EFFECTIVE FLOW RESISTIVITY AND TIRE / PAVEMENT NOISE

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DEPARTMENT OF CIVIL, ENVIRONMENTAL and SUSTAINABLE ENGINEERING
ASU ARIZONA STATE UNIVERSITY
IRA A. FULTON School of Engineering

TRB ADC40 Summer Meeting

- **Pavements Noise studies at ASU since 2004**
- **2007 San Luis Obispo, CA – Influence of pavement materials' viscoelastic properties on road surface noise**
- **2008 Key West, FL – Tire / pavement noise characteristics of different wearing course asphalt mixtures**
- ***2009 Dayton, OH – Effective Flow Resistivity of Pavements***

EFFECTIVE FLOW RESISTIVITY (EFR) – FIELD TECHNIQUE

PEI: EFR

- Pavement absorption study
  - Augmented ANSI S1.18-1999
- Potential inclusion in TNM
- Default pavement reflectivity is 20,000 cgs rayls

Pavement type	Sidewalk (cement concrete)	Old DGAC	New DGAC (30mm thick)	New OGAC (30mm thick)	New RAC (30mm thick)	New OGAC (75mm thick)
EFR value [cgs rayls, g/(s·cm³) or (kPa·s)/m²]	20,000	14500	8800	8700	6100	4200

Source: Alexander, 2009; FHWA Noise Team

OBJECTIVE

- ***Develop a laboratory test procedure to estimate the Effective Flow Resistivity (EFR) for different pavement materials / mixtures.***
  - ***Based on the Ultrasonic Pulse Velocity Test***
- ***Investigate the use of a predictive model based on the pavement mixture's volumetric properties.***

FIELD VS. LABORATORY EFR

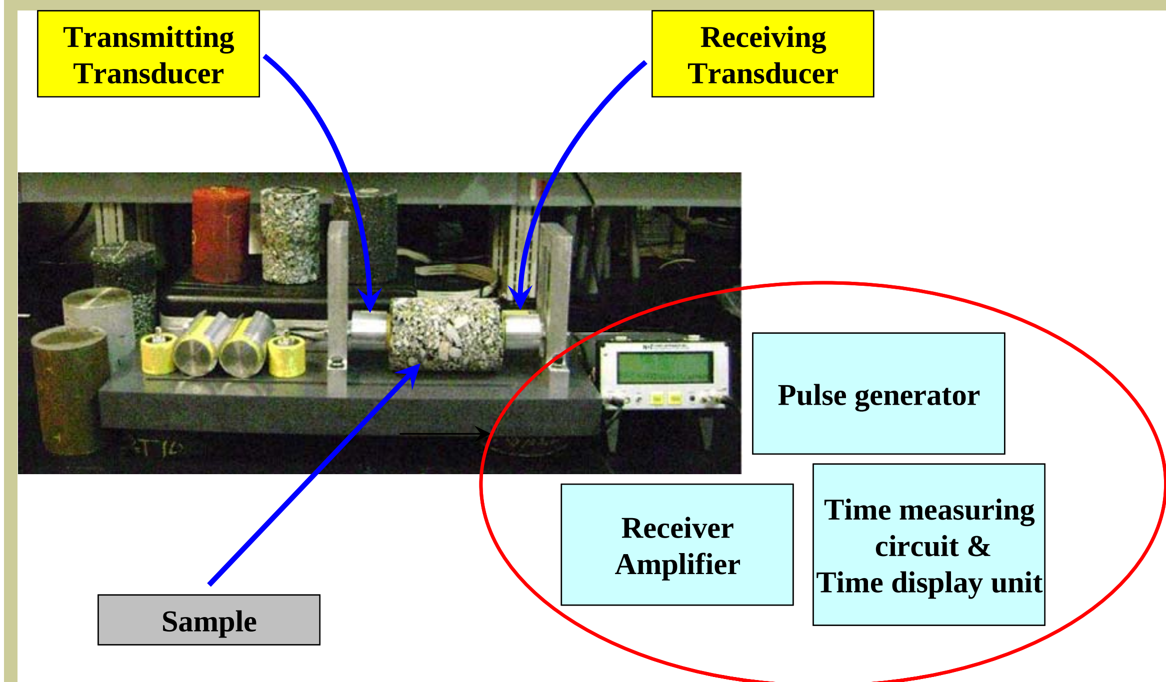
Field EFR	***Laboratory EFR***
ANSI S1.18-1999	ASTM E494-05, 2005; ASTM C597-02, 2002
Template Method for Ground Impedance	Non-destructive Ultrasonic Pulse Velocity
Frequency: 250-4000 Hz (sonic)	Frequency: > 20000 Hz (ultrasonic)
Used only in the field	Can be used in-situ and laboratory
Requires traffic control	Traffic control required only if field cores are needed
Influenced by environmental conditions	Can be done under controlled environmental conditions
Tests can be performed only after pavements are constructed	Laboratory mixtures can be evaluated as part of the mix design process

ULTRASONIC PULSE VELOCITY (UPV) TEST

- **Ultrasonic Pulse Velocity =** $v = \dfrac{L}{T}$

L = Distance (in or m);

T = Ultrasonic Pulse Time (sec)



(ASTM E494-05, 2005; ASTM C597-02, 2002)

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

v = velocity (in/s or m/s),

ρ = density of material (lb/ft^3 or kg/m^3)

E = modulus of elasticity (psi or kPa)

μ = Poisson’s ratio

ULTRASONIC PULSE TIME (UPT) & EFFECTIVE FLOW RESISTIVITY (EFR)

- **Ultrasonic Pulse Time, UPT =** $t_i = \frac{V_i}{v_i}$

t_i = time for the ultrasonic wave to transit into any component (sec)

V_i = unit volume of any component (lb^3 or m^3)

v_i = ultrasonic wave velocity through any component (in/sec or m/sec)

- **Acoustic Impedance (EFR) =** $Z = \rho * v$

Z = acoustic impedance or effective flow resistivity (N-sec/m^3)

ρ = density of material (lb/ft^3 or kg/m^3)

v = ultrasonic wave velocity through the material (in/sec or m/sec)

PRELIMINARY EXPERIMENTAL PROGRAM

Laboratory Mixtures

Mixture Type	Sample ID	Height (in)	Air Voids (%)	Asphalt Content (%)
ADOT-DGAC	KR724	6.0	6.98	5.40
	KR726	6.0	7.29	5.40
	KR727	6.0	6.93	5.40
ADOT-US180-ARAC	I8507	6.0	7.21	8.40
	I8508	6.0	7.08	8.40
	I8509	6.0	7.34	8.40
ADOT-US70-ARAC	70501	6.0	11.34	9.40
	70502	6.0	12.34	9.40
	70503	6.0	13.34	9.40
ADOT-ARFC	AW435	6.0	21.49	8.80
	AW436	6.0	21.49	8.80
	AW437	6.0	21.82	8.80
SRA-E-06-GGAC	SWR01	6.0	1.93	6.00
	SWR02	6.0	1.87	6.00
	SWR03	6.0	1.82	6.00
SRA-E-06-GGAR	SWG01	6.0	1.97	6.70
	SWG02	6.0	1.77	6.70
	SWG03	6.0	2.01	6.70
VTI-OGAR	OGAR90-4	2.7	17.50	9.00
	OGAR90-8	2.8	17.30	9.00
	OGAR70-2	2.4	19.60	7.00
	OGAR70-3	2.7	20.40	7.00
VTI-OGAC	OGAC-OR6	2.4	18.10	7.00
	OGAC-OR2	2.5	12.50	7.00
VTI-GGAR	GGAR-30	2.7	11.20	9.00
	GGAR-40	2.7	12.00	9.00
	GGAR-2G	2.7	13.10	8.00
VTI-GGAC	GGAC-GR1	2.4	3.90	7.00
	GGAC-GR3	2.4	3.90	7.00
	GGAC-GR10	2.4	13.10	7.00
	GGAC-GR13	2.4	11.50	7.00

California Field Cores

Mixture Type	Sample ID	Height (in)	Air Voids (%)	Asphalt Content (%)
UCD-DGAC	QP-40	1.6	5.80	4.80
UCD-RAC-G	ES-12	0.9	8.12	7.00
UCD-RAC-G	QP-02	2.9	8.40	7.00
UCD-DGAC	QP-09	3.9	4.23	4.80
UCD-DGAC	QP-43	4.3	4.73	4.80
UCD-RAC-O F-mix	QP-47	2.0	11.43	8.00
UCD-RAC-G	QP-19	1.7	10.67	7.00
UCD-DGAC	06-N434	2.7	4.10	5.00
UCD-RAC-O F-mix	QP-50	3.0	12.28	8.00
UCD-RAC-O F-mix	QP-52	1.8	8.95	8.00
UCD-RAC-G	ES-12	1.2	8.12	7.00
UCD-OGAC	QP-03	1.6	19.50	8.00
UCD-RAC-G	QP-33	2.5	13.78	7.00
UCD-RAC-G	QP-39	2.4	7.71	7.00
UCD-EU Gap Graded	ES-10	2.3	11.77	7.00
UCD-RAC-G	QP-26	1.7	9.03	7.00
UCD-OGAC	QP-44	1.3	18.78	8.00
UCD-OGAC	QP-04	1.9	16.50	8.00
UCD-RAC-O	QP-51	1.7	21.10	8.00

FIELD CORES – Arizona, California and Sweden

AR-ACFC	SMA	P-ACFC	PEM	ACFC

20.2%	9.7%	18.3%	15.6%	10.9%

Arizona I-10 (Carlson et al, 2008, 2009)

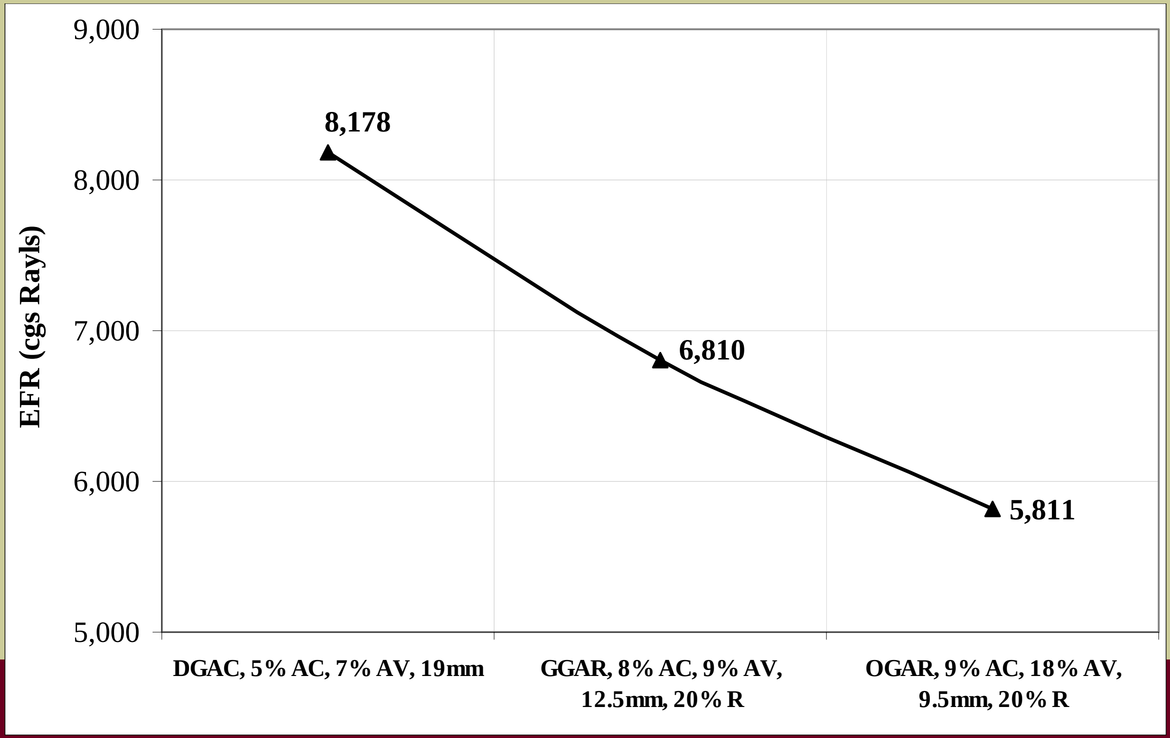
UC Davis, California (Kohler, Dynatest, 2007)

Swedish Transport Institute (Sandberg, VTI, 2007)

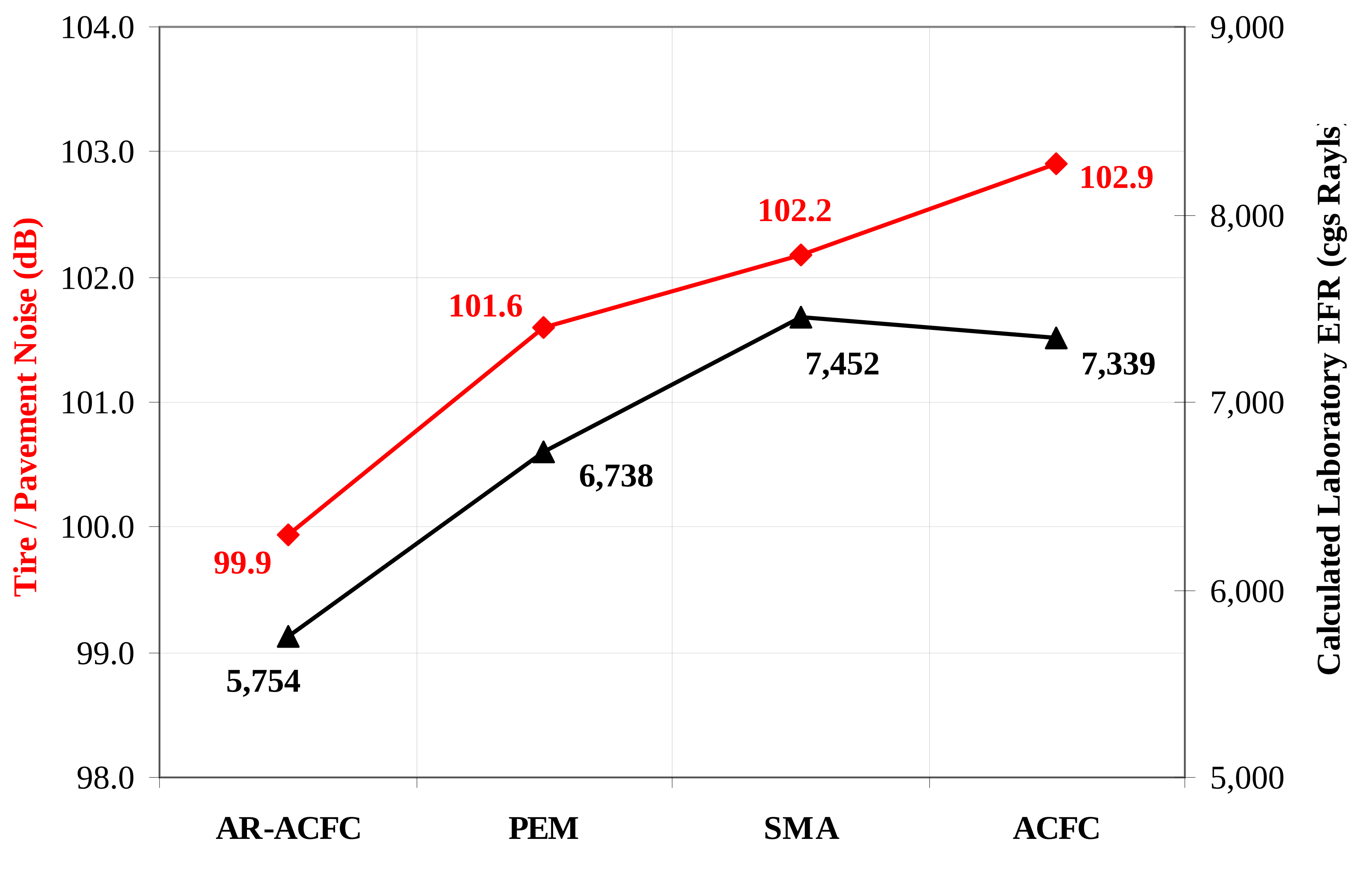
EFR Correlations – Laboratory Mixtures

Pavement Type	EFR [cgs Rayls]
Portland Cement Concrete (PCC)	20,000
Old Dense Graded Asphalt Concrete (DGAC)	14,500
New Bonded Wearing Course (BWC), 30 mm	12,300
Asphalt Rubber Friction Course (ARFC or RAC-O)	6,000 - 6,100
Open Graded Asphalt Concrete (OGAC)	2,000 - 4,200

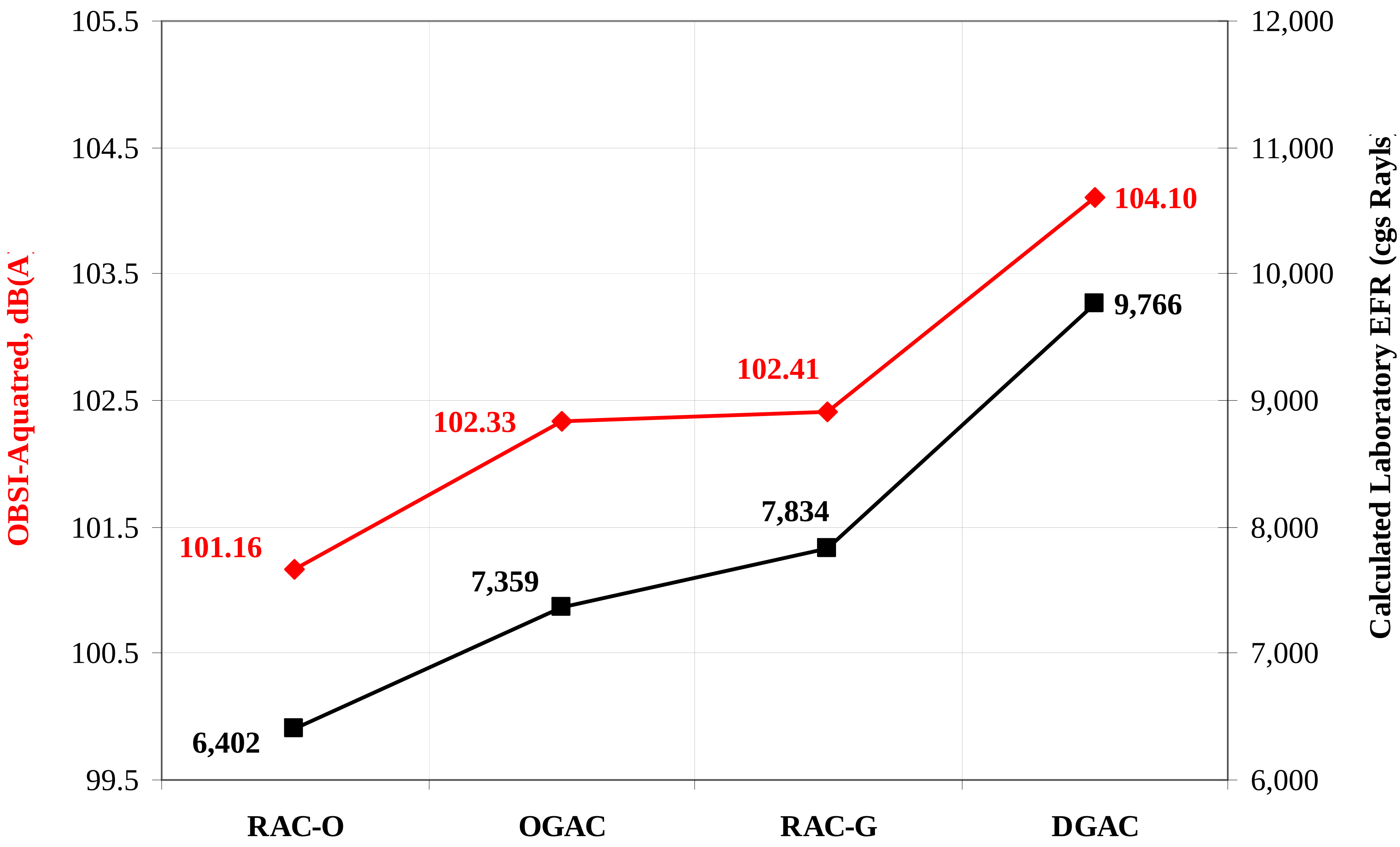
Source: Rochat and Hastings, 2008



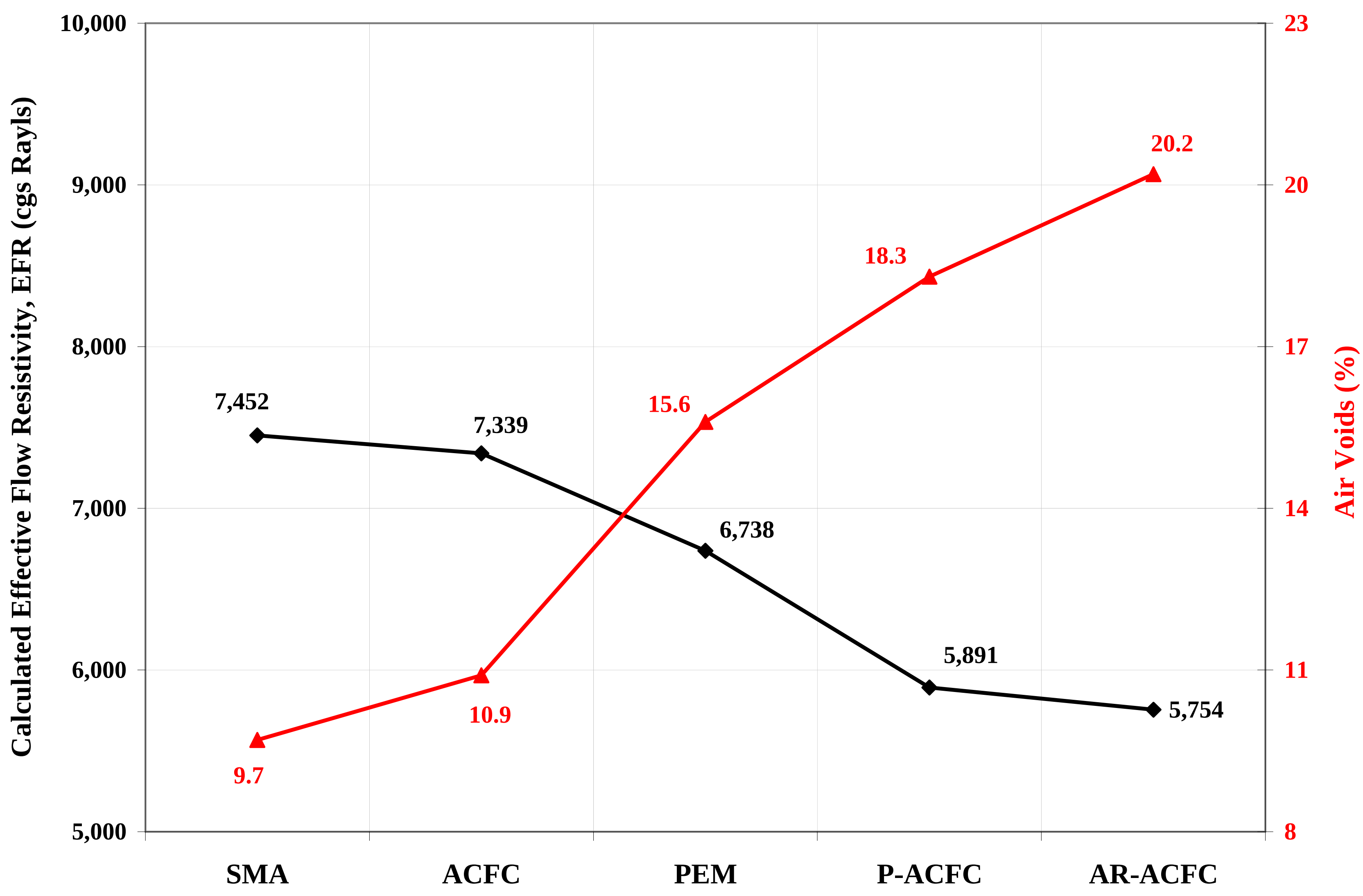
Tire / Pavement Noise and EFR
I-10 Test Sections (Arizona)



Tire / Pavement Noise and EFR
U C Davis California Field Cores (Kohler, Dynatest, 2007)



EFR and Air Voids Relationship – I-10 Test Sections



EFR versus Air Voids

BASIS OF PREDICTIVE MODEL

- **Ultrasonic Pulse Time, UPT =** $t_i = \frac{V_i}{v_i}$

t_i = time for the ultrasonic wave to transit into any component (sec)

V_i = unit volume of any component (lb^3 or m^3)

v_i = ultrasonic wave velocity through any component (in/sec or m/sec)

Total Transit Time = $T_i = t_{aggregate} + t_{bitumen} + t_{air} + t_{rubber}$

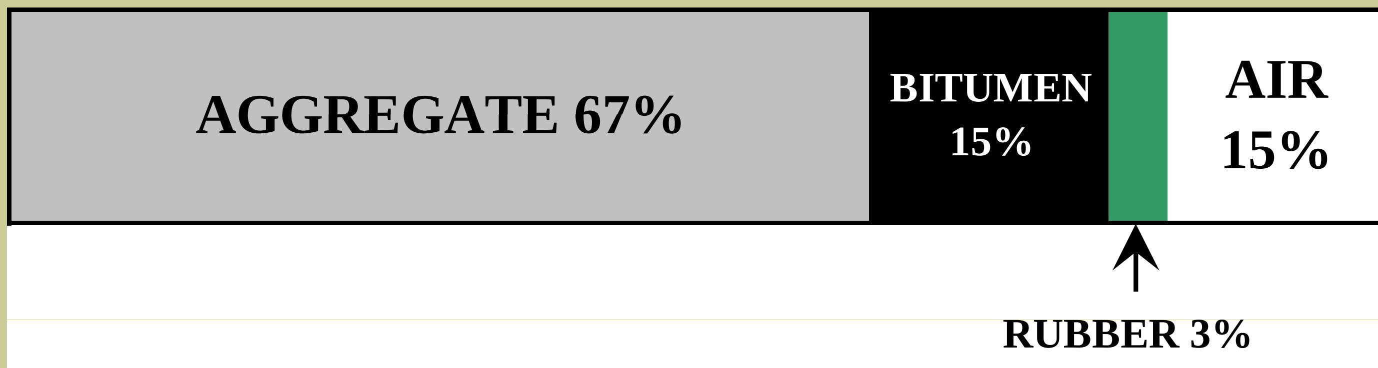
- **Acoustic Impedance (EFR) =** $Z = \rho * v$

Z = acoustic impedance or effective flow resistivity ($N\text{-}sec/m^3$)

ρ = density of material (lb/ft^3 or kg/m^3)

v = ultrasonic wave velocity through the material (in/sec or m/sec)

PREDICTIVE MODEL CONT'D.



Mix	Component	Vol, cc	Surface Area, sq-cm	Velocity, cm/s	Time, s	Total Transit Time, s
Conventional Dense Graded Asphalt	Air Voids	6.86	2500	34,000	8.0738E-08	4.1990E-05
	Rubber	0.00	0	211,500	0	
	Asphalt Cement	11.29	5.8745	180,000	1.0674E-05	
	Aggregate	91.74	5.8745	500,000	3.1235E-05	
Asphalt Rubber Friction Course (ARFC)	Air Voids	17.89	2500	34,000	2.1050E-07	3.1044E-05
	Rubber	3.29	2.1552	211,500	7.2159E-06	
	Asphalt Cement	17.91	10.7758	180,000	9.2342E-06	
	Aggregate	77.49	10.7758	500,000	1.4383E-05	

UPT Analysis Spreadsheet (Draft)

COMPONENT	VALUE
Gb	1.01
Gr	1.1
Gca	2.600
Gfa	2.700
Gmf	2.690
Gmb	2.032
Gmm	2.448
Pb	9
Pr	20
Ma	0
Pca	96
Pfa	4
Pmf	0.4
Ps - Unc1	100.4
Ps - Unc2	91
Ps - Cor	91
Mb	0.1829
Mr	0.0366
Ms	1.8491
M	2.0686
V	1
Gsb	2.3604
Gse	2.8492
VFA	0.2154
Vr	0.0333
Mbe	0.0471
Air Voids	16.9935
Pbe	2.2784
Pba	6.7216
ρ	2.0686

Surface Area Factors of Aggregates					Determination of Weighted Average Sieve Size and its Area		
Aggregate Gradation							
[Sieve Size (in)]	[Sieve Size (mm)]	% Passing	SAF	SA	% Retained	Cum. % Ret.	Wt. Avg.
1.50	37.500	100	2	2	0	0	0.0
1.00	25.000	100	2	2	0	0	0.0
0.75	18.750	100	2	2	0	0	0.0
0.50	12.500	100	2	2	0	0	0.0
0.38	9.375	100	2	2	0	0	0.0
0.25	6.250	68	0	0	32	32	200.0
No. 4	4.750	36	2	0.72	64	32	152.0
No. 8	2.360	4	4	0.16	96	32	75.5
No. 10	2.000	3	0	0	97	1	2.0
No. 16	1.180	2	8	0.16	98	1	1.2
No. 30	0.600	1	14	0.14	99	1	0.6
No. 40	0.475	1	0	0	99	0	0.0
No. 50	0.300	1	30	0.3	99	0	0.0
No. 100	0.150	0	60	0	100	1	0.2
No. 200	0.075	0.4	160	0.64	99.6	0.4	0.0
		ΣSA (sq.ft per lb) =		12.12		100.4	
		ΣSA (sq.m per kg) =		2.4824			

D, ΣWA (mm)	4.3	mm
Area of D (mm^2)	58.4886	mm^2
Area of D (cm^2)	0.5849	cm^2
Area of D (m^2)	5.84886E-05	m^2
Total Vol. of Aggs.	0.7834	cc
Vol. of D size agg.	0.0421	cc
No. of D sieves	19	
D	0.21574	cm

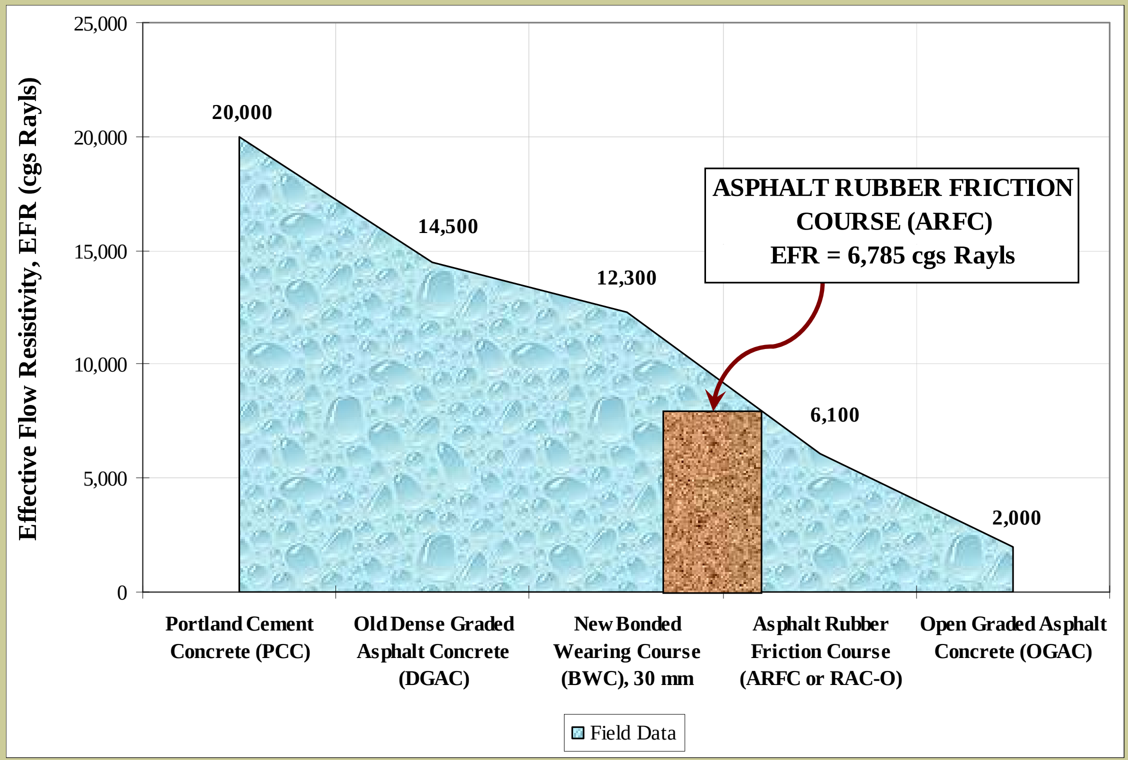
CALCULATIONS OF ULTRASONIC PULSE TIME (UPT); ULTRASONIC PULSE VELOCITY (UPV); IMPEDANCE, Z; EFFECTIVE FLOW RESISTIVITY, EFR

Component	Vol, cc	Density, g/cc	Surface Area, sq-cm	Thickness, cm	Velocity, cm/s	Time, s	Time, µs
Air Voids, a	16.9935	0.0012	2500.0000	0.00680	34,000	1.99923E-07	1.9992E-01
Rubber, R	3.3251	1.1000	2.1787	1.52615	211,500	7.21585E-06	7.2159E+00
Bitumen, b	18.1069	1.0100	10.8937	1.66215	180,000	9.23415E-06	9.2342E+00
Aggregate, A	78.3402	2.6000	10.8937	7.19133	500,000	1.43827E-05	1.4383E+01
					ΣTime (sec) =	3.10326E-05	
					ΣTime (µsec) =	31.03259577	

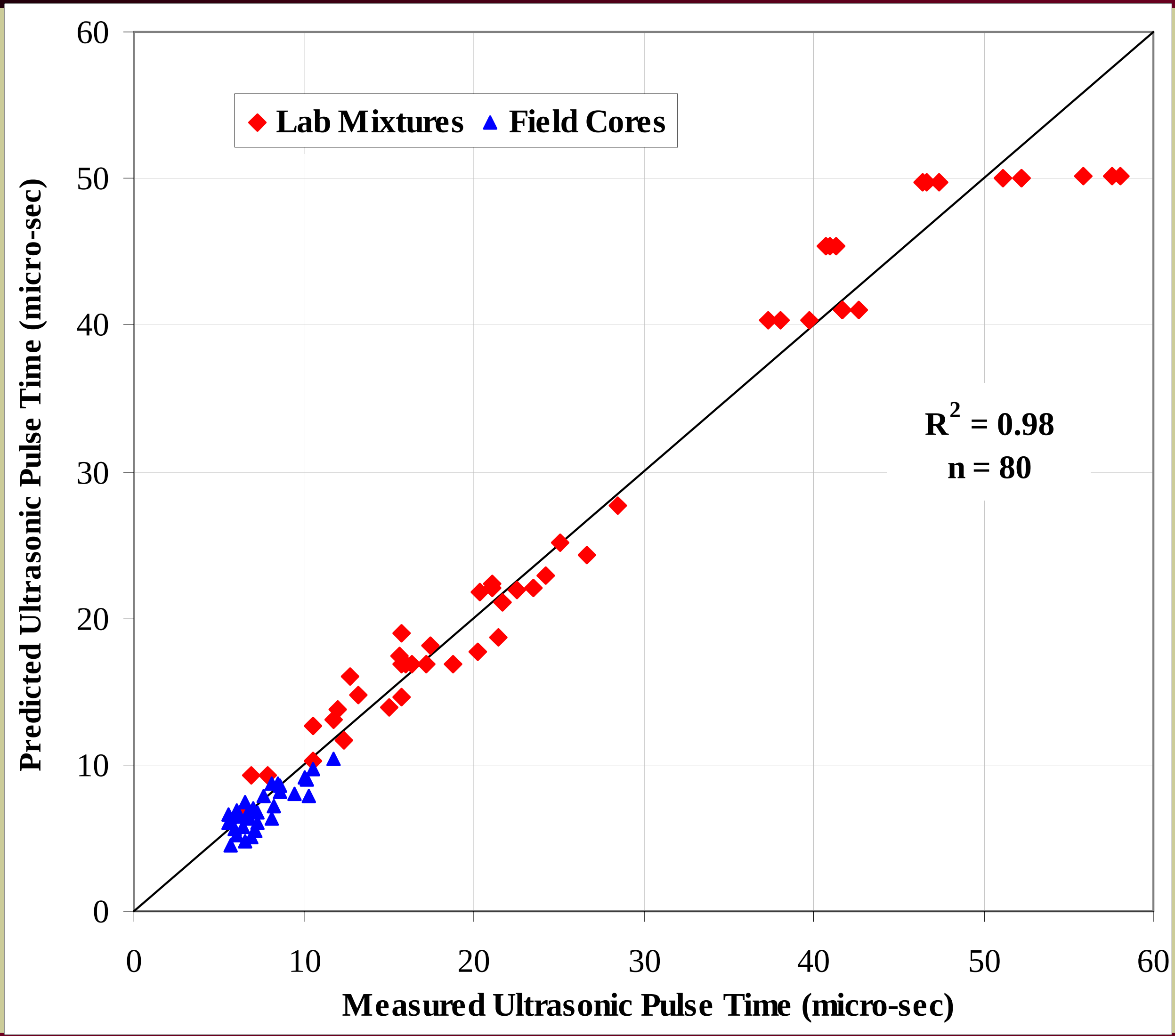
ASU UPT Model

UPT Analysis Spreadsheet (Draft)

ULTRASONIC PULSE TIME (UPT)	31.032596	μs
CALCULATED SAMPLE THICKNESS	10.386431	cm
SAMPLE LENGTH	2.75	in
SAMPLE LENGTH	6.985	cm
CORRECTED ULTRASONIC PULSE TIME (UPT)	20.86979413	μs
SAMPLE LENGTH	0.06985	m
ULTRASONIC PULSE TIME (UPT)	2.08698E-05	sec
ULTRASONIC PULSE VELOCITY (UPV)	3,347	m/sec
DENSITY, ρ	2.0686	g/cc or kg/m^3
Z, IMPEDANCE	67,849	N-sec/m^3 or MKS Rayls
Z, IMPEDANCE [EFR = Input in TNM]	6,785	cgs Rayls



Predicted vs. Measured UPT

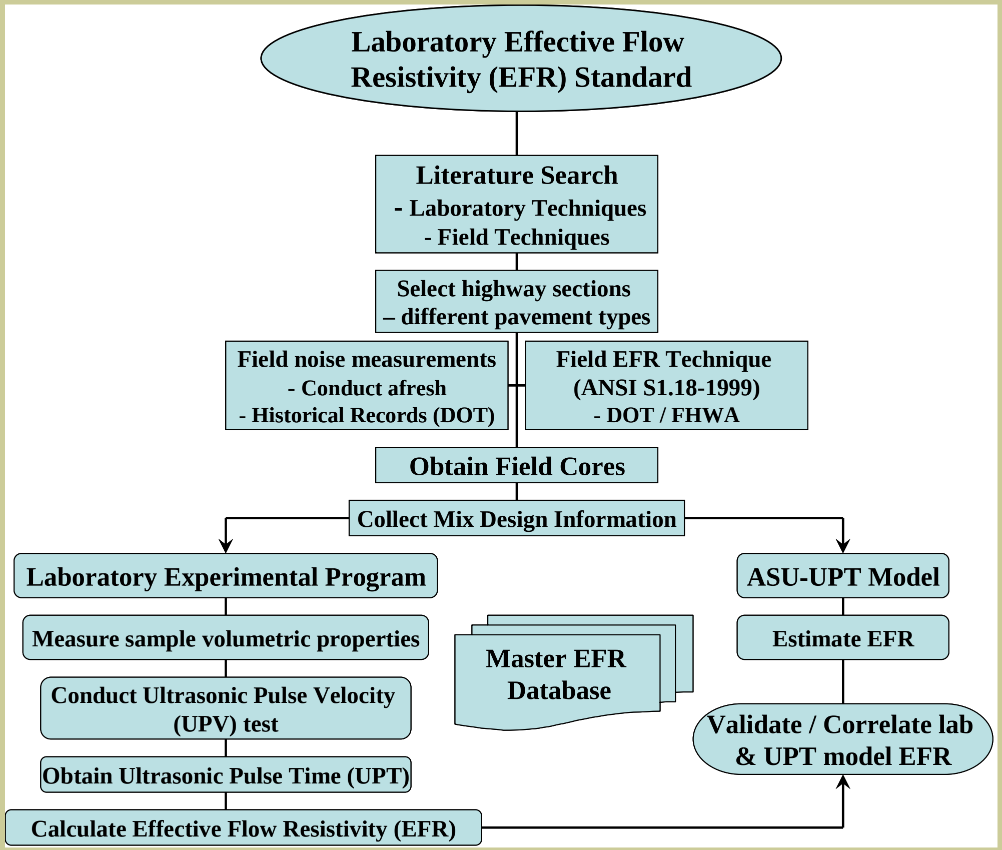


PRELIMINARY CONCLUSIONS

1. **Ultrasonic Pulse Velocity test >> simple assessment tool to calculate EFR of pavement materials.**
2. **Laboratory EFR is in agreement with field measurements (additional testing is needed).**
3. **ASU Ultrasonic Pulse Time Predictive Model:**
   - ***A. Useful and practical tool.***
   - ***B. Requires simple input >> mix volumetrics for the specific pavement type.***
   - ***C. Excellent preliminary correlations (R^2~0.98)***

FOLLOW UP WORK / STUDY

1. Identify and select additional pavement types with different but known noise characteristics; obtain field cores and mix design data from these test sections.
2. Estimate EFR using ultrasonic pulse velocity tests using the field cores.
3. Validate the ASU UPT model using mix design data.
4. Draft a laboratory standard / protocol to estimate the EFR of pavement materials.



Questions & Comments