Biligiri (2008).

4. Damping acoustical measurement parameter

Damping acoustical measurement parameter (DAMP), an acoustic parametric index, was devised and established mathematically as a power expression to obtain noise-damping values of the different pavement surface materials between the finite values of 1% and 100%. Although one can distinguish noise characteristics of the different materials using the impedance (Z) values that are easily obtained from the UPV tests (Section 2, Equation (2)), it is much easier to compare mathematically when the noise-damping parameter is of the order between the definitive and comparable values in the range of 1–100%. Thus, in this study, Z of the different materials was simplified using a unique mathematical parameter that is comprehensibly easier. Thus, DAMP was inversely related to the acoustic flow resistivity (Z) of a mix and expressed as:

$$\text{DAMP (\%)} = 100\left(\frac{100}{Z}\right)^{0.4}. \tag{3}$$

Note: 1 (no to low damping) $\leq$ DAMP (%) $\leq$ 100 (high to complete damping).

The mathematical basis for devising such a relationship was purely based on obtaining the values of noise-damping characteristic of materials as a per cent damping parameter within a discrete (finite) zone. For example, a value of $Z = 100$ cgs Rayls (very soft material) would yield a DAMP equal to 100% and a value of $Z = 10^7$ cgs Rayls (very hard material) would produce a DAMP equal to 1%. Since Z and DAMP are inversely related, lower the value of Z, higher is the value of DAMP and hence, higher is the noise-damping or acoustic absorption capacity of the pavement material under investigation. It is important to note that the volumetric mix properties such as the density (or specific gravity), air voids (porosity), bitumen content, aggregate properties in the mixture, and modifiers such as crumb rubber inclusions in the different pavement materials are inherently correlated to the noise-damping properties of the different mixes, which formed the theoretical basis for developing the DAMP indices.

4.1. *DAMP of road surface wearing course variants*

DAMP values were estimated using Equation (3) for the different pavement surface wearing courses presented previously. Table 2 gives DAMP of the different pavement surface course

Table 2. DAMP estimations, different pavement surface course variants.

Mix	AV (%)	AC (%)	UPV (m/s)	ρ (kg/m^3)	Z (cgs Rayls)	DAMP (%)
PERS	37.08	0	898	1.34	1184	37.31
ARFC	17.44	8.48	2818	2.11	5832	19.67
P-ACFC	20.96	6.00	2988	2.01	5891	19.58
PEM	17.14	6.00	3316	2.07	6738	18.56
OGAC	17.52	7.75	3576	2.03	7088	18.31
ACFC	13.80	6.00	3391	2.19	7339	17.94
SMA	9.65	6.50	3566	2.13	7452	17.83
ARAC	9.04	7.47	3544	2.24	7786	17.57
GGAC	7.25	6.67	3786	2.29	8494	16.95
DGAC	5.19	4.96	3941	2.32	8963	16.58
PCC	1.85	0	7721	2.65	20,052	12.00

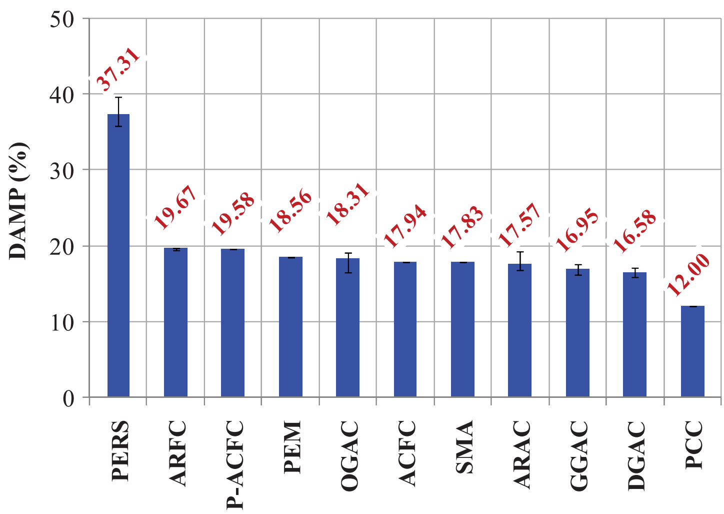

Figure 5. Average DAMP (%) for the different pavement surface course types.

variants. The Table also gives mixtures' air voids or porosity (AV %), bitumen content (AC %), material density ρ, and the estimated UPV and 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 (2013) project. PERS mix presented in this study had about 9% (ground tyre) rubber content by weight of the mix, high porosity in the order of 37–40%, and bound by a non-asphaltic binder (Biligiri, Kalman, & Samuelsson, 2013). Portland cement concrete (PCC), another non-asphaltic material was also compared for its acoustical properties with respect to the other mixtures under investigation.

Figure 5 shows a pictorial representation of the average DAMP for the different mixtures, including the minimum and maximum values (shown as error bars) as applicable. As observed

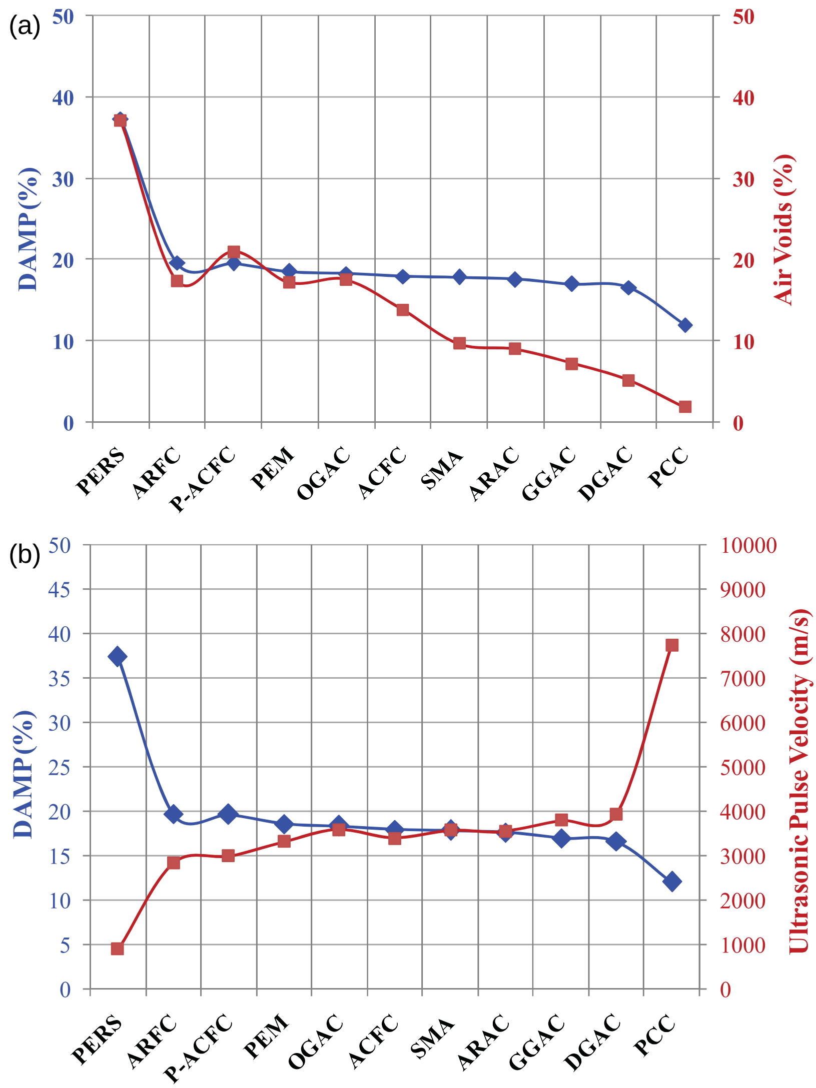

Figure 6. For different pavement surface course types, average DAMP (%) vs.: (a) air voids (%) and (b) UPV (m/s).

(from Table 2 and Figure 5), PERS mix provided the highest DAMP (37%), while PCC had the lowest DAMP (12%). In the group of asphaltic mixtures, ARFC had the highest DAMP (20%) compared to the other mixes. This is 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 and conventional dense-graded materials. Overall, ARFC was the quietest pavement material, also confirming the various past field studies.

In addition, when DAMP and air voids (%) were correlated for each mix type, a direct trend (i.e. higher the air voids, higher the DAMP) was observed as shown in Figure 6(a). It showed that air pockets in the materials also aid in noise absorption/attenuation/damping. DAMP and UPV were related as shown in Figure 6(b). Since UPV and Z are directly related and Z and DAMP are inversely related, the lower the value of UPV, the higher was the DAMP for the different materials. If the acoustic wave traverses through the material at a higher velocity, the material impedes the absorption of noise and hence the material has lower noise-damping capacity (also lower DAMP). In the case of porous materials such as open-graded PERS or ARFC, noise damping is mainly attributed to their softer characteristics, open-graded gradation (having large

Table 3. DAMP estimations at three temperatures, Arizona I-10 wearing course types.

					4°C		21°C		38°C	
Mix type	Sample ID	AV (%)	AC (%)	ρ (kg/m^3)	Z (cgs Rayls)	DAMP (%)	Z (cgs Rayls)	DAMP (%)	Z (cgs Rayls)	DAMP (%)
ARFC	7A	20.44	9.1	2.096	5340	20.37	4778	21.30	4669	21.49
	7B	21.10	9.1	2.078	6402	18.94	5649	19.92	5462	20.19
	8A	19.99	9.1	2.108	6015	19.42	5913	19.56	5627	19.95
	8B	20.87	9.1	2.085	7443	17.84	5770	19.75	5575	20.02
	9A	18.68	9.1	2.142	7272	18.00	5778	19.74	5407	20.27
	9B	20.04	9.1	2.106	7146	18.13	6635	18.67	5283	20.46
P-ACFC	2A	15.81	6	2.071	6871	18.42	6401	18.94	6241	19.14
	2B	15.50	6	2.079	6885	18.40	6622	18.69	6560	18.76
	4A	20.21	6	1.963	5569	20.03	5055	20.82	4672	21.49
	4B	19.50	6	1.980	6230	19.15	5791	19.72	5633	19.94
	6A	18.90	6	1.995	7011	18.27	6244	19.13	6148	19.25
	6B	20.06	6	1.967	5735	19.80	5234	20.53	5183	20.61
PEM	3A	15.41	6	2.078	7773	17.53	6446	18.89	6318	19.04
	3B	14.85	6	2.092	6544	18.78	6544	18.78	6544	18.78
	1A	16.35	6	2.056	7367	17.91	6581	18.74	5983	19.46
	1B	12.73	6	2.145	7917	17.40	7488	17.79	7076	18.20
	5A	17.04	6	2.039	6590	18.73	5958	19.50	5877	19.60
	5B	17.44	6	2.029	7933	17.39	7411	17.87	6144	19.26
ACFC	10A	7.34	6	2.277	8772	16.70	7017	18.26	6865	18.42
	10B	10.06	6	2.210	9334	16.29	8349	17.04	8212	17.15
	11A	3.75	6	2.365	10712	15.42	9756	16.01	8956	16.56
	11B	6.52	6	2.297	9162	16.41	8159	17.19	7932	17.39
	12A	17.42	6	2.029	7851	17.46	5447	20.21	4801	21.26
	12B	20.52	6	1.953	7110	18.17	5308	20.42	4958	20.98
SMA	13A	11.98	6.5	2.080	8764	16.71	8100	17.24	7529	17.75
	13B	8.66	6.5	2.158	8785	16.69	7342	17.93	6929	18.35
	14A	7.29	6.5	2.190	9624	16.09	8567	16.86	7874	17.44
	14B	8.00	6.5	2.174	6245	19.13	5498	20.13	5084	20.77
	15A	11.13	6.5	2.100	8299	17.08	7786	17.52	7884	17.43
	15B	10.85	6.5	2.106	8557	16.87	7416	17.86	7302	17.97

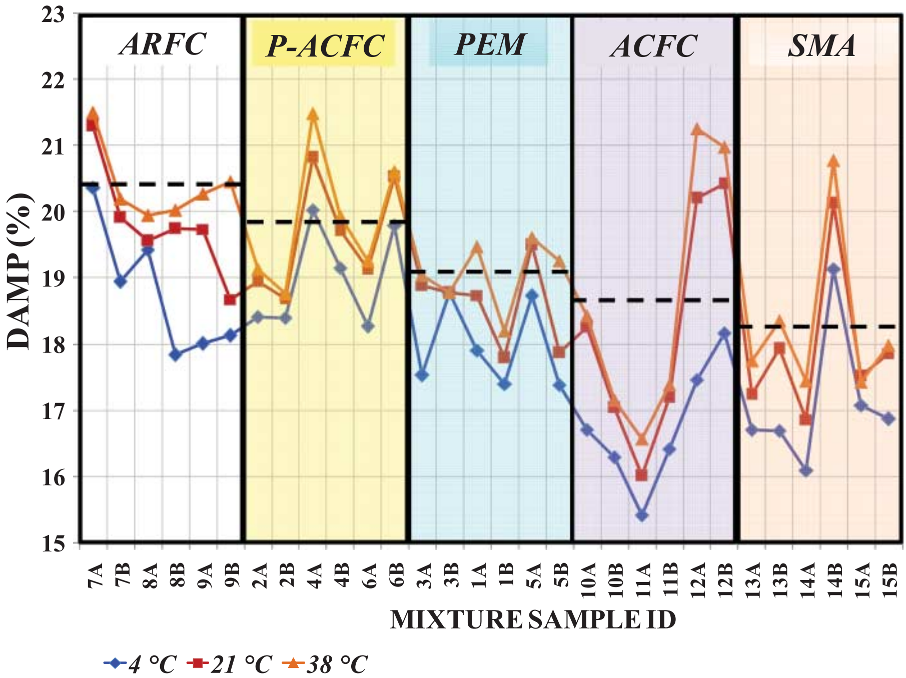

Figure 7. DAMP (%) for the Arizona I-10 wearing course at three temperatures.

proportion of one-sized aggregates in the mix's skeleton), and higher air voids which aid in absorbing significant amount of acoustical energy.

4.2. *Effect of temperature on DAMP*

Since DAMP for the different materials is inherently related to the mixture properties, another effort was undertaken to understand the influence of temperature on the acoustical properties of the different asphalt mixtures that are fundamentally viscoelastic in nature. To understand the effect of temperature on DAMP, the five Arizona I-10 mixtures were subjected to the UPV technique at 4°C, 21°C, and 38°C. Table 3 gives the estimated DAMP for the five wearing courses at three temperatures. The Table also includes air voids, asphalt content, density, and impedance estimations for each sample within each mix type. A comprehensive scrutiny of DAMP indicated that with an increase in temperature, there was an increase 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 mobilisation 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 highest DAMP on average compared to the other mixtures at all temperatures, mainly due to a high amount of binder (3% higher than other mixes) and a high porosity (air voids) in the mix matrix. Figure 7 shows DAMP for the five different Arizona I-10 wearing courses at three temperatures. The Figure also shows the average DAMP lines for the mixtures at 38°C (represented by black dashed line for each mix); this temperature was so chosen because the asphalt mixtures show predominately higher viscous behaviour at higher temperatures. As observed in the figure, on average, DAMP for ARFC, P-ACFC, PEM, ACFC, and SMA at 38°C were 20.4, 19.86, 19.06, 18.63, and 18.29, respectively.

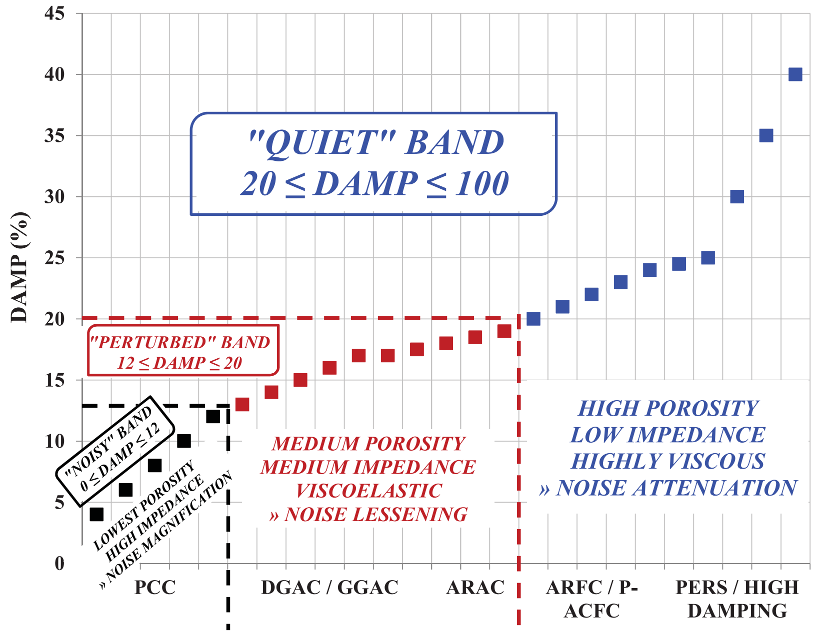

Figure 8. DAMP noise-distinguishing bands for the different pavement surface course materials.

4.3. *DAMP noise-distinguishing bands*

Figure 8 shows DAMP noise-distinguishing bands for all the different pavement surface course materials used in this study. As observed, three DAMP bands were created which represent three unique noise characteristics. ARFC material was placed in the "Quiet" band since both laboratory (DAMP value) and field (actual readings) noise investigations indicated that it was the quietest pavement material till 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. However, the PCC mix type, which has shown to be noisier than the asphalt mixes by more than 10 dB, was placed in the "Noisy" band that also had the lowest DAMP. PERS, a pavement surface course that is under development is also shown in the "Quiet" band as it had the highest DAMP amongst all the mixtures estimated from the laboratory UPV tests. In fact, PERS was placed further extreme in the "Quiet" band even before the current quietest pavement material ARFC as it is expected that this material could be quieter than ARFC in the field owing to a high porosity and much softer characteristics. The mix material properties are also shown in the figure for complete understanding of the DAMP bands.

5. Conclusions

The main purpose of this research investigation was to conduct the field and laboratory noise evaluation of 11 different types of pavement surface course materials to characterise their acoustical properties, including: field cores from Arizona I-10 asphalt wearing courses; several laboratory-blended sample mixes and field cores from Arizona and California in the USA and laboratory mixes from Sweden in Europe; and two different non-asphaltic mixtures for comparison purposes.

Furthermore, a new and unique parameter referred to as DAMP was developed mainly to characterise fundamental acoustical properties of the different road surface course materials.

Based on the findings of the study, the following conclusions are made:

- *Field noise measurements at 96 km/h* were recorded on a highly trafficked highway in Arizona, USA, which included five pavement surfaces. Apart from the authors' field noise evaluation experiments in 2007 and 2011, measurements were also conducted in 2002 and 2008 using the OBSI method, respectively, by ADOT and Dynatest. In all the years, ARFC was the quietest; furthermore, the surfaces which exhibited higher noise had greater amount of ravelling and cracking distresses. Field cores were sampled from these sections for the laboratory acoustical evaluation.
- *Laboratory acoustical evaluation using UPV* was performed on 36 laboratory-blended and 49 field pavement cores covering 11 different pavement types using the UPV technique; UPT, UPV, and Z were estimated. Overall, the correlations between tyre/pavement noise levels and laboratory calculated Z for each of the field mixtures were excellent and rational and lower Z was indicative of lower field tyre/pavement noise level.
- *DAMP* of the different materials was inversely related to the Z a mix. Amongst all the surface course variants used in the study, PERS provided the highest DAMP (~37%), while PCC had the lowest DAMP (12%). In the group of asphaltic mixtures, ARFC had the highest DAMP (~20%) compared to the other mixes. In the case of porous materials such as PERS or ARFC, noise damping was mainly attributed to their softer characteristics, open-graded gradation, and higher air voids which aid in absorbing significant amount of acoustical energy.
- *Sensitivity of DAMP to air voids, UPV, and temperature*: When DAMP and air voids were correlated for each mix type, a direct relationship was observed between the two parameters. When DAMP and UPV were compared, a lower UPV illustrated higher DAMP. It is noteworthy that if the acoustic wave traverses through the material at a higher velocity, the material impedes noise absorption and hence the materials will have lower DAMP. DAMP vs. increasing temperature relationship indicated an increase in DAMP for the Arizona I-10 asphalt mixtures at 4°C, 21°C, and 38°C indicative of asphalt mixtures' viscoelastic nature and softness due to asphalt binder.
- *DAMP noise bands* for the pavement surface types were created which represented three unique noise characteristics, namely, Quiet, Perturbed, and Noisy bands. ARFC was placed in the "Quiet" band since both laboratory (DAMP) and field noise investigations indicated that it is the quietest pavement material till date. Since asphalt mixtures are viscoelastic, the rest of the asphalt variants were placed in the zone of noise lessening or "Perturbed" band. PCC, which has shown to be noisier than asphalt mixes by about 8–10 dB in actual practice, it was placed in the "Noisy" band that also had the lowest DAMP. PERS, a surface course under development was placed in the "Quiet" band as it had the highest DAMP amongst all the mixtures.
- *Future scope of research*: Apart from the relationships developed between the different damping parameters, a major contribution of this study was to investigate the mutual connection between DAMP and the pavement material properties. It is very important to note that DAMP bands genuinely determine the position of the physical noise properties of the commonly available pavement mixtures. The study depicted that DAMP is consequential of field tyre/road noise characteristics. However, efforts must be made to test additional pavement materials' variants and use the UPV test method described to devise noise-reducing road surfaces. Also, a technique and/or standard must be produced that describes how to conduct the simple laboratory UPV test illustrated in this research study and obtain noise-damping acoustical parameters of interest.

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