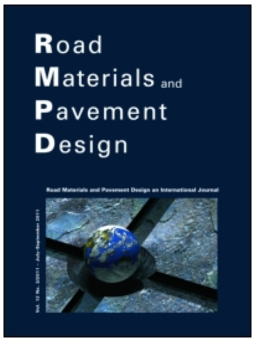

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Prediction of Pavement Materials' Impedance Using Ultrasonic Pulse Velocity

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ABSTRACT. *There are many factors that influence tire/pavement noise such as road friction and acoustic absorption as well as pavement texture. Highway noise is addressed through several models such as Traffic Noise Model (TNM) developed by the Federal Highway Administration (FHWA) of the United States. The TNM computer program is capable of predicting highway noise, but currently does not take into account the pavement type, or specifically allow the input of pavement material properties. The objective of this study was to develop a mathematical model to calculate the acoustic absorption (impedance) of pavement materials. The model developed was based on mix volumetrics for the specific pavement type. Knowing the volume of each component in the pavement mixture, dampening properties such as the Ultrasonic Pulse Time (UPT) for acoustic wave transmission and the Effective Flow Resistivity (EFR) through the material can be obtained. The scope of work included the evaluation of the dampening properties of different pavement materials obtained through laboratory testing; and validating the results using a predictive model. The Ultrasonic Pulse Velocity (UPV) testing method was adopted to assess the dampening properties of pavement materials. The experimental program included the evaluation of 31 laboratory pavement specimens and 49 field cores obtained from national and international pavement sections. A total of twenty three different pavement types were evaluated. Correlations between predicted and laboratory measured UPT was excellent. The UPT results were used to calculate the EFR, which is the direct main input into the TNM. Correlations between tire/pavement noise levels and laboratory calculated EFR for each of the field mixtures were excellent and rational in that lower the EFR, lower was the tire/pavement noise level for a pavement material. Since the EFR is used as a main input into the FHWA Traffic Noise Model (FHWA TNM), the model and test data collected in this research will prove to be a potential enhancement to a wider use of different pavement types into the Ground Zones module of the TNM.*

KEYWORDS: *Dampening Properties, Ultrasonic Pulse Velocity Test, Ultrasonic Pulse Time, Effective Flow Resistivity, Air Voids, Tire/Pavement Noise.*

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1. Introduction

Road traffic noise has become a growing problem in urban areas. A continuing increase in traffic volume has been adding more noise pollution. Bernhard reported increasing values as high as 8 decibels (dB) to the overall highway noise (Road Noise, 2004). Highway noise is generated by three sources: propulsion (engine and exhaust), aerodynamic (turbulence of vehicle) and tire/pavement noise. At speeds higher than 40 km/h, tire/pavement interaction is the dominant source of highway noise (Sandberg and Ejsmont, 2002). There are many factors that influence tire/pavement noise such as road friction and acoustic absorption as well as pavement texture. For asphalt mixtures, air voids, asphalt cement, aggregates, and modifications such as using crumb rubber are also hypothesized to play a role in tire/pavement noise. The contribution of each factor to the overall effect on tire/pavement noise has not been well-established and is an ongoing research (Sandberg and Ejsmont, 2002; Bernhard and Wayson, 2005; Rasmussen *et al.*, 2007; WRI, 2007).

This paper focuses on the dampening properties of the different types of pavement materials. Measurement of material dampening property is important. The correlation between acoustic dampening effects and noise reduction performance of pavements is complex and not fully understood. A recommended field practice for measuring pavement acoustical properties is still under development. Current methods in use for laboratory measurement of the pavement absorption include impedance tube method using ASTM E-1050; or *in-situ* pavement tests as described in ISO 13472-1, 2002 (ASTM E1050-98; ISO 13472-1:2002).

Highway noise is also addressed through several models such as Traffic Noise Model (TNM) developed by the Federal Highway Administration (FHWA) of the United States (Menge *et al.*, 1998). The TNM computer program is capable of predicting highway noise, but currently does not take into account the pavement type, or specifically allow the input of pavement material properties. The pavement material properties are considered to be useful input into the TNM, which will improve the modeling process in designing noise-reducing pavements.

2. Objective and scope of work

The objective of this study was to develop a mathematical model to calculate the dampening properties such as Ultrasonic Pulse Time (UPT) and Effective Flow Resistivity (EFR), which is also the acoustic impedance of pavement materials. The model developed was based on the mixture volumetrics of the specific pavement type. The scope of work also included the evaluation of the dampening properties of different pavement materials obtained through laboratory testing. The Ultrasonic Pulse Velocity (UPV) testing method was adopted to assess the dampening properties of pavement materials. The UPT results were used to calculate the EFR, which is the direct main input into the TNM.

3. Non-destructive Ultrasonic Pulse Velocity (UPV) test

Non destructive evaluation techniques have been widely used in industry to measure the elastic or shear modulus of composite materials (Pellinen, 2001). Birgisson *et al.* reported the use of UPV test as a tool to monitor changes in the integrity of mixtures due to moisture conditioning (Birgisson *et al.*, 2003).

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). Ultrasonic testing of materials utilizes mechanical waves composed of sinusoidal elastic oscillation of discrete particles of material. Ultrasonic thickness gauges use a transducer, which is a piezoelectric crystal that converts a pulse of an electrical energy to an ultrasonic shock wave. The crystal typically has a resonant frequency of 20 to 100 kHz in the case of longitudinal waves in concrete or asphalt concrete. The shock wave is coupled from the transducer into the material to be measured, usually with the aid of a couplant such as glycerin or honey. The sound travels through the test material, although a flaw or lamination can cause the reflection as well. The ultrasound couples back to the probe through the coupling medium and is converted back to an electrical impulse. If the sample thickness or length is known, the wave velocity can be determined by measuring the wave pulse time. The velocities of the ultrasonic pulses traveling in a solid material depend on the material density and elastic properties. The pulse velocity, v is related to the density and elastic properties of a solid by Krautkämer and Krautkämer in 1990:

$$v = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad [1]$$

Where:

v = velocity (m/s),

ρ = density of material (kg/m^3)

E = modulus of elasticity (kPa)

μ = Poisson's ratio

The equation can be used when the material is confined or whose lateral expansion is not possible. The velocity of sound computed for materials when unconfined or whose lateral expansion is possible is as follows.

$$v = \sqrt{\frac{E}{\rho}} \quad [2]$$

The ultrasonic test setup is shown in Figure 1. The setup consists of a pulse generator, two transducers (transmitter and receiver), an amplifier, a time measuring circuit, a time display unit, and connecting cables. A triggering voltage from the pulse generator initiates the time measuring circuit and operates at the repetition frequency of the latter. The time measuring circuit provides an output when the reflected pulse is detected. The output is used to determine the transit time displayed on the time-display unit. The transmitting and receiving transducers both consist of lead zirconate titanate (PZT4) ceramic piezoelectric elements mounted in stainless steel cases.

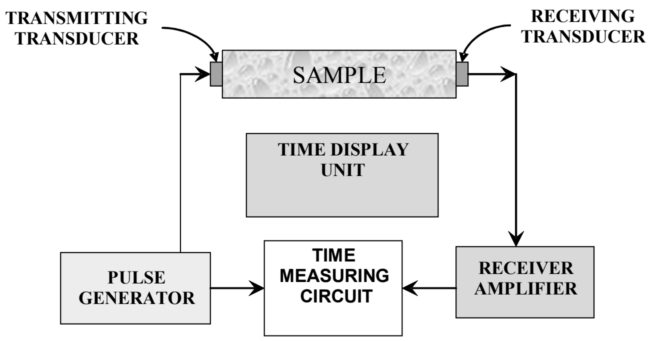


Figure 1. *Schematic of ultrasonic pulse velocity measurement test apparatus*

The pulse velocity is calculated as a ratio of the measured path length to the measured pulse time. That is,

$$v = \frac{L}{T} \qquad [3]$$

where:

L = Distance between centers of transducer faces (m)

T = Ultrasonic Pulse Time for transit (μs or s)

The Elastic Modulus can also be expressed as follows (similar to Equation [1]):

$$E = K\, \rho\, v^2 \qquad [4]$$

Where:

E = Modulus of Elasticity (kPa)

K = a constant dependent on the Poisson's ratio and confinement

ρ = density of material (kg/m^3);

v = velocity (m/s)

4. Ultrasonic pulse time transit model

The ultrasonic pulse time transit model developed in this study was based on mathematical calculations programmed in an Excel™ spreadsheet (Biligiri, 2008). The input parameters included pavement volumetric properties such as asphalt cement, air voids; aggregate gradation (and type), and any admixtures such as crumb rubber inclusions. Portland cement concrete mixtures can be also analyzed in this spreadsheet by manipulation of input properties. Salient features of the model are as follows.

4.1. *Calculation of mixture volumetrics*

a) Input Parameters: percentage of asphalt cement, P_b and rubber, P_r; specific gravity of bitumen, G_b, rubber, G_r, coarse and fine aggregate as well as mineral filler, G_{ca}, G_{fa}, G_{mf}; bulk specific gravity of the compacted mix, G_{mb}; maximum theoretical specific gravity of the mix, G_{mm}.

b) Calculated Parameters: Volume of air voids in the total mix, V_a (%), Volume of rubber, V_r (%), Effective Volume of asphalt or bitumen, V_b (%) and Volume of aggregate solids, V_s (%).

4.2. *Calculation of surface area of mix components*

Knowing the gradation of aggregates, weighted average of the sieve size, D is calculated. Surface area and volume components of the representative sieve size, D are calculated which are further used to calculate the number of representative sieve size aggregates. The surface area of aggregates was based on the addition of surface area of each type of sieve size present in the mix; the surface area of each sieve being the product of surface area factor for each sieve size and percent passing each sieve. The surface area factor for each sieve was obtained from NCAT Handbook (Roberts *et al.*, 1996). After the aggregate surface area was calculated, weighted average of the sieve size, D was estimated based on the assumption that the shape of D was spherical and had an area of [$4 \pi r^2$]. Here, r is the radius of the sieve size which is equal to half of the sieve size in magnitude. Once the weighted average sieve size D was estimated, the number of D size aggregates was calculated as follows.

No. of D Sieve Size Aggregates = Total Vol. of Agg./Vol. of D Size Agg.

Total Volume of aggregates is simply the total volume of aggregate solids in the mix and volume of D size aggregates is equal to $\frac{4}{3}\pi r^3$.

Using mixture volumetrics, the amount of effective bitumen in the mixture as well as thickness of bitumen film are calculated. All these components aid in the calculation of surface area of aggregates, bitumen and rubber components. Formulae for calculations of surface area of different components are based on methodologies presented in NCAT Handbook by Roberts *et al.*

4.3. *Calculation of ultrasonic pulse time, ultrasonic pulse velocity, impedance, Z, and effective flow resistivity, EFR*

Sections 4.1 and 4.2 provide a basic understanding and the underlying analogy used in the estimation of pavement mixture volumetrics. To start with, if one assumes a 1 cc of volume of the mix, with the known values of specific gravities of the different components in the mixture (aggregates, bitumen, crumb rubber inclusion if any), one can easily calculate the volume of each of the components by percent weight of the mix using mass-volume phase relationships. Using the mix designs of the mixtures, one can obtain each mixture component's density in g/cc. As already elucidated in Sections 4.1 and 4.2, one can calculate material component's surface areas. Once volume, density and surface area values are estimated using the aforementioned analogies, the thickness of each of the material's components can be estimated as the ratio of volume to surface area of each of the components.

Ultrasonic pulse velocities (UPV) for standard materials have been reported in the literature (Turner and Pretlove, 1991; Howe, 1998; Cha and Cho, 2007; Demirboga *et al.*, 2004; Aracne-Ruddle *et al.*, 1999; Mochinaga *et al.*, 2006). For example, the ultrasonic velocity in rubber is about 2115 m/s and for bitumen, it is about 1800 m/s. Standard UPV values for the different elements are required so as to calculate the UPT for each component given by the following relation. For a known pavement material thickness, L, and UPV, Ultrasonic Pulse Time (UPT) can be calculated as follows.

$$\text{Ultrasonic Pulse Time } (\mu\text{s or s}) = UPT = \frac{L}{UPV} \qquad [5]$$

Thus, UPT of the total mix can be calculated by the addition of each of the pavement material component's respective UPT as follows:

$$\text{Total UPT } (\mu\text{s or s}) = T_i = t_{air} + t_{rubber} + t_{bitumen} + t_{aggregate} \qquad [6]$$

The UPT addition of various pavement materials' components is justified based on the at least three types of mixture properties present in the pavement material. The theory is based on the basic assumption that the mixture is a unit volume and the wave traverses through each component. The difficulty of measuring time through each component can be easily manipulated if one adds transit times of each pavement material component. An example of the analysis from the model calculations is shown in Table 1. The table contains results of two pavement materials: a conventional dense graded asphalt mixture, and an asphalt rubber mixture that is known to dampen noise. The total transit time is calculated as a summation of transit times of different asphalt mixture's components. It is observed that the total transit time for the asphalt rubber friction course mixtures is 1.35 times greater than the conventional mixture. This represents the dampening characteristic of the asphalt rubber mixture over the dense graded asphalt mixture.

Table 1. *Model results of Ultrasonic Pulse Time (UPT)*

Mix	Component	Volume, cc	Surface Area, sq-cm	Velocity, cm/s	Time, s	Total Transit Time, s
Conventional Dense Graded Asphalt	Air Voids	6.86	2500	34000	8.07×10^{-8}	4.199×10^{-5}
	Rubber	0	0	211500	0	
	Asphalt Cement	11.29	5.8744	180000	1.07×10^{-5}	
	Aggregate	91.74	5.8744	500000	3.13×10^{-5}	
Asphalt Rubber Friction Course (ARFC)	Air Voids	17.89	2500	34000	2.11×10^{-7}	3.104×10^{-5}
	Rubber	3.29	2.1551	211500	7.22×10^{-6}	
	Asphalt Cement	17.91	10.7757	180000	9.24×10^{-6}	
	Aggregate	77.49	10.7757	500000	1.44×10^{-5}	

Knowing the total sample length (or assumed for calculation purposes), and calculated total UPT (Equation [6]), UPV of the total mix can be calculated using Equation [7] as follows:

$$\text{Ultrasonic Pulse Velocity (m/s)} = UPV = \frac{L}{UPT} \qquad [7]$$

With the calculated value of the total density of the pavement materials as described in Section 4.1, and UPV (Equation [7]), one can calculate the values of mixture's Impedance as well as Effective Flow Resistivity, EFR as detailed next. The value of EFR can be directly input in the TNM. With the available density and transit velocity, one can calculate the impedance of the material, which is given by

$$Z = \rho * v \qquad [8]$$

Where:

Z = Impedance, N-s/m^3, ρ = density of the material (kg/m^3),

v = ultrasonic wave velocity through the material, m/s.

As explained previously, the higher the transit time, the lower the velocity and *vice versa*. Therefore, if the acoustic velocity is lower, transit time is shorter which holds good for air pockets as well. In the case of air component, the surface area component is much higher compared to the other components as one will find large amounts of air pockets in the mixture which is distributed over a larger volume of the mix; hence, the product of velocity and ratio of volume to surface area is much smaller yielding a lower transit time. It must be understood that volume of air presented here is the total volume of air voids in the mix which is much larger in magnitude.

FHWA TNM uses another form of sound absorption, the Effective Flow Resistivity, EFR which is basically the impedance of the material; also defined as the property of the material offering resistance to acoustic wave through an open pore (Menge *et al.*, 1998; Sandberg and Ejsmont, 2002; Rochat *et al.*, 2007). The TNM Technical Manual provides values of EFR in cgs Rayls for various ground types. Mathematically, EFR, σ is directly proportional to Impedance, Z. Both are expressed in the same units, N-s/m^3 (MKS units) or cgs Rayls (cgs units). It is noteworthy that

$$\text{EFR, } \sigma \text{ in cgs Rayls} = 0.1 * \text{EFR in N-s/m}^3 \qquad [9]$$

Measured typical values of EFR for different pavement materials as reported by Rochat *et al.* are shown in Table 2 (Rochat and Hastings, 2008).

Table 2. *Typical effective flow resistivity values for different types of pavements (Rochat and Hastings, 2008)*

Pavement Type	EFR [cgs Rayls]
Portland Cement Concrete (PCC)	20000
Old Dense Graded Asphalt Concrete (DGAC)	14500
New Bonded Wearing Course (BWC), 30 mm	12300
Asphalt Rubber Friction Course (ARFC or RAC-O)	6000 – 6100
Open Graded Asphalt Concrete (OGAC)	2000 – 4200

By definition, EFR is simply the impedance in different units. Although it might be true that EFR is frequency dependent, the measurement of ultrasonic wave velocity is not in the sonic range. Sound absorption properties may be frequency dependent if the measured waves are in sonic range but in ultrasonic range, frequency is not of a concern as the tests conducted in this research study were verified using two different frequency transducers, namely, 20 and 54 kHz which yielded exactly the same results. The predictive model was based on the measured transit time of the pavement material and not just the pores present in the structural matrix. Moreover, the model as well as the test data was based on the estimations of acoustic velocity through the whole structure and hence, the formalism of considering acoustic absorption makes sense.

Although it might be true that impedance obtained through the product of UPV and density is mechanical impedance per unit area of the whole structure, it is also the characteristic impedance of the material itself. This is nothing but EFR. Here, EFR is being referred to as characteristic impedance and not specific acoustic impedance. Characteristic impedance of a medium such as rock, air or any component is a material property whilst specific impedance is the resonance of the wave which is not of interest in this study. Traffic Noise Model (TNM), Section D.4.5 details and documents the relationship between absorption and flow resistivity of different pavement materials. The same analogy was used in this research work to understand the effects of EFR which is nothing but impedance of the pavement material to noise propagation.

5. Experimental program

The laboratory testing program included the evaluation of 31 laboratory pavement specimens and 49 field cores obtained from national and international pavement sections. A total of twenty three different pavement types were evaluated. These samples represented laboratory compacted field mixes obtained from: the Arizona Department of Transportation (ADOT), Swedish Road Administration (SRA), and Swedish Transport Institute (VTI). The field cores covered eleven different pavement materials were obtained from the Pavement Research Center (UCPRC) at University of California, Davis (UCD), in conjunction with CALTRANS as well as ADOT I-10 test sections. The mixtures were all part of the California Quiet Pavement Research Program (Kohler *et al.*, 2007). The purpose of that study was to understand the properties/materials that impact pavement noise levels and it is a separate effort from this research. The ADOT field cores were obtained from the conducted preventative maintenance pavement preservation experiment on Interstate – 10 (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 wearing courses types. The location of these test sections on the I-10 were randomly sequenced; starting at section number 99-0 and ending at section number 99-31 (Carlson *et al.*, 2008). The purpose of this study was to conduct field noise measurements on five different pavement wearing courses; noise measurements were performed using a vehicle similar to On-Board Sound Intensity (OBSI) technique. The specific sample geometries are shown in Tables 3 and 4.

Table 3. *Measured ultrasonic pulse velocity test results for laboratory mixtures*

Mixture Type	Sample ID	Height (m)	Air Voids (%)	Asphalt Content (%)	UPT (s)	Average Velocity (m/s)	Density (kg/m^3)	Z, Impedance (N-s/m^3)	Z*, Impedance (cgs Rayls)
ADOT-DGAC	KR724	0.152	6.98	5.40	4.17×10^{-5}	3652	2.302	82382	8238
	KR726	0.152	7.29	5.40	4.17×10^{-5}	3652	2.302	82382	8238
	KR727	0.152	6.93	5.40	4.27×10^{-5}	3572	2.302	80580	8058
ADOT-US180-ARAC	I8507	0.152	7.21	8.40	4.74×10^{-5}	3217	2.350	74092	7409
	I8508	0.152	7.08	8.40	4.67×10^{-5}	3263	2.350	75150	7515
	I8509	0.152	7.34	8.40	4.64×10^{-5}	3284	2.350	75636	7564
ADOT-US70-ARAC	70501	0.152	11.34	9.40	5.22×10^{-5}	2920	2.126	60835	6083
	70502	0.152	12.34	9.40	5.22×10^{-5}	2920	2.126	60835	6083
	70503	0.152	13.34	9.40	5.12×10^{-5}	2977	2.126	62023	6202
ADOT-ARFC	AW435	0.152	21.49	8.80	5.76×10^{-5}	2646	2.224	57679	5768
	AW436	0.152	21.49	8.80	5.59×10^{-5}	2728	2.224	59468	5947
	AW437	0.152	21.82	8.80	5.81×10^{-5}	2623	2.224	57182	5718
SRA-E-06-GGAC	SWR01	0.152	1.93	6.00	3.73×10^{-5}	4086	2.406	96338	9634
	SWR02	0.152	1.87	6.00	3.80×10^{-5}	4011	2.406	94563	9456
	SWR03	0.152	1.82	6.00	3.97×10^{-5}	3839	2.406	90514	9051
SRA-E-06-GGAR	SWG01	0.152	1.97	6.70	4.13×10^{-5}	3690	2.379	86048	8605
	SWG02	0.152	1.77	6.70	4.09×10^{-5}	3723	2.379	86819	8682
	SWG03	0.152	2.01	6.70	4.07×10^{-5}	3741	2.379	87245	8724
VTI-OGAR	OGAR90-4	0.068	17.50	9.00	2.35×10^{-5}	2897	2.069	58722	5872
	OGAR90-8	0.071	17.30	9.00	2.43×10^{-5}	2927	2.069	59331	5933
	OGAR70-2	0.061	19.60	7.00	2.15×10^{-5}	2835	2.060	57252	5725
	OGAR70-3	0.069	20.40	7.00	2.17×10^{-5}	3184	2.060	64288	6429
VTI-OGAC	OGAC-OR6	0.061	18.10	7.00	1.88×10^{-5}	3243	2.100	66732	6673
	OGAC-OR2	0.064	12.50	7.00	2.02×10^{-5}	3169	2.100	65212	6521
VTI-GGAR	GGAR-30	0.068	11.20	9.00	2.11×10^{-5}	3226	2.240	70808	7081
	GGAR-40	0.069	12.00	9.00	2.11×10^{-5}	3274	2.240	71865	7186
	GGAR-2G	0.069	13.10	8.00	2.04×10^{-5}	3387	2.235	74185	7418
VTI-GGAC	GGAC-GR1	0.061	3.90	7.00	1.58×10^{-5}	3858	2.300	86964	8696
	GGAC-GR3	0.061	3.90	7.00	1.60×10^{-5}	3810	2.300	85877	8588
	GGAC-GR10	0.061	13.10	7.00	1.72×10^{-5}	3544	2.300	79886	7989
	GGAC-GR13	0.061	11.50	7.00	1.64×10^{-5}	3717	2.300	83783	8378

** EFR = Input in TNM.*

Descriptions of the mixtures are as follows:

– ADOT – DGAC: Conventional Dense Graded Asphalt Concrete

– ADOT – ARAC: Asphalt Rubber Asphalt Concrete (Asphalt Rubber Gap Graded)

– ADOT – ARFC: Asphalt Rubber Friction Course (Asphalt Rubber Open Graded)

– SRA – E-06 – GGAC: Gap Graded Asphalt Concrete (without rubber)

– SRA – E-06 – GGAR: Gap Graded Asphalt Rubber

– VTI – OGAR1 and OGAR2: Open Graded Asphalt Rubber 1 and 2

– VTI – OGAC: Open Graded Asphalt Concrete (without rubber)

– VTI – GGAR1 and GGAR2: Gap Graded Asphalt Rubber 1 and 2

– VTI – GGAC1 and GGAC2: Gap Graded Asphalt Concrete 1 and 2 (without rubber)

– 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

– ADOT I-10 – PEM: Permeable European Mixture

– ADOT I-10 – SMA: Stone Matrix Asphalt

– ADOT I-10 – AR-ACFC: 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

Table 4. *Measured Ultrasonic Pulse Velocity Test Results for Field Cores*

Mixture Type	Sample ID	Height (m)	Air Voids (%)	Asphalt Content (%)	UPT (s)	Average Velocity (m/s)	Density (kg/m^3)	Z, Impedance (N-s/m^3)	Z*, Impedance (cgs Rayls)
UCD-DGAC	QP-40	0.041	5.80	4.80	1.06×10^{-5}	3873	2.325	88252	8825
UCD-RAC-G	ES-12	0.023	8.12	7.00	6.50×10^{-6}	3518	2.231	76921	7692
UCD-RAC-G	QP-02	0.073	8.40	7.00	2.25×10^{-5}	3234	2.231	70712	7071
UCD-DGAC	QP-09	0.100	4.23	4.80	2.51×10^{-5}	3961	2.325	90246	9025
UCD-DGAC	QP-43	0.109	4.73	4.80	2.84×10^{-5}	3845	2.325	87605	8760
UCD-RAC-O F-mix	QP-47	0.050	11.43	8.00	1.27×10^{-5}	3952	2.065	79958	7996
UCD-RAC-G	QP-19	0.042	10.67	7.00	1.05×10^{-5}	3984	2.231	87089	8709
UCD-DGAC	06-N434	0.069	4.10	5.00	1.56×10^{-5}	4401	2.325	100270	10027
UCD-RAC-O F-mix	QP-50	0.076	12.28	8.00	2.67×10^{-5}	2854	2.065	57741	5774
UCD-RAC-O F-mix	QP-52	0.046	8.95	8.00	1.32×10^{-5}	3481	2.065	70429	7043
UCD-RAC-G	ES-12	0.031	8.12	7.00	7.90×10^{-6}	3894	2.231	85135	8514
UCD-OGAC	QP-03	0.040	19.50	8.00	1.24×10^{-5}	3272	2.000	64137	6414
UCD-RAC-G	QP-33	0.063	13.78	7.00	1.57×10^{-5}	4019	2.129	83863	8386
UCD-RAC-G	QP-39	0.060	7.71	7.00	1.75×10^{-5}	3455	2.282	77253	7725
UCD-EU Gap Graded	ES-10	0.058	11.77	7.00	1.58×10^{-5}	3649	2.150	76876	7688
UCD-RAC-G	QP-26	0.043	9.03	7.00	1.18×10^{-5}	3674	2.231	80320	8032
UCD-OGAC	QP-44	0.032	18.78	8.00	6.90×10^{-6}	4634	2.000	90823	9082
UCD-OGAC	QP-04	0.048	16.50	8.00	1.51×10^{-5}	3194	2.000	62596	6260
UCD-RAC-O	QP-51	0.043	21.10	8.00	1.20×10^{-5}	3570	1.930	67544	6754
ADOT-I10	PEM	0.032	17.14	6.00	8.65×10^{-6}	3316	2.073	67379	6738
ADOT-I10	P-ACFC	0.019	20.96	6.00	9.14×10^{-6}	2988	2.009	58914	5891
ADOT-I10	AR-ACFC	0.019	17.17	9.10	6.60×10^{-6}	2792	2.103	57538	5754
ADOT-I10	ACFC	0.019	13.80	6.00	6.60×10^{-6}	3391	2.189	73393	7339
ADOT-I10	SMA	0.019	9.65	6.50	7.16×10^{-6}	3566	2.135	74516	7452

** EFR = Input in TNM*

Ultrasonic pulse velocity test results

Figure 2 shows an actual setup of the UPV test equipment. Ultrasonic pulse velocity test methodology was conducted using 20 kHz transducers on all test samples. Honey was used as couplant between sample and transducer interface. UPT was noted for the samples under investigation. The measured length of the sample was used to calculate UPV and hence, Impedance and EFR for all pavement material samples. Table 3 summarizes the ultrasonic pulse velocity test results for the 31 laboratory samples.

Figure 2. *Actual Ultrasonic Pulse Velocity (UPV) test setup with an asphalt concrete mix*

The experimental test results for the 24 field cores obtained from UCPRC and ADOT I-10 test sections are as shown in Table 4. Since each wearing course type of Arizona I-10 test sections constituted six replicate cores, they were averaged and grouped; therefore, Table 4 presents five UPV test results for ADOT I-10 wearing course types instead of 30 values. Thus, 19 field core samples from UCPRC and 5 average values from ADOT I-10 test sections summed up to 24 field core test results.

6. Model predictions *versus* laboratory measurements

Both model predictions and actual test results were compared and the results are shown in Tables 5 and 6. Table 5 shows the predicted versus measured UPT for laboratory compacted mixtures. Similarly, Table 6 shows the predicted versus measured UPT for the field cores.

Table 5. *Predicted* versus *measured UPT for laboratory mixtures*

Mixture Type	Sample ID	Measured UPT (s)	Predicted UPT (s)
ADOT-DGAC	KR724	4.17×10^{-5}	3.74×10^{-5}
	KR726	4.17×10^{-5}	3.74×10^{-5}
	KR727	4.27×10^{-5}	3.74×10^{-5}
ADOT-US180-ARAC	I8507	4.74×10^{-5}	4.53×10^{-5}
	I8508	4.67×10^{-5}	4.53×10^{-5}
	I8509	4.64×10^{-5}	4.53×10^{-5}
ADOT-US70-ARAC	70501	5.22×10^{-5}	4.55×10^{-5}
	70502	5.22×10^{-5}	4.55×10^{-5}
	70503	5.12×10^{-5}	4.55×10^{-5}
ADOT-ARFC	AW435	5.76×10^{-5}	4.56×10^{-5}
	AW436	5.59×10^{-5}	4.56×10^{-5}
	AW437	5.81×10^{-5}	4.56×10^{-5}
SRA-E-06-GGAC	SWR01	3.73×10^{-5}	3.66×10^{-5}
	SWR02	3.80×10^{-5}	3.66×10^{-5}
	SWR03	3.97×10^{-5}	3.66×10^{-5}
SRA-E-06-GGAR	SWG01	4.13×10^{-5}	4.13×10^{-5}
	SWG02	4.09×10^{-5}	4.13×10^{-5}
	SWG03	4.07×10^{-5}	4.13×10^{-5}
VTI-OGAR	OGAR90-4	2.35×10^{-5}	2.00×10^{-5}
	OGAR90-8	2.43×10^{-5}	2.09×10^{-5}
	OGAR70-2	2.15×10^{-5}	1.70×10^{-5}
	OGAR70-3	2.17×10^{-5}	1.92×10^{-5}
VTI-OGAC	OGAC-OR6	1.88×10^{-5}	1.53×10^{-5}
	OGAC-OR2	2.02×10^{-5}	1.61×10^{-5}
VTI-GGAR	GGAR-30	2.11×10^{-5}	2.01×10^{-5}
	GGAR-40	2.11×10^{-5}	2.03×10^{-5}
	GGAR-2G	2.04×10^{-5}	1.98×10^{-5}
VTI-GGAC	GGAC-GR1	1.58×10^{-5}	1.53×10^{-5}
	GGAC-GR3	1.60×10^{-5}	1.53×10^{-5}
	GGAC-GR10	1.72×10^{-5}	1.54×10^{-5}
	GGAC-GR13	1.64×10^{-5}	1.54×10^{-5}

Table 6. *Predicted* versus *measured UPT for field cores*

Mixture Type	Sample ID	Measured UPT (s)	Predicted UPT (s)
UCD-DGAC	QP-40	1.06×10^{-5}	9.36×10^{-6}
UCD-RAC-G	ES-12	6.50×10^{-6}	6.26×10^{-6}
UCD-RAC-G	QP-02	2.25×10^{-5}	1.99×10^{-5}
UCD-DGAC	QP-09	2.51×10^{-5}	2.29×10^{-5}
UCD-DGAC	QP-43	2.84×10^{-5}	2.51×10^{-5}
UCD-RAC-O F-mix	QP-47	1.27×10^{-5}	1.46×10^{-5}
UCD-RAC-G	QP-19	1.05×10^{-5}	1.15×10^{-5}
UCD-DGAC	06-N434	1.56×10^{-5}	1.59×10^{-5}
UCD-RAC-O F-mix	QP-50	2.67×10^{-5}	2.21×10^{-5}
UCD-RAC-O F-mix	QP-52	1.32×10^{-5}	1.34×10^{-5}
UCD-RAC-G	ES-12	7.90×10^{-6}	8.42×10^{-6}
UCD-OGAC	QP-03	1.24×10^{-5}	1.06×10^{-5}
UCD-RAC-G	QP-33	1.57×10^{-5}	1.73×10^{-5}
UCD-RAC-G	QP-39	1.75×10^{-5}	1.65×10^{-5}
UCD-EU Gap Graded	ES-10	1.58×10^{-5}	1.32×10^{-5}
UCD-RAC-G	QP-26	1.18×10^{-5}	1.19×10^{-5}
UCD-OGAC	QP-44	6.90×10^{-6}	8.38×10^{-6}
UCD-OGAC	QP-04	1.51×10^{-5}	1.26×10^{-5}
UCD-RAC-O	QP-51	1.20×10^{-5}	1.25×10^{-5}
ADOT-I10	PEM	8.65×10^{-6}	7.25×10^{-6}
ADOT-I10	P-ACFC	9.14×10^{-6}	7.06×10^{-6}
ADOT-I10	AR-ACFC	6.60×10^{-6}	5.60×10^{-6}
ADOT-I10	ACFC	6.60×10^{-6}	5.60×10^{-6}
ADOT-I10	SMA	7.16×10^{-6}	6.60×10^{-6}

Figure 3 shows comparison of predicted versus measured UPT for all 80 samples (includes 31 laboratory samples and 49 field cores). As observed in Figure 3, there is an excellent correlation between the model predictions and laboratory measured Ultrasonic Pulse Time (R^2~0.98). It is noted that the model under-predicts higher UPT values; one reason for the under-prediction is attributed to the input parameters used in the model, such as the use of literature reported ultrasonic wave velocity for rubber particles and aggregates. Nevertheless, there is an excellent rational correlation between both the predicted and measured values. Higher correlations could be achieved by measuring specific ultrasonic wave velocity values for standard materials (rubber or aggregates) rather than relying on literature values.

Thus, EFR values can be calculated based on the predicted UPT from the ultrasonic pulse time transit model. However, EFR values can also be estimated based on the measured UPT on the laboratory samples.

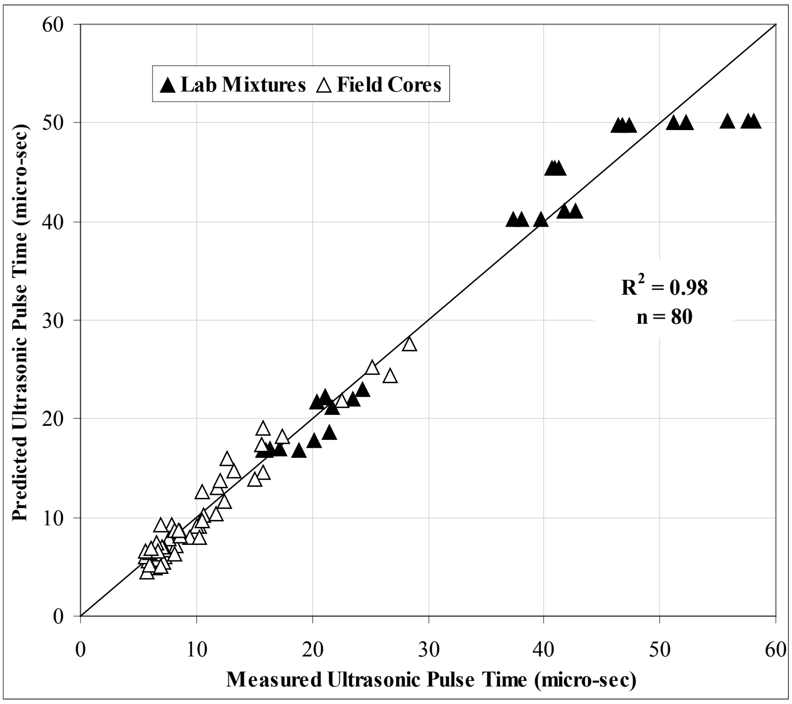


Figure 3. *Comparisons between predicted and measured Ultrasonic Pulse Time (UPT) (micro-sec)*

7. Ultrasonic pulse time transit model sensitivity

The developed model can be also used to understand the impact of material's volumetric change on EFR. An example showing changes in OGAR mix's air voids is shown in Figure 4. The figure shows the predicted values of EFR for five different air voids levels: 15, 17, 18, 20 and 25%. With an increase in air voids, there is a decrease in EFR which means that there is a positive effect of air voids increase on noise dampening. This is rational and agrees with expert opinion on the role of the air voids in the mix's noise characteristics. Although historically, UPV tests have been used to evaluate strength of various materials, it must be understood that UPV tests in this research study were not performed to measure stiffness of the materials but to check the noise-dampening response of the materials through simple analogy of ultrasonic pulse transit time. It gets very complicated to measure stiffness of the material through these tests and have proven to be not as worthy as other pavement material characterization tests currently used (Pellinen, 2001).

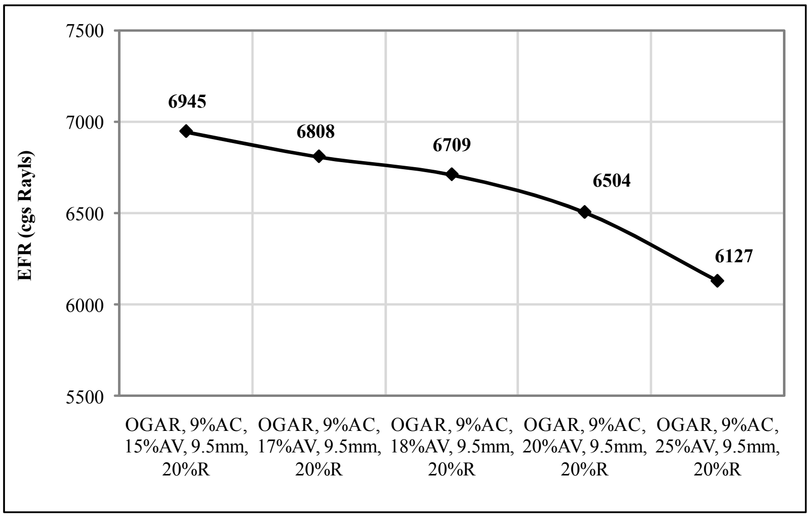


Figure 4. *Sensitivity of EFR (cgs Rayls) calculated from model predicted UPT to varying air voids levels*

Figure 5 shows a change in EFR for three different Arizona asphalt concrete mixtures: conventional dense graded (DGAC), gap graded asphalt rubber (GGAR), and an open graded asphalt rubber (OGAR) mixture. The figure shows calculated EFR values from model predicted UPT for all the three mixtures. It can be seen that the EFR values are higher for DGAC mixtures followed by GGAR and then, followed by OGAR mixtures. Other similar volumetric analysis could be easily conducted using the developed model.

An overall relationship between calculated EFR (estimated from measured UPT) and air voids for all the mixtures under investigation is shown in Figure 6. As can be observed, there is a definite decreasing EFR trend with increasing air voids. The correlation is fair to good (R^2~0.62). An exponential model has been fitted to the data as the trend is decreasing. This relationship assumes importance in that it agrees with expert opinion on the role of the air voids in the mix's noise characteristics. The EFR pavement material properties are envisioned to be useful input into the TNM, which will improve the modeling process in designing noise-reducing pavements.

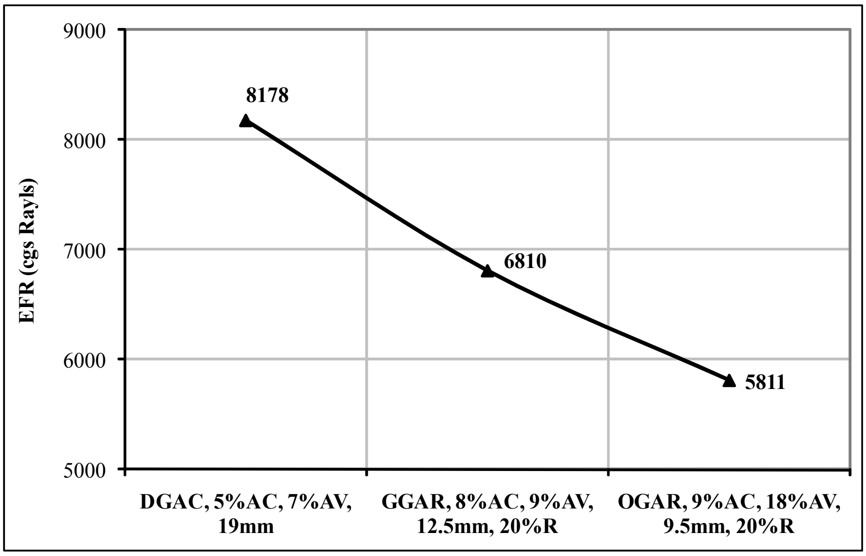


Figure 5. *Sensitivity of EFR (cgs Rayls) calculated from model predicted UPT to different asphalt mixtures*

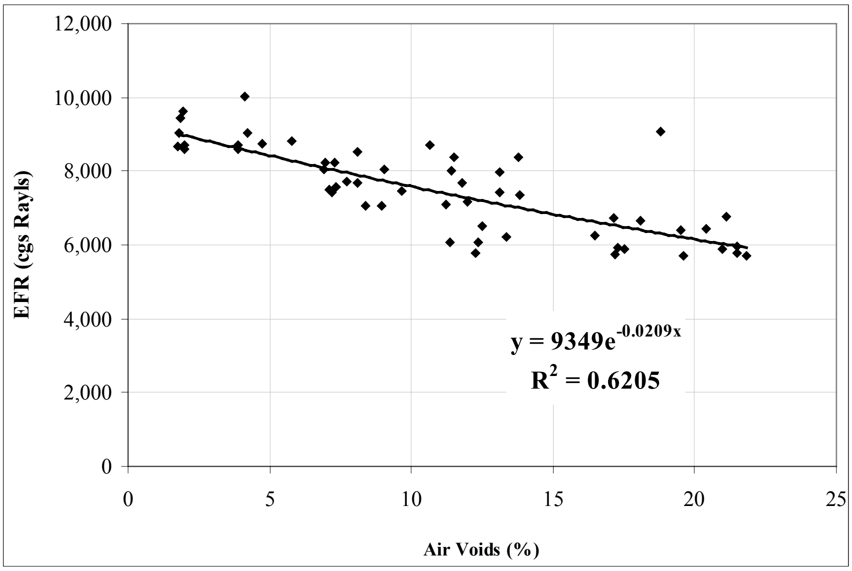
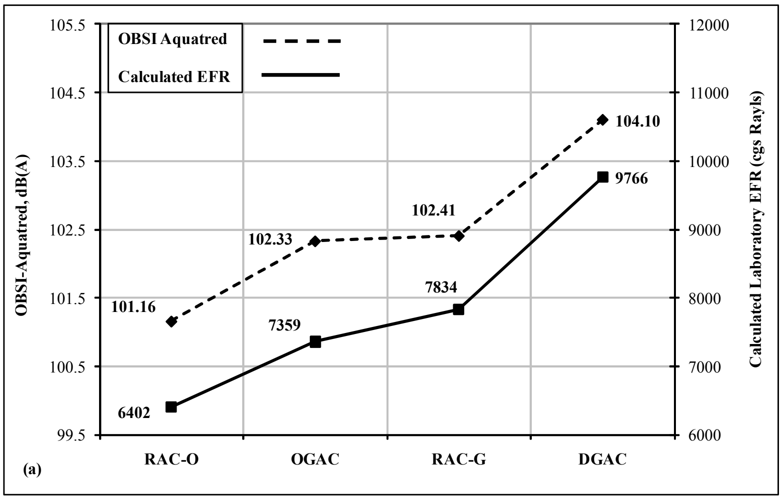


Figure 6. *Relationship between calculated Effective Flow Resistivity (EFR) and sample air voids for all mixtures*

8. EFR and tire/pavement noise

The laboratory estimated dampening properties such as ultrasonic pulse time and Effective Flow Resistivity (EFR), also the acoustic impedance of pavement materials were correlated to the field measured noise levels. As already mentioned, EFR is the direct main pavement specific input into the TNM to predict highway traffic noise. Section 5 presented the field cores collected as part of the experimental program.



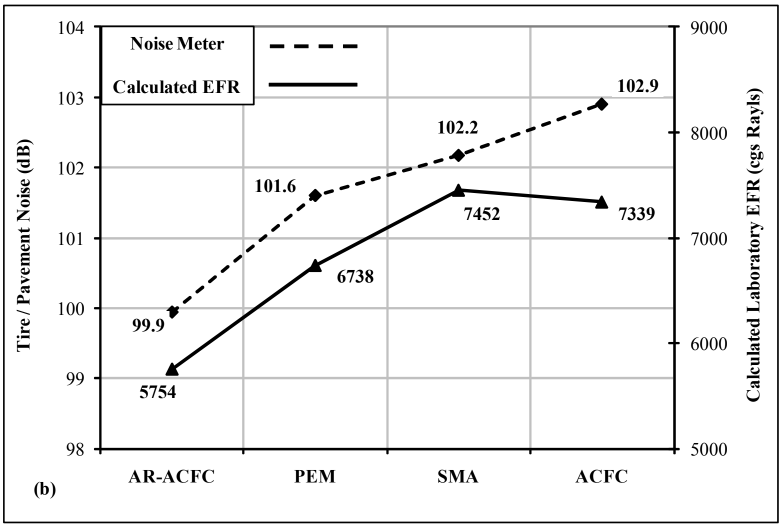


Figure 7. *Relationship between tire/pavement noise and calculated laboratory effective flow resistivity for (a) California; and (b) Arizona I-10 field mixtures*

The pavement sections from which the field cores were gathered were also tested for their noise properties using On-Board Sound Intensity (OBSI) and hand-held noise meter techniques, and were reported by Kohler *et al.* and Carlson *et al.* (Kohler *et al.*, 2007; Carlson *et al.*, 2008; Biligiri, 2008). The EFR test results on these field cores presented in Table 4 were correlated with the average noise levels for each of the mixtures and are as shown in Figures 7a and 7b. As observed, tire/pavement noise levels have excellent correlations with laboratory calculated EFR for each of the mixtures. The relations are also rational in that lower the EFR, lower is the tire/pavement noise level. Thus, the pavement material dampening properties estimated through this research study are envisioned to be a useful input into the TNM, which will improve the modeling process in designing noise-reducing pavements.

9. Summary and conclusions

This study focused on the development of a mathematical model to calculate the dampening properties of pavement materials. The model developed was based on the mix volumetrics for the specific pavement type. Knowing the volume of each component in the pavement mixture, dampening properties such as the Ultrasonic Pulse Time (UPT) for acoustic wave transmission or the Effective Flow Resistivity (EFR) through the material was obtained.

The scope of work included the evaluation of the dampening properties of different pavement materials obtained through laboratory testing; and validating the results using the model. The Ultrasonic Pulse Velocity (UPV) testing method was adopted to assess the dampening properties of pavement materials.

The laboratory testing program included the evaluation of 31 laboratory pavement specimens and 49 field cores obtained from national and international pavement sections. A total of twenty three different pavement types were evaluated. Ultrasonic Pulse Velocity techniques using 20 kilo Hertz (20 kHz) transducers were evaluated on the 80 laboratory pavement samples.

Correlations between predicted and laboratory measured UPT for all the pavement materials under investigation were performed. The correlation between the model prediction and laboratory measured UPT was excellent. The authors believe that higher correlations could be achieved by measuring specific ultrasonic wave velocity values for the standard materials (e.g., rubber or aggregates) rather than relying on literature values.

The developed model can be also used to understand changes in materials volumetric on UPT and calculated EFR (from UPT), such as changes in air voids, binder content, admixtures, or aggregate type.

Correlations between tire/pavement noise levels and laboratory calculated EFR for each of the field mixtures were excellent and rational in that lower the EFR, lower was the tire/pavement noise level for a pavement material. Since the EFR is used as a main input into the Federal Highway Administration Traffic Noise Model (TNM), the model and test data collected in this research will prove to be a potential enhancement to a wider use of different pavement types into the Ground Zones module of the TNM.

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10. Bibliography

Aracne-Ruddle C.M., Bonner B.P., Trombino C.N., Hardy E.D., Berge P.A., Boro C.O., Wildenschild D., Rowe C.D., and Hart D.J., *Ultrasonic Velocities in Unconsolidated Sand/Clay Mixtures at Low Pressures*, submitted to American Geophysical Union Fall Meeting, San Francisco, CA, December 13-17, 1999.

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

ASTM E1050-98, *Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, two Microphones and a Digital Frequency Analysis System*, 2006.

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

Bernhard R.J., and Wayson R.L., 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., Asphalt Mixtures' Properties Indicative of Tire/Pavement Noise, Ph.D. Dissertation, Department of Civil and Environmental Engineering, Arizona State University, December 2008.

Birgisson B., Roque R., Page G.C., "Ultrasonic Pulse Wave Velocity Test for Monitoring Changes in Hot-Mix Asphalt Mixture Integrity from Exposure to Moisture", *Journal of Transportation Research Record*, No. 1832, Bituminous Paving Mixtures, National Academies, Washington, D. C., 2003, p. 173-181.

Carlson D.D., Way G.B., Zareh A., Biligiri K.P. and Kaloush K.E., "Tire/Pavement Noise Characteristics of Wearing Course Asphalt Mixtures", SURF 2008, *6th Symposium on Pavement Surface Characteristics*, Portoroz, Slovenia, Europe, 20-22 October 2008.

Cha M and Cho G., "Compression Wave Velocity of Cylindrical Rock Specimens: Engineering Modulus Interpretation", *Japanese Journal of Applied Physics*, Vol. 46, No. 7B, 2007, p. 4497-4499.

Demirboga R., Turkmen I and Karakoc M., "Relationship between Ultrasonic Velocity and Compressive Strength for High-Volume Mineral-Admixtured Concrete", *Cement and Concrete Research* 34, 2004, p. 2329-2336.

Howe M.S., *Acoustics of Fluid-Structure Interactions*, Cambridge University Press, 1998.

ISO 13472-1:2002, *Acoustics - Measurement of sound absorption properties of road surfaces in situ - Part 1: Extended surface method*, 2002.

Kohler E., Ongel A., Harvey J., and Rymer B., "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.

Krautkämer J., Krautkämer H., *Ultrasonic Testing of Materials*, Part A, 4th Fully Revised Edition, Springler-Verlag, 1990, p. 1-153.

Menge C.W., Rossano C.F., Anderson G.S and Bajdek C.J., *FHWA Traffic Noise Model Technical Manual*, FHWA-PD-96-010, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., February 1998.

Mochinaga H., Onozuka S., Kono F., Ogawa T., Takahashi A and Torigoe T., *Properties of Oil sands and Bitumen in Athabasca*, 2006 CSPG – CWLS Convention, 2006.

Pellinen T.K., Investigation of the Use of Dynamic Modulus as an Indicator of Hot-Mix Asphalt Performance, Ph.D. Dissertation, Arizona State University, Tempe, AZ. May 2001.

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

Road Noise, *The Osgood File, American Communications Foundation website*, Presented in CBS Radio Network, 17th May 2004.
http://www.acfnewsource.org/science/road_noise.html

Roberts F.L., Kandhal P.S., Brown E.R., Lee D.Y. and Kennedy T.W., *Hot Mix Asphalt Materials, Mixture Design and Construction*, Second Edition, NAPA Education Foundation, Lantham, MD, 1996.

Rochat J., Hastings A. and Ferroni M., *Investigating the Implementation of Pavement Effects via OBSI Data in the FHWA Traffic Noise Model (FHWA TNM)*, NOISE-CON 2007, Reno, Nevada, USA, 22-24 October 2007.

Rochat J. and Hastings A., *Volpe Center Research and Activities Update*, Presentation at the Transportation Research Board ADC40 Committee Summer Meeting 2008, Key West, Florida, USA, July 2008.

Sandberg U. and Ejsmont J.A., *Tyre/Road Noise Reference Book*, INFORMEX, 2002.

Scofield L. *Arizona's Pavement Preservation Experiment*, Arizona Department of Transportation, 2000.

WRI First Year Work Plans, June 18 – December 25, 2007, Prepared for Federal Highway Administration, Contract No. DTFH61-07-H-00009, Asphalt Research Consortium, May 2007.

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